

Monitoring of soil nutrient levels by an EC sensor during spring onion (*Allium fistulosum*) cultivation under different fertilizer treatment

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Abstract

Balanced nutrients are essential for healthy plant growth, but there is no sensor available to monitor essential nutrients such as N and K. Electrical conductivity (EC) is one of the key parameters that could be adopted to monitor these nutrient contents because soil EC is influenced by available nutrients. Therefore, the main objective of this study was to examine the effects of different basal fertilizers including inorganic, organic, and compost fertilizers, and the application ratio of basal and additional fertilizers on nutrient contents by EC sensor. The applied basal and additional fertilizer ratios were N 30:70, K 40:60, and N 20:80, K 20:80, respectively, for each fertilizer treatment. EC sensor value was positively associated with water content. Soil EC response increased with the application of inorganic fertilizer and fertigation and was positively correlated with soluble nutrients and exchangeable ammonium. The principal component analysis also determined that inorganic fertilizer was positively associated with sensor EC, soluble Na, Ca, Mg, and nitrate among the variables. This work suggested that soil available nutrients especially N can be monitored by an EC sensor which can be used to control soil nutrient status for better plant growth.

Introduction

Crop development and productivity are hampered without sufficient nutrients, but 60% of cultivated soils globally have growth-restraining problems from shortages and excess mineral nutrients (Cakmak et al. 2002). Worldwide population growth will necessitate a greater than 70% increase in food production (Godfray et al. 2010). As a result, farmers' preferred strategy for successfully raising yield is the prolonged use of a huge quantity of agrochemicals and nutrient fertilizers (Zhang et al. 2018). This has gotten worse because of ongoing agricultural practices without adequate knowledge (Kimani et al. 2003). However, excess usage of fertilizers can lead to a variety of issues including nutrient loss, ground and surface water contamination, eutrophication, acidification or basification of the soil, and declines in beneficial microbial populations (Wu et al. 2020).

As a result, it is now commonly accepted that organic residues like crop leftovers, animal manure, or compost are essential sources of agricultural fertilizer that can be used to boost agricultural yield and soil health. Nevertheless, the adequate quantity of basal fertilizer may not be enough when plants are in different growth phases, which results in several symptoms like reduced plant growth, decreased chlorophyll content, browned leaves, and curled leaf tips (Morgan and Connolly 2013). Therefore, it must be taken into consideration while applying fertilizer at various phases of plant growth. However, applying fertilizers without monitoring soil nutrients could severely affect the plant, soil, and surrounding environment suggesting that the agricultural sector be less reliant on conventional farming (PSA 2016).

Excess nutrients are not necessarily beneficial for crop yield. According to Qu et al. (2019), cucumber yield rose with increasing fertilizer rate up to a threshold, but it declined once the usage of fertilizer is beyond the threshold. Therefore, balanced nutrients are essential for optimum plant growth, which can be accomplished by smart farming technology (Paharaj et al. 2007). The agricultural sector needs to adopt high-tech technologies to meet the food demand while reducing the detrimental environmental impact caused by over and inappropriate fertilization management (Zhang et al. 2018; Willett et al. 2019). This technology enables farmers to reduce resource input and increase crop yield by providing accurate nutrient information (Burton et al. 2020). The yield of bitter melon is enhanced by providing a sufficient amount of fertilizers with smart farming technology compared to conventional farming (Zhang et al. 2018b).

Therefore, over the last few decades, developing countries have taken the initiative to integrate information technology into the agriculture sector to monitor real-time nutrients (Ishida et al. 2019). Different techniques are available to measure soil nutrients including the random grid sample, visible near-infrared spectroscopy (Vis-NIR), attenuated total reflectance (ATR) spectroscopy, Raman, and electrochemical sensor-ion selective electrode (ISE) and ion-selective field effect transistor (ISFET) (Burton et al. 2020). However, no direct sensors are available to monitor essential nutrients such as N and K in soil.

The EC sensor can be used to monitor available nutrients in soil because a higher EC denotes a higher number of ions in soil solution (Othaman et al. 2021). However, in order to properly monitor soil nutrient status, it is crucial to identify the variables that influence sensor EC. Therefore, the main objective of the study is to evaluate the possibility of employing an EC sensor to monitor the nutrient status of different fertilizers applied to the soil and factors related to EC sensor values.

