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# The Impact of Single and Cumulative Applications of Biogas Liquid Digestate on Soil and Plant

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## Abstract

The surge in biogas energy production has resulted in an accumulation of liquid digestate, a byproduct with possible agricultural utility. To discern its benefits and shortcomings, a field trial was conducted to evaluate the effects of different doses of liquid digestate on maize yield, soil salinity, leaf and grain nitrogen (N) content. The study included both single-year and consecutive two-year applications of liquid digestate at doses of 10, 30, 50, and 70 t ha$^{-1}$. Based on maize N requirements, any N deficit was supplemented with chemical fertilizers. For the one-year experiment, the highest grain yield was obtained from the chemical fertilization treatment and 70 t ha$^{-1}$ dose of liquid digestate. In the two consecutive years, 70 t ha$^{-1}$ dose gave the highest grain yield. Liquid digestate provided N to the soil as effectively as chemical fertilization and stabilized the soil pH within approximately 1 month. However high doses of digestate resulted in increased soil salinity and decreased N use efficiency (NUE). Consecutive two-year application increased electrical conductivity (EC) and pH stabilization in the soil to a greater extent than single-year applications. However, there was no difference in the N content of the plant between single-year and two consecutive applications. In summary, liquid digestate provides significant agricultural benefits such as pH stabilization and increased inorganic N levels. However, our findings indicate that overuse can lead to soil salinity and N losses, underscoring the importance of balanced application to maximize its benefits while minimizing potential drawbacks.

**Keywords**: Liquid digestate, maize, nitrogen, soil, electrical conductivity, pH.

## 1. Introduction

Modern agricultural practices aim to continually increase productivity to meet the food needs of the growing global population. However, the excessive use of chemical fertilizers not only disrupts the natural structure of the soil but also leads to environmental issues (Geisseler

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& Scow, 2014; Marschner et al., 2003; Zhong et al., 2010). Among these problems are the adverse effects on soil microorganisms and contamination of water reservoirs (Rohila et al., 2017). Soil conservation and enhancement are at the core of sustainable agriculture. At this juncture, the consideration of natural resources and recyclable wastes as alternatives to chemicals gains significance. In this context, introducing the liquid digestate (LD) resulting from biogas energy production to agricultural use carries the potential to reduce environmental pollution while enhancing soil productivity.

Biomass-based fuels are increasingly crucial in meeting energy needs (Canisares et al., 2017; Rawoof et al. 2021). In particular, biogas stands out as a bioenergy source with a low ecological footprint (Deviren et al., 2017; SAPEA, 2012). The globally rising number of biogas facilities results in an increase in the amount of digestate waste produced (Karimi et al., 2022). Sustainable biogas production necessitates the reuse of by-products to maintain economic balance (Holm-Nielsen et al., 2009). Considering climate change, this can be seen as an opportunity to return digestate to the soil, thereby reducing greenhouse gas emissions and enhancing carbon sequestration in the soil (Karimi et al., 2022). When properly utilized, this material can serve as a soil enhancer and fertilizer, strengthening the concept of circular agriculture (Shi et al., 2018; Jurgutis et al., 2021; Sürmen and Kara, 2022).

During the biogas production process, energy is transferred to methane molecules from organic waste through anaerobic digestion (Angelidaki and Ellegaard, 2003), while nitrogen (N) and other nutrients are retained in the digestate (Massé et al., 2007). The solid fraction of the waste material released after biogas production represents carbon (C) sequestration, while the liquid fraction signifies richness as a plant nutrient source (Robles-Aguilar et al., 2019; Barduca et al., 2021). Although the solid digestate has the potential to increase the carbon content of the soil (Möller, 2015), it carries a risk of significant $NH_3$-N (ammonia) loss during storage due to its high pH value (Brito et al., 2008). When LD is managed correctly, it can serve as a fertilizer and soil amendment (Chookietwattana et al., 2016). The presence of N, phosphorus (P), and potassium (K) elements in LD and the improvement of soil physical properties due to its organic compounds suggest its agricultural importance (Insam et al., 2009). However, since not all organic material can be utilized by microorganisms within the biogas process, digestate can come with potential risks to the soil and environment (Bationo et al., 2007). Residual organic compounds in the digestate may include phytotoxic substances, heavy metals, or excess nutrients that can accumulate in the soil (Singh et al., 2010). For effective use of digestate, outcomes should be determined based on dosage, cumulative effects, and soil type (Karim et al., 2022), and environmental impacts should be researched (Urra et al. 2019).

Especially concerns arise due to its high ammonium ($NH_4^+$) and salinity content, which might lead to adverse effects on soil and plants (Fransman & Nihlgard, 1995). In some regions, these concerns have restricted the agricultural use of LD (Piccoli et al., 2022). Determining the positive and negative effects of this material on soil and plant development is important for assessing its agricultural impact (Diacono ve Montemurro, 2010). However, many studies are based solely on one cultivation season or are short-term experiments under controlled conditions (Głowacka et al., 2020). Furthermore, while the high ammonia nitrogen content in LD seems advantageous in terms of making nitrogen available in a form plants can use, it suggests potential issues like ammonia nitrogen evaporating into the atmosphere and losses in the form of nitrates (Fransman & Nihlgard, 1995; Gurbuz & Oz, 2016; Basak et al., 2020).

This study aims to examine the effect of LD on some soil properties and the yield of maize plants under field conditions. The study evaluated the cumulative effects of LD over two years. Furthermore, effective management and usage of LD in terms of sustainable agriculture were determined as the primary objectives.

## 2. Materials and Methods

### 2.1. Trial area and material

The trial was conducted in 2022 at the Kırklareli Atatürk Soil, Water, and Agricultural Meteorology Research Institute's field, located at a latitude of 41°42'11" N and a longitude of 27°12'29" E. The region's annual average temperature is 13.3 °C, and the total average rainfall is 48.7 mm (TSMS, 2022). There was no rainfall for 9 days following the application of the liquid digestate, but on the 10th day, a precipitation of 5.7 mm was recorded. Rainfall data was monitored with the institute's meteorological station. The soil in the top 0-30 cm layer has a pH of 8.01, a loamy texture, and an organic matter content of 1.39% (Table 1). The soil was analyzed at three depths (0-30 cm, 30-60 cm, and 60-90 cm) to capture the vertical distribution of key soil properties. Soil samples for the results were taken from the 0-30 cm depth. The soil sampling was carried out on 10 May, 20 June, 2 Aug. and 21 Oct. using a soil auger. These dates represent the 1st, 2nd, 3rd, and 4th sampling periods, respectively. These periods were chosen to monitor soil properties at regular intervals from the time of LD application to harvest. For each treatment plot, five soil samples were randomly collected and combined to form a composite sample for this depth. For the study, the DKC6630 grain corn seed from Monsanto, which is commonly used in the region, was selected as the plant material. This variety belongs to the FAO 600 maturity group and is known for its drought tolerance, and resistance to common diseases. It is cultivated as a main crop in the region due to its adaptability to local conditions. Water for irrigation was sourced from a deep well located within the institute's premises. The used water has values of 7.30 ± 0.03 pH, 1.10 ± 0.05 dS m$^{-1}$ EC, 0.14 ± 0.001 $NH_4^+$-N, and 0.68 ± 0.02 $NO_3^-$-N.