Materials And Methods

Fertilizer treatment of spring onion field

Before planting spring onions (*Allium fistulosum*), the soil was sampled and tested for available nutrients. According to the soil test results, the recommended dose of basal fertilizer was added to the experimental area. Experimental areas were divided into six different parts (3.4 m in each part) and different basal fertilizers were applied on 15th April 2021 as inorganic, organic (mixed oilcake), and manure compost fertilizers. Spring onion seedlings were transplanted on 23rd April 2021 and cultivated by applying additional fertilizer with an automatic fertigation system to supply N and K as urea and KCl, respectively. During the spring onion cultivation, the water potential was maintained at -33 kPa. The applied basal and additional fertilizer ratio was N 30:70, K 40:60, and N 20:80, K 20:80, respectively, for each basal fertilizer treatment. The additional fertigation (five times) was supplied 30 days after transplanting (DAT) and every two weeks from June to July 2021 (Supplementary Table 1) (Lee et al. 2022).

Monitoring Of Soil Ec Using A Sensor

During the cultivation, electrical conductivity (EC) sensors (Teros 12, Meter Group, USA) were inserted into the soil to monitor water content and changes in soil bulk EC. The soil sensor was buried about 10 cm from the soil surface between two spring onions in a furrow in the middle of the treated plot. Soil sensors were connected to a data logger (Zn6, Meter Group, USA), and water content, soil temperature, and bulk EC were collected every 15 min.

Analysis Of Soil Chemical Properties

Spring onion plants were harvested on 6th August 2021 (105 DAT) and soils were collected from the different fertilizer-treated plots at 32 DAT, 66 DAT, and 102 DAT. Composite soil samples were mixed properly and air-dried at room temperature for 2 days. After air drying, the soil was passed through a 2 mm stainless steel sieve and stored in an airtight polythene bag until further use. For analyzing pH and EC, 5 g of soil was placed in a 50 mL conical centrifuge tube with 25 mL of distilled water, shaken at 120 rpm for 30 min, and pH and EC of the supernatant were measured using pH and EC meter (Orion Star A215, Thermo Scientific). Water soluble soil nutrient contents were determined by an inductively coupled plasma optical emission spectroscopy (ICP-OES, Avio 500, Perkin Elmer) after extracting 5 g soil with 25 mL distilled water in a 50 mL conical centrifuge tube at 120 rpm for 30 min. Available nutrient concentrations in soil were analyzed by ICP-OES after extracting 2 g of soil with 20 mL 1 M ammonium acetate solution (NH₄OAC) for 30 min.

Statistical analysis

Statistical analysis of experimental data was performed using Statistical Packages for Social Sciences (SPSS Statistics 27, IBM). The correlation analysis among soil properties under different fertilizer treatments and principal component analysis (PCA) was conducted using XLSTAT software. Analysis of variance (ANOVA) was used for mean comparisons among treatment groups at p-value < 0.05.

Results And Discussion

Effect of different basal fertilizers on soil chemical properties

Soil pH was moderately affected by the treatment of various basal fertilizers (Table 1). The results revealed that soil applied with organic fertilizer (N80; K80) exhibited lower pH and a higher amount of basal fertilizer (N70, K60) showed a relatively higher pH (Table 1). The release of a hydrogen ion from the quick degradation of biomass by microbial flora may be the cause of the lower soil pH following the application of organic fertilizer. Anda et al. (2008) stated that the initial soil pH decreased from 6.4 to 4.6 because of the application of organic fertilizer and quick degradation of the biomass into dissolved organic acids. According to Chang et al. (1990), soil pH decreased when organic fertilizer was applied more frequently or in a higher dose. Rapid nitrification of NH₄-N in the soil also could reduce pH (Eghball 2002). The pH was inversely related to nitrate concentration because nitrification releases protons and reduces soil pH (Table 2) (Souza et al. 2023).