**Table 1.** Physical and chemical characteristics of the experiment site soil at different depths (0-30 cm, 30-60 cm, and 60-90 cm).

| | **0-30** | **30-60** | **60-90** |
|---|---|---|---|
| **pH** | 8.01 ± 0.1 | 8.04 ± 0.1 | 8.07 ± 0.15 |
| **EC (dS/m)** | 0.18 ± 0.02 | 0.19 ± 0.02 | 0.19 ± 0.01 |
| **$CaCO_3$ (%)** | 11.02 ± 0.3 | 10.78 ± 0.25 | 9.45 ± 0.25 |
| **Orcanic matter (%)** | 1.39 ± 0.08 | 1.24 ± 0.07 | 1.07 ± 0.06 |
| **$NH_4^+$-N (mg kg$^{-1}$)** | 9.22 ± 2 | 9.10 ± 1,8 | 4.17 ± 2,3 |
| **$NO_3^-$-N (mg kg$^{-1}$)** | 3.41 ± 0,7 | 8.02 ± 1,4 | 14.95 ± 3,6 |
| **$P_2O_5$ (kg da$^{-1}$)** | 9.71 ± 0.3 | 10.14 ± 0.3 | 11.86 ± 0.4 |
| **$K_2O$ (kg da$^{-1}$)** | 44.55 ± 2 | 33.12 ± 1.5 | 25.89 ± 1.2 |
| **Texture (%)** | 47 sand, 30,65 silt, 22,35 clay | | |

EC: Electrical Conductivity; $NO_3^-$-N: nitrate.
Data are presented as mean ± standard error.

## 2.2. Liquid digestate

LD was sourced from a private biogas plant facility situated in the Babaeski district of Kırklareli. This establishment processes roughly 1,050 tons of animal and agricultural organic waste daily, including cattle manure (60%), plant waste (primarily maize and sunflower residues; 20%), sheep manure (10%), and industrial waste (10%), to generate biogas energy. At the facility, the resultant solid-liquid mixture (slurry) is separated using a centrifuge, and the liquid fraction is hygienized at 70°C for 1 hour to neutralize pathogens. Specific characteristics of the liquid digestate are outlined in Table 2.

**Table 2.** Chemical charactiristic of liquid digestate

| | | | |
|---|---|---|---|
| **pH** | 8,90 ± 0.2 | **Organic Carbon (%)** | 0,67 ± 0.03 |
| **Dry matter (%)** | 2,41 ± 0.13 | **K (mg l$^{-1}$)** | 2.387,00 ± 20 |
| **EC (dS m$^{-1}$)** | 23,61 ± 0.4 | **P (mg l$^{-1}$)** | 284,20 ± 2.8 |
| **Total N (%)** | 0,47 ± 0.02 | **Cl (mg l$^{-1}$)** | 6.980,00 ± 69 |
| **$NH_4^+$-N (%)** | 0,37 ± 0.01 | **Na (mg l$^{-1}$)** | 845,00 ± 8.4 |

Data are presented as mean ± standard error.

## 2.3. Experiment set up and practices

The study was conducted in two separate experiment areas: The first area (A) was chosen for a one year liquid digestate application (OYA), while the second area (B) was selected for consecutive two-year liquid digestate applications (TYA) (Fig. 1). Liquid digestate was applied to plots at different doses (10, 30, 50, and 70 tons ha$^{-1}$) 20 days before planting, and in cases of nitrogen deficiency, the specified doses were supplemented with chemical fertilizer. Each treatment had three replicates. Based on the study by Yakan and Saglam (1997), which recommended 210 kg N ha$^{-1}$ to obtain the highest N rate per grain in maize under regional conditions, this amount was adopted for our experiment. The remaining nitrogen requirement after LD treatments (e.g., 10 tons of liquid digestate provides 47 kg N$^{-1}$) was supplemented with urea fertilizer as shown in Table 3. Since the soil already contained adequate levels of phosphorus (P), potassium (K), and trace elements necessary for maize plants, no additional fertilization containing these elements was carried out. Drip irrigation was applied based on the plant's water needs. During the growth period of the plant, soil samples were taken five times in total, and inorganic nitrogen, organic matter, pH, and salinity analyses were conducted. Harvesting was done upon determining the R6 maturity phase, grains were separated from their cobs, moisture percentages were calculated, and samples were taken for protein analyses. The raw yields of all plots were recorded by weighing the grains. Agricultural practices carried out during the study are presented in Table 4.

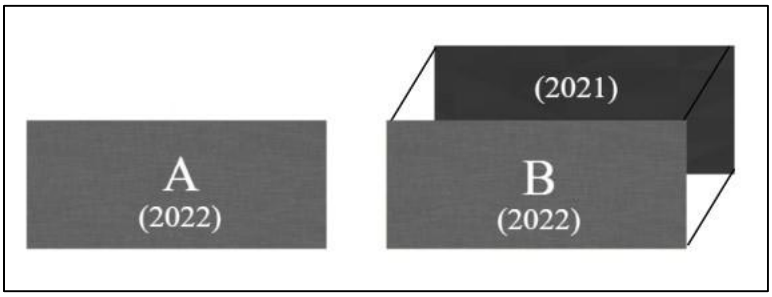



**Fig. 1**. Experiment site layout.

**Table 3.** Experiment topics, application amounts, and periods.

| Treatments | Applications | Mineral Fertilization Periods | |
|---|---|---|---|
| | | *Sowing Period* | *Hoeing Period* |
| **$G_0$** | Control | - | - |
| **$G_M$** | (456 kg $ha^{-1}$ urea) | 228 kg $ha^{-1}$ urea | 228 kg $ha^{-1}$ urea |
| **$G_1$** | 10 ton LD + 330,4 kg $ha^{-1}$ urea | 102,1 kg $ha^{-1}$ urea | 228,2 kg $ha^{-1}$ urea |
| **$G_3$** | 30 ton LD + 78,2 kg $ha^{-1}$ urea | - | 78,2 kg $ha^{-1}$ urea |
| **$G_5$** | 50 ton LD | - | - |
| **$G_7$** | 70 ton LD | - | - |

**Table 4.** Agricultural practices.

| Date | Practices | Date | Practices |
|---|---|---|---|
| 23.04.2022 | Liquid digestate application | 05.06.2022 | Weedicide application |
| 02.05.2022 | Soil tillage | 11.06.2022 | Hoeing |
| 02.05.2022 | Weeding | 07.07.2022 | Second fertilization |
| 11.05.2022 | Fertilization | 14.07.2022 | Weeding |
| 11.05.2022 | Sowing | 19.10.2022 | Harvesting |

## 2.4. Analysis methods

Soil samples' pH and EC values were determined using a 1:2.5 soil-pure water mixture (Soil Survey Lab. Staff, 1975). Organic matter content was detected with the modified Walkley-Black method (Jackson, 1979) while lime (% $CaCO_3$) contents were measured using the Scheibler calcimeter method (Loeppert and Suarez, 1996). Micro-elements were determined in samples digested with a 1:3 $HNO_3$ solution using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) (Sutherland, R. A., 2018). Inorganic nitrogen contains values of

$NH_4^+$-N and $NO_3^-$-N extracted with KCl solution (Bremner, 1965). Available phosphorus was analyzed in the ICP-OES device after being extracted according to the Olsen method. Exchangeable potassium was determined based on potassium values extracted with 1 N ammonium acetate (Soil Survey Lab., 1975). Soil texture was identified using the Hydrometer method (Gee and Bauder,1986).

In LD, a glass electrode pH meter was used to determine pH values (Soil Survey Lab. Staff, 1975), and an electrical conductivity measurement device was used for salinity (EC). Total nitrogen amount was detected using the Kjeldahl method (Bao, 2005). The same method was preferred for inorganic nitrogen values (Apha et al., 2012). Organic carbon was determined after the ashing method. ICP-OES (Kacar and Inal 2010) was chosen for macro-micro elements and heavy metals, and silver nitrate with chromate indicator was selected for Chlorine (Cl) amount (Apha et al., 2012).

For maize grain, yield calculation based on moisture was carried out taking weights at 15.5% moisture value as the basis. Nitrogen ratio in leaves and grain was analyzed with the Kjeldahl method (Apha et al., 2012). Nitrogen use and uptake efficiencies were calculated using the following formulas (Moll et al., 1982). In these formulas, yield with fertilizer (YF) represents the treatment to which fertilizer was applied, and yield with control (YC) represents the control treatment without fertilizer.

Nitrogen uptake amount in grain: % N in grain * YF (t $ha^{-1}$)

Nitrogen use efficiency: [(YF-YC) / N application amount (t $ha^{-1}$)] * 100

### 2.5. Statistical analysis

Statistical analysis of the obtained data was conducted in the SPSS software (IBM Corp., 2017). The experimental design used was the Randomized Complete Block Design, and variance analysis was applied to these data. Potential differences between the resulting mean values were evaluated with the help of the Duncan's multiple range test.

## 3. Results

### 3.1. Soil EC and pH

The LD, due to its high salinity content (25.86 dS $m^{-1}$), has increased soil salinity levels (Fig 2). In OYA, no significant difference in salinity was observed after the 3rd period, while in the TYA, differences were determined in every period. However, starting from the 3rd period, an increase in salinity was also observed in the GM (mineral fertilizer application), so the effect of LD could not be clearly determined for the periods after this. It is assumed that the rainfall over time has reduced the salt content in the soil.

After high-dose LD applications (G5 and G7), an increase in salinity was observed in the 3rd and 4th periods (Fig. 9). However, this increase is not sufficient to change the classification of the soil EC values.

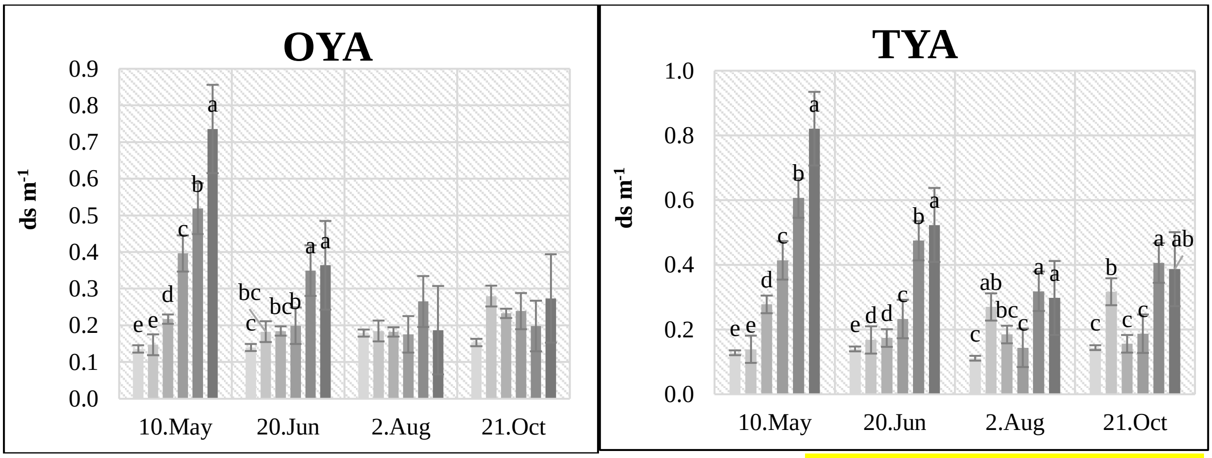
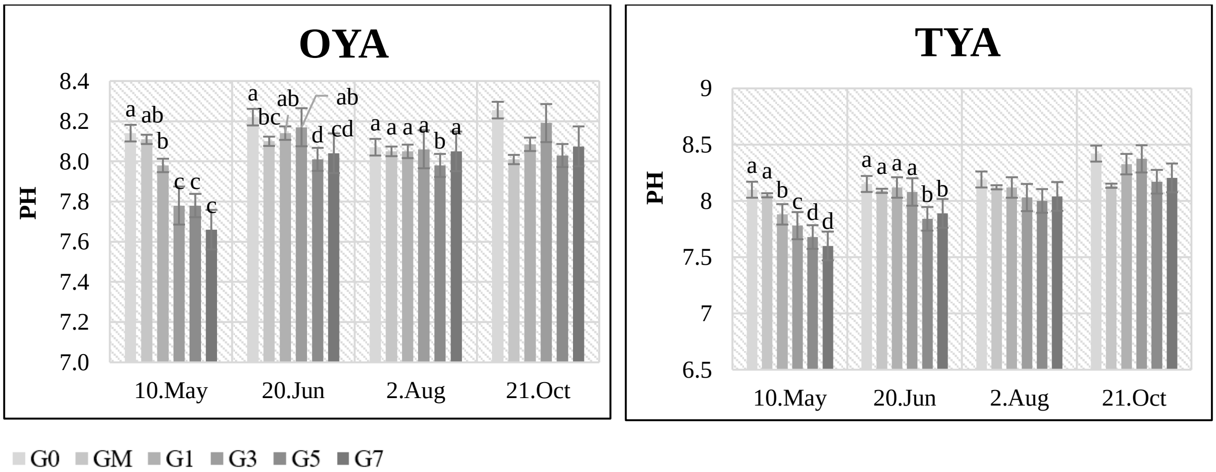



**Fig. 2.** Electrical Conductivity results of the soils sampled on different dates in two types of experiments (one year application, OYA; two consecutive year application, TYA).




<u>Agricultural Applications: </u>23 Apr: LD application.; 11 May: Fertilization, Sowing; 7 Jul: Fertilization; 13 Oct: Harvest

**Fig. 3.** pH results of the soils sampled on different dates in two types of experiments (one year application, OYA; two consecutive year application, TYA). Different letters in each histogram indicate significant differences at $p < 0.05$ (Duncan's Multiple Range Test) among means.

Following the LD application, a decrease in soil pH was observed in the 1st period (Fig. 3), and this decrease was more pronounced in TYA. In the 2nd period, the acidifying effect of the high dose of LD continued in TYA, while the acidic effect of chemical fertilizer application was determined in OYA. In the subsequent periods, no significant difference in pH was observed in either method.

According to the 1st period results of this study, the difference in soil EC results due to the method is statistically significant. In the 2nd period, both the method difference and the interaction between the method and the LD dose are statistically significant (Table 5). TYA led to an increase in soil EC results in both the 1st and 2nd periods. In the same periods, compared to OYA, an increase in soil EC results was observed with all applications except for the G1 treatment (Fig. 4). The changes in soil pH results are consistent with those observed in EC results. In the 1st period, only the method difference was statistically significant, whereas in the 2nd period, the interaction between the method and the LD dose also became important. It was determined that the TYA accelerated the decrease in soil pH values caused by LD (Fig. 5). However, from the 3rd period onwards, the effect of LD on these parameters has decreased.

**Table 5.** Statistical analysis of EC and pH results based on method.

| | **EC (1st Period)** | | **EC (2nd Period)** | | **EC (3rd Period)** | | **PH (1st Period)** | | **PH (2nd Period)** | | **PH (3rd Period)** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *F* | *P.* | *F* | *P.* | *F* | *P* | *F* | *P.* | *F* | *P.* | *F* | *P* |
| Method | 15,718 | ** | 58,152 | ** | 2,933 | * | 6,469 | * | 91,558 | ** | 0,511 | ns |
| Method*Treatments | 1,012 | ns | 15,026 | ** | 2,494 | ns | 0,474 | ns | 7,763 | ** | 1,096 | ns |

F: Indicate the statistical significance from ANOVA
P: ns: not significant, *:<0,05, **:<0,01.

In the 2nd period, a significant interaction was observed between the method and the LD dose. This reveals the impact of both the application method and the LD dose on the soil's pH and EC values. This pronounced effect was detected in measurements taken two months after the application of LD.

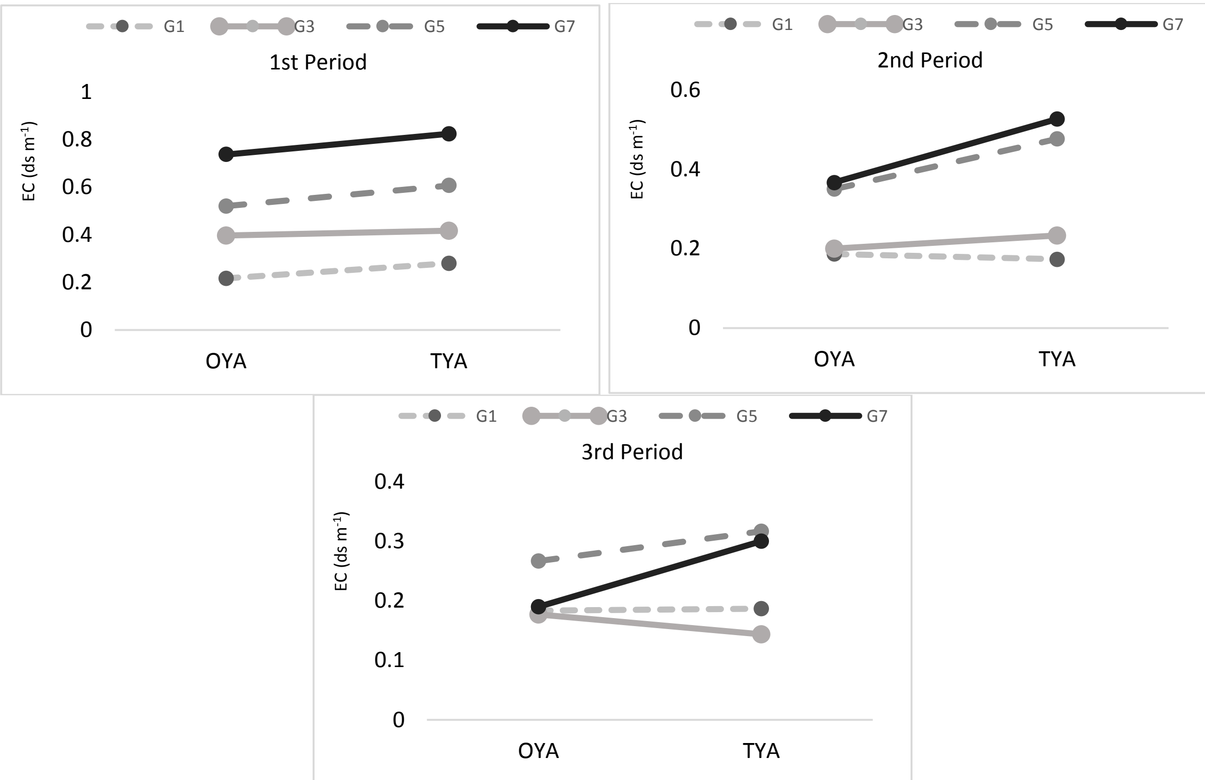



**Fig. 4.** Effect of the method on EC results.

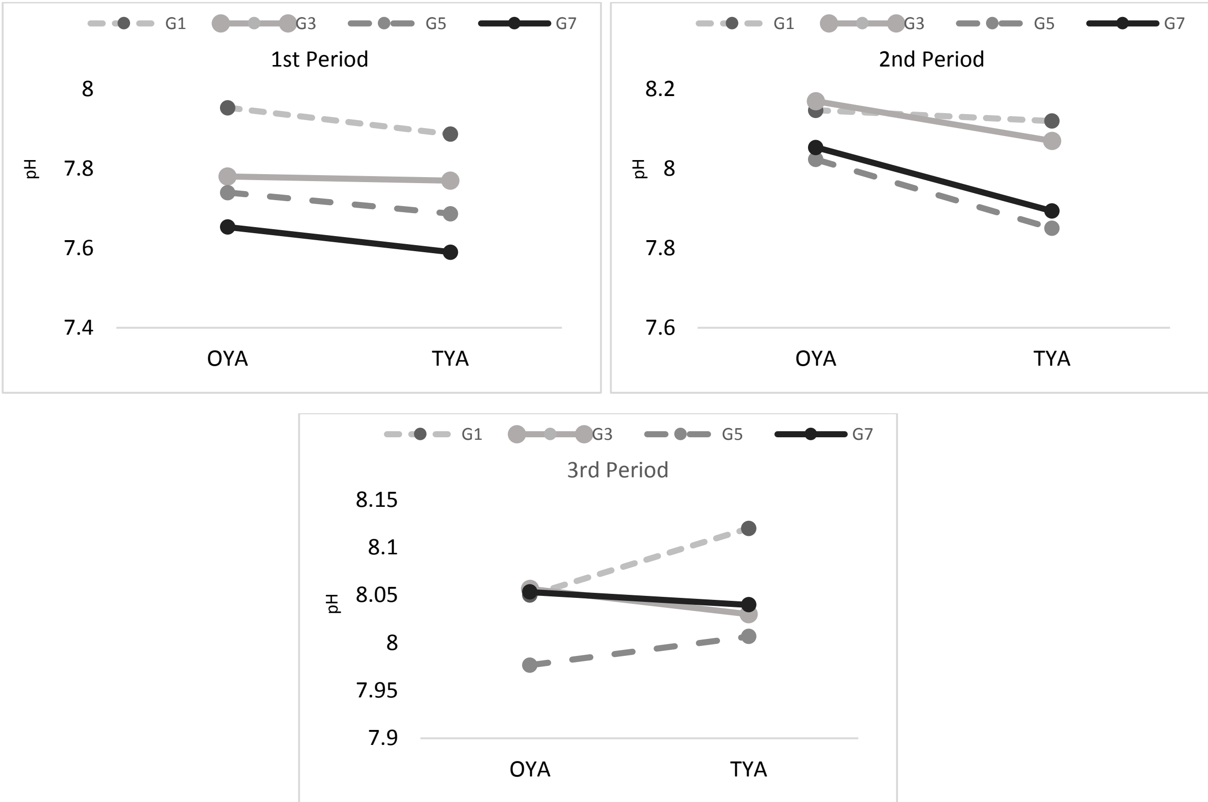
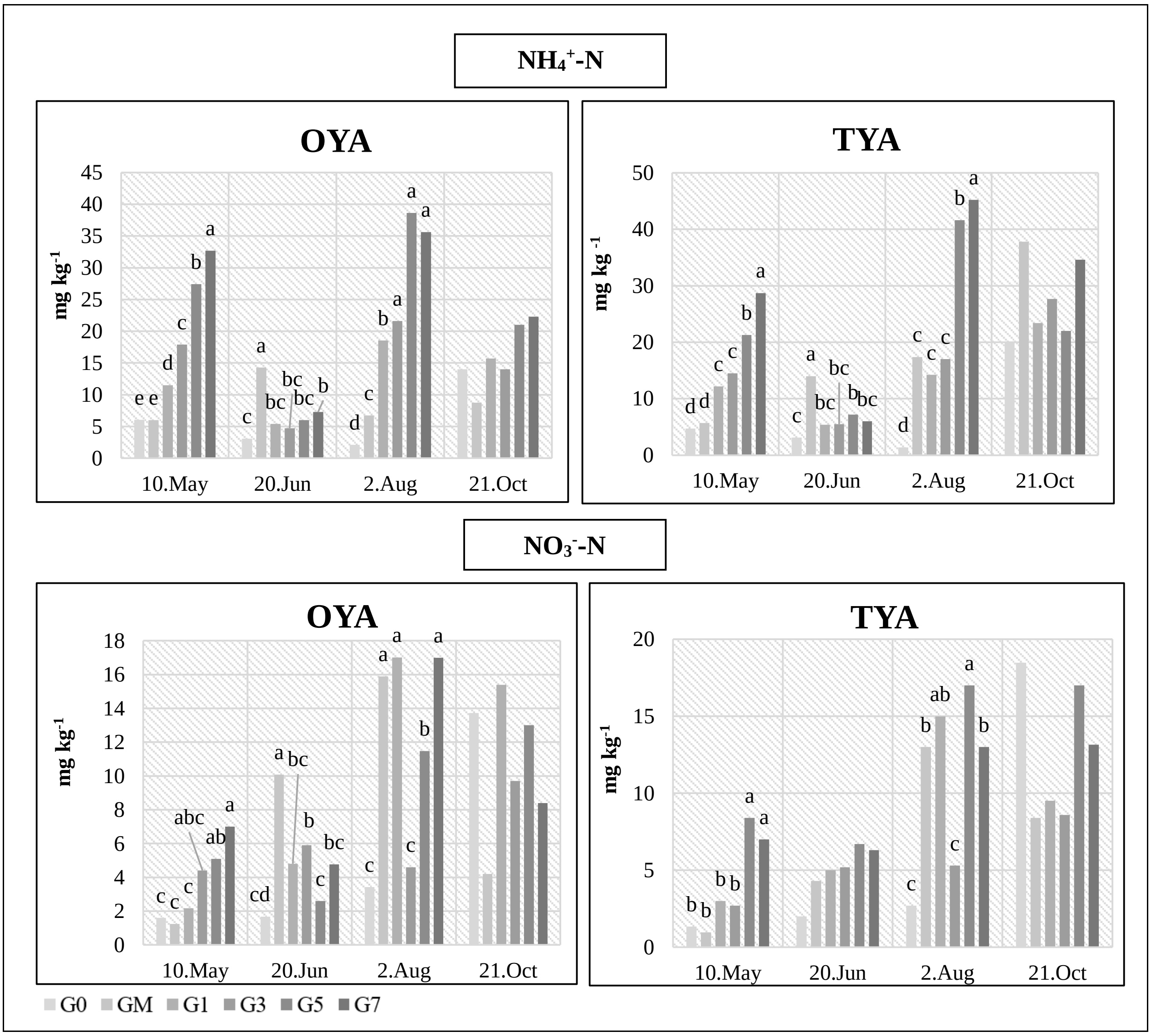



**Fig. 5.** Effect of the method on pH results.

### 3.2. Soil inorganic nitrogen content

LD application on April 23 resulted in monitoring soil inorganic nitrogen ($NH_4^+$-N, $NO_3^-$-N) levels at specific dates (May 10, June 20, August 2, and October 21). When investigating the effect of LD on soil ammonium nitrogen ($NH_4^+$-N) levels, it was identified that as the dosage of LD increased, so did this value (Fig. 9). In the plots where LD was applied, the amount of inorganic nitrogen provided by the mineral fertilizer was observed to be added to the soil (Fig. 6). This finding suggests that LD applications are effective in adding the necessary inorganic nitrogen to the soil for maize plants. When the inorganic nitrogen levels of the soils were analyzed periodically, no significant difference was detected between the application methods. Both after mineral fertilizer application and LD applications, the added soil inorganic nitrogen levels showed similar values.




Agricultural Applications: 23 Apr: LD application.; 11 May: Fertilization, Sowing; 7 Jul: Fertilization; 13 Oct: Harvest.

**Fig. 6.** Values of inorganic nitrogen in the soil in two types of experiments (one year application, OYA; two consecutive year application, TYA). Different letters in each histogram indicate significant differences at $p < 0.05$ (Duncan's Multiple Range Test) among means.

### 3.3. Grain yield and nitrogen parameters in the plant

When comparing the OYA (one-year application) and TYA (two-year application) methods, it was observed that the highest yield in OYA was obtained from the G7 and GM applications, while in TYA, the highest yield was obtained only from the G7 application. During the tassel emergence stage, the highest nitrogen (N) value in the leaves was identified in the G7 application with the OYA. However, in TYA, this value was recorded highest for GM. On the other hand, the lowest nitrogen values were determined for G0 (control) in both methods. Nitrogen ratios of harvested grains were found to be highest in GM and G7 for OYA, and in GM, G5, and G7 for TYA (Table 6).

**Table 6.** Maize grain yield and percentage of total nitrogen in leaves and grains for different treatments in two types of experiments (one year application, OYA; two consecutive year application, TYA).

| Method | Treatments | Grain Yield (t ha$^{-1}$) | N in Leaf (%) | N in Grain (%) |
|---|---|---|---|---|
| OYA | G0 | 13,0 ± 0.5 d | 1,86 ± 0.03 d | 1,03 ± 0.02 c |
| | GM | 18,2 ± 0.6 a | 2,67 ± 0.06 ab | 1,17 ± 0.03 a |
| | G1 | 16,0 ± 0.4 bc | 2,50 ± 0.05 c | 1,09 ± 0.02 b |
| | G3 | 15,7 ± 0.5 c | 2,54 ± 0.04 bc | 1,07 ± 0.02 b |
| | G5 | 17,4 ± 0.5 ab | 2,58 ± 0.05 abc | 1,09 ± 0.02 b |
| | G7 | 19,1 ± 0.7 a | 2,70 ± 0.06 a | 1,18 ± 0.03 a |
| *F* | | 18,09** | 51,89** | 18,34** |
| TYA | G0 | 8,9 ± 0.2 c | 1,59 ± 0.04 d | 0,99 ± 0.02 c |
| | GM | 17,0 ± 0.5 b | 2,79 ± 0.06 a | 1,18 ± 0.03 a |
| | G1 | 16,0 ± 0.4 b | 2,51 ± 0.05 c | 1,09 ± 0.02 b |
| | G3 | 16,4 ± 0.4 b | 2,54 ± 0.05 c | 1,09 ± 0.02 b |
| | G5 | 17,9 ± 0.6 ab | 2,67 ± 0.07 b | 1,14 ± 0.03 a |
| | G7 | 19,4 ± 0.8 a | 2,73 ± 0.06 ab | 1,17 ± 0.03 a |
| *F* | | 38,64** | 182,19** | 26,01** |

Different letters in each histogram indicate significant differences at $p < 0.05$ (Duncan's Multiple Range Test) among means.
F: Indicate the statistical significance from ANOVA.; *: < 0.05, **: < 0.01

Between the methods, although the effect of LD on yield and nitrogen ratios in the plant has not shown a statistically significant change (Table 7), higher yields have been achieved with the TYA in G3, G5, and G7 treatments (Fig. 7). Additionally, in the TYA, a dose of 50 tons ha$^{-1}$ of LD has provided a higher yield compared to mineral fertilization, which is different from the OYA. Within the method framework, there is no linear increase in the amount of nitrogen in the plant with the LD dose.

**Table 7.** Statistical analysis of yield and nitrogen results based on the method.

| | Yield | | N in Leaf | | N in Grain | |
|---|---|---|---|---|---|---|
| | F | P. | F | P | F | P. |
| Method | 1,023 | ns | 1,284 | ns | 2,532 | ns |
| Method*Treatments | 0,135 | ns | 0,463 | ns | 1,604 | ns |

F: Indicate the statistical significance from ANOVA.
P: ns: not significant.

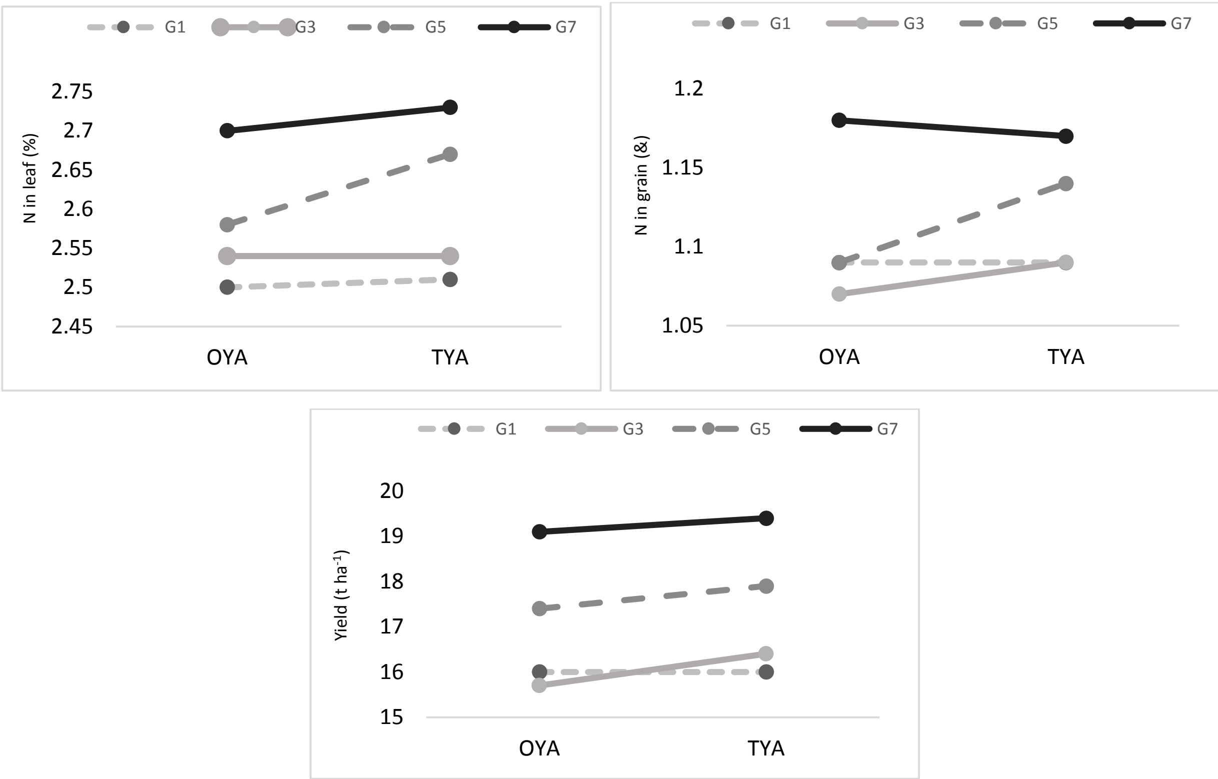



**Fig. 7.** The effect of the method on grain yield and nitrogen values.

Nitrogen uptake and nitrogen use efficiencies have followed similar trends for both methods. An increase in LD dosage has increased yield and thus grain nitrogen uptake, and a higher value has been determined at a dosage of 70 tons ha$^{-1}$ compared to mineral fertilization.

G5 and G7 applications have had the lowest nitrogen use efficiency (NUE) compared to other treatments (Fig. 8). This is because the amount of N applied in these treatments was higher than in other treatments. In terms of NUE results, GM, G1, and G3 treatments can be compared as they were given the same amount of nitrogen to the soil. GM had the highest nitrogen use efficiency. However, despite the difference in LD dosages between G1 and G3 applications, obtaining similar NUE values indicates that an increase in dosage after 1 t ha$^{-1}$ LD did not create a significant change in NUE. In G1 and G3 applications, which are combinations of LD with chemical fertilizer, NUE has shown a similar trend. However, in the TYA, G3 has had higher nitrogen uptake and NUE values compared to G1.

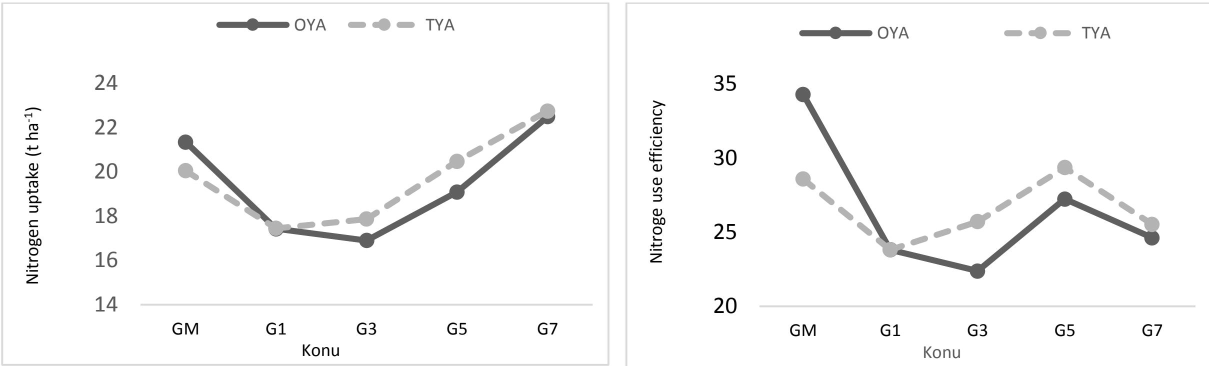
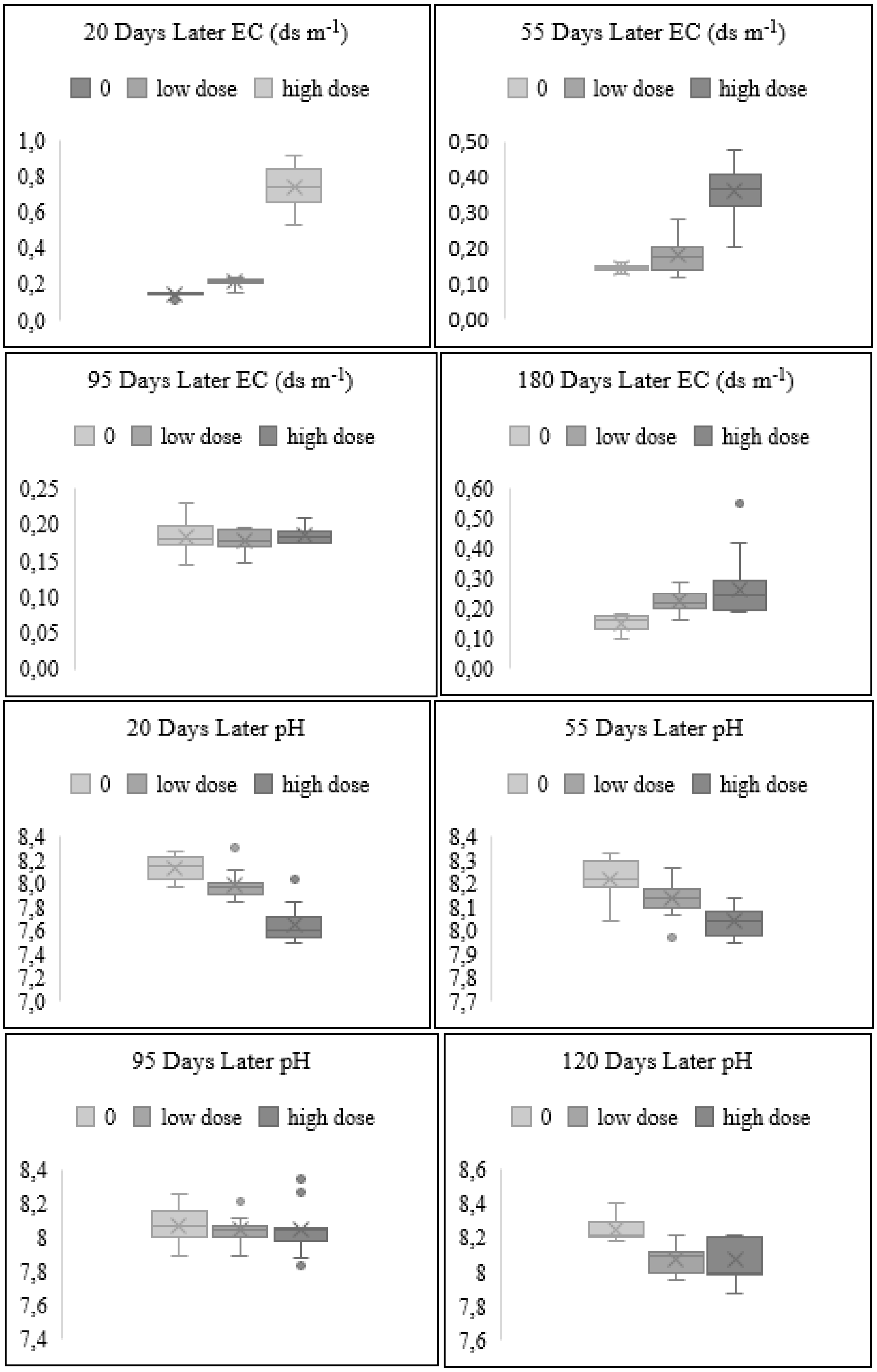
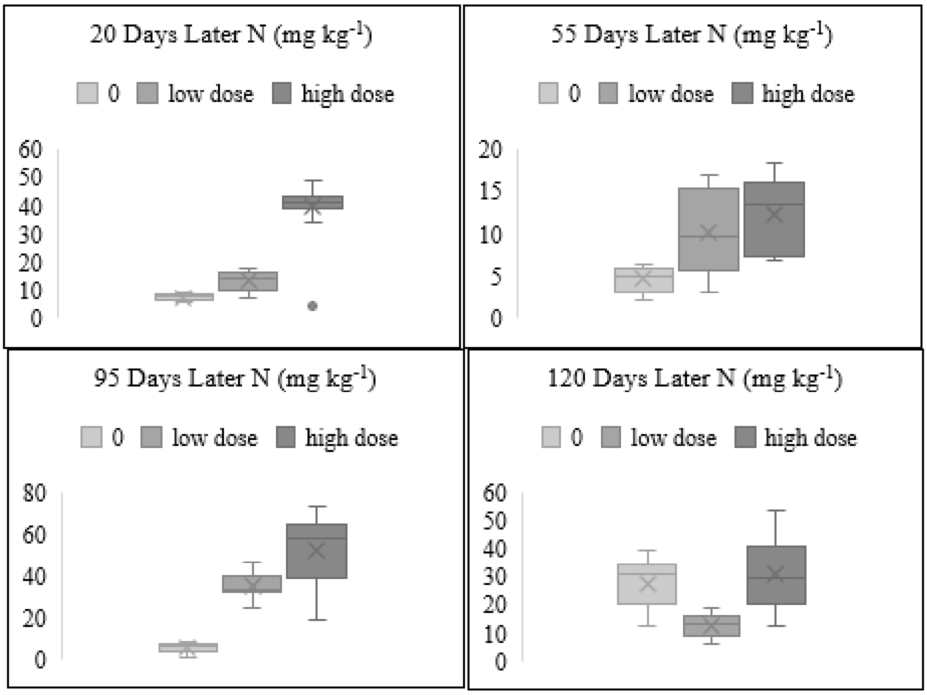



**Fig. 8.** Grain nitrogen uptake and nitrogen use efficiency.






Low dose: 10 t ha$^{-1}$ LD, High dose: 70 t ha$^{-1}$ LD

**Fig. 9.** The effect of low and high doses of LD on inorganic nitrogen (N), pH, and EC parameters in the OYA.

## 4. Discussion

### 4.1. EC and pH

Throughout the first two periods, an increase in the application of the LD was observed to proportionally elevate the salinity (EC) values in the soil. However, after the 3rd period, this rise was noted to decrease. This suggests that the rainfall during the trial period might have reduced the salt content in the soil. Additionally, the high sand content of the research soil has facilitated the leaching of EC. While Panuccio et al. (2021) emphasized that the solid fraction of biogas increased the EC value in the soil, Aimrun et al. (2009) have pointed out that soil salinity can vary with many factors and determining these dynamics is complex.

A notable decrease in soil pH values was recorded after LD application. Similar reductions were observed in the first period with doses of 3.5 and 7 tons/da, whereas in the second period, it was determined that chemical fertilizer applications also caused a slight acidifying effect in the soil. The acidification became more pronounced with the impact of LD but diminished in subsequent periods. While Jia et al. (2013) stated that the LD raised soil pH values, Ren et al. (2020) observed a slight decrease. Panuccio et al. (2021) also pointed out that LD application neutralized the pH value in high pH soil. El-Khatib et al. (2018) noted that biogas fermentation residues lowered the soil pH and that the main reason for this decrease was organic acids and ammonium ions. Brady and Weil (2016) also mentioned that high $NH_4^+$-N concentrations in the soil could lead to acidification by releasing $H^+$ ions through nitrification.

### 4.2. Yield and nitrogen results

The application of LD positively affects grain yield and increases the yield as the dosage amount increases. The results of various studies have demonstrated the positive effects of LD on different plants. Specifically, Zhao et al. (2022) and Yaraşır (2018) noted a significant increase in plant height, branch count, pod count, and yield in the rapeseed plant due to LD. These findings are corroborated by another study conducted by Du et al. (2019) in maize. Furthermore, Głowacka et al. (2020) reported the potential to obtain a higher biomass by reducing the use of mineral fertilizers with digestate. In their study, where they applied doses of biogas digestate compared with irrigation water in a maize experiment, it was determined that an increase in the applied dose amount also increased the yield.

According to the study, the effect of LD on the soil's inorganic nitrogen amount is similar to that of chemical fertilizer application. Due to the high $NH_4^+$-N content of the LD, it is anticipated to have a positive impact on grain yield compared to organic fertilizers (Möller & Müller, 2012; Nkoa, 2014; Du vd., 2019). This positive effect has been identified by Al-Juhaimi et al. (2014) on alfalfa and by Ernst et al. (2008) as well as Chantigny et al. (2008) on other plants. Barłóg et al. (2020) have suggested that the digestate can replace urea fertilizer as a nitrogen source in the soil.

The nitrogen levels detected in leaves and grains have been found to be consistent with the effect of LD on the inorganic nitrogen values in the soil. Variability in the concentration of $NH_4^+$-N or $NO_3^-$-N in the soil can be a determinant on the nitrogen uptake of plants (Pan et al., 1995; Barber et al., 1992). In maize, in particular, the amount of inorganic N in the soil, as well as the form in which the plant takes up nitrogen, can influence the nitrogen rate in the leaves at different growth stages. Significant findings on the dynamics of $NH_4^+$-N in the soil have been provided by Köster et al. (2011) and Nyberg et al. (2004). Notably, it has been indicated that certain substances that limit losses of $NH_4^+$-N in the form of $NH_3^-$-N may be present depending on the dose of LD.

In the study, no difference was determined between the one-year application (OYA) and the consecutive two-year application (TYA) methods in terms of inorganic nitrogen amounts in the soil. However, De França et al. (2021) in their study pointed out that the effect of the digestate on the amount of nitrogen in the soil is more effective with the OYA than the TYA.

Compared to chemical fertilization, the NUE has decreased with LD applications, but there has been no significant difference in terms of NUE between the 10 and 30 t $ha^{-1}$ applications. This suggests that LD application could lead to nitrogen losses in the soil. Materials with a low C/N ratio can promote a rapid mineralization process in the soil, leading to nitrogen losses

(Brady & Weil, 2008). The fermentation process reduces the C/N ratio of organic wastes. In this context, the C/N ratio of 1.42 of the LD applied to the soil in our study may have triggered nitrogen losses.

## 5. Conclusion

This study comprehensively examines the effects of the liquid digestate (LD) obtained following biogas energy production on soil and maize plants. The impacts of various LD doses (10, 30, 50, and 70 tons $ha^{-1}$) have been evaluated in one-year and consecutive two-year applications.

The results show that for maize grain yield and nitrogen parameters, mineral fertilization treatment and 70 tons $ha^{-1}$ liquid digestate dose were the most efficient in one-year application, while 70 tons $ha^{-1}$ dose application was the most efficient in consecutive two-year application. Especially, the grain yield obtained with a 70 tons $ha^{-1}$ dose was found to be considerably higher than the control group and other doses. However, it was determined that with the increase in liquid digestate doses, soil salinity also increased. This became particularly pronounced in two-year applications. It was observed that within the first two months, the digestate application lowered the soil pH value, but this effect did not show significant change in the subsequent months. The effect of the liquid digestate on the soil's inorganic nitrogen amount is similar to chemical fertilizer applications. However, it was observed that nitrogen use efficiency is lower in 50 and 70 tons $ha^{-1}$ dose applications. In the applications of liquid digestate, potential nitrogen losses were determined due to its high ammonium content.

Based on the findings of this study, future experiments should consider the application of similar N, P, and K inputs, as well as uniform water application in each period for all treatments, to ensure a comprehensive evaluation of the effects of liquid digestate.

In conclusion, it was noted that the liquid digestate has potential value for agricultural applications. However, it was concluded that with an increase in the dose amount of this product, soil salinity might increase and ammonia and nitrate losses should not be overlooked in high-dose applications. This study contributes to the accurate evaluation of the impacts of the liquid digestate obtained after biogas energy production in agricultural applications. Taking into consideration the sustainability and environmental effects of the applications will ensure the efficient and effective use of liquid digestate.

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