Table 1
Biochemical properties of soil applied with different fertilizers

	pH	EC (mS/cm)	NO ₃ -N (mg/kg)	Ex. K (mg/kg)	Ex. Ca (mg/kg)	Ex. Mg (mg/kg)
Inorganic fertilizer (N70, K60)	5.64 ± 0.05ab	1.15 ± 0.04c	32.7 ± 5.2b	0.81 ± 0.01b	5.53 ± 0.02b	1.91 ± 0.01a
Organic fertilizer (N70, K60)	5.51 ± 0.23bc	0.8 ± 0.01d	19.7 ± 5c	0.65 ± 0.02c	5.23 ± 0.02c	1.67 ± 0.01b
Compost (N70, K60)	5.44 ± 0.04c	1.67 ± 0.06a	56.2 ± 7.7a	1.28 ± 0.00a	5.97 ± 0.07a	1.92 ± 0.03a
Inorganic fertilizer (N80, K80)	5.50 ± 0.06abc	1.36 ± 0.03b	31.2 ± 4.9b	0.64 ± 0.01c	4.5 ± 0.09d	1.55 ± 0.01c
Organic fertilizer (N80, K80)	5.39 ± 0.04c	0.77 ± 0.01d	39.6 ± 2.5b	0.45 ± 0.01d	4.23 ± 0.07e	1.36 ± 0.01d
Compost (N80, K80)	5.73 ± 0.01a	0.66 ± 0.01e	20.3 ± 1.5c	0.33 ± 0.02e	4.52 ± 0.05d	1.43 ± 0.01d

Table 2

Correlation matrix of sensor EC value, pH, soil EC (1:5 soil:water extract), soluble elements and exchangeable elements Values in bold indicate a significant correlation at $p < 0.05$.

Variables	Sensor EC	pH	Soil EC	Sol. Ca	Sol. K	Sol. Mg	Sol. Na	Sol. P	Sol. S	NO ₃ -N	Sum of sol. nutrients	Ex. Ca	Ex. K	Ex. Mg	Ex. Na
Sensor EC	1														
pH	-0.307	1													
Soil EC	0.927	-0.431	1												
Sol. Ca	0.883	-0.496	0.972	1											
Sol. K	0.582	-0.305	0.512	0.559	1										
Sol. Mg	0.858	-0.603	0.972	0.974	0.487	1									
Sol. Na	0.918	-0.417	0.885	0.901	0.647	0.844	1								
Sol. P	-0.639	0.430	-0.519	-0.599	-0.552	-0.572	-0.653	1							
Sol. S	0.703	-0.559	0.906	0.888	0.321	0.934	0.693	-0.264	1						
NO ₃ -N	0.855	-0.512	0.921	0.977	0.603	0.937	0.911	-0.714	0.804	1					
Sum of sol. nutrients	0.868	-0.551	0.972	0.993	0.592	0.984	0.887	-0.581	0.911	0.968	1				
Ex. Ca	-0.375	0.265	-0.598	-0.510	0.201	-0.601	-0.375	-0.102	-0.759	-0.412	-0.525	1			
Ex. K	-0.318	0.072	-0.514	-0.416	0.302	-0.485	-0.299	-0.169	-0.650	-0.298	-0.411	0.932	1		
Ex. Mg	0.302	0.111	0.243	0.345	0.501	0.184	0.426	-0.274	0.045	0.424	0.306	0.245	0.291	1	
Ex. Na	0.597	-0.576	0.511	0.599	0.762	0.531	0.798	-0.637	0.347	0.677	0.608	0.077	0.192	0.477	1
Ex. NH ₄ ⁺ -N	0.645	-0.451	0.776	0.800	0.314	0.802	0.537	-0.315	0.798	0.725	0.794	-0.358	-0.249	0.237	0.269
Sum of ex. nutrients	-0.281	0.199	-0.494	-0.390	0.308	-0.494	-0.264	-0.171	-0.671	-0.281	-0.405	0.980	0.962	0.398	0.185

Values in bold indicate a significant correlation at the p -value < 0.05 .

The EC response of soil treated with various fertilizers varied in accordance with the type of basal fertilizer and dose. The EC of inorganic fertilizer-treated soil was relatively higher than other treatments. The increase in soil EC might be attributed due to the easy release of nutrients from the applied fertilizers (Do Carmo et al. 2016). In comparison with the organic fertilizer, soil treated with compost fertilizer exhibited a greater EC response, which might be due to the greater amount of organic matter present in the compost (Walker and Bernal 2008). The earlier report demonstrated that EC response is strongly associated with the amount of organic matter present in compost and manure (Walker and Bernal 2008). The EC response of compost increased as the dose of basal fertilizer application increased (Table 1). Manure compost has various soluble salts including Mg, Ca, and HCO_3^- which leads to increased EC (Wong et al. 1999; Ozlu and Kumar 2018). A similar finding was noticed by Lakshmi (1991), soil treated with farmyard manure (FYM) had a larger EC response compared to the inorganic treatment group because FYM released more electrolytes.

The amount of nitrate in the soil was substantially higher after a high amount of compost application (compost (N70, K60)) over the other treatment groups, which was highly correlated to soil EC (Table 1). The higher nitrate concentration in soil treated with compost might be caused by more mineralization of N by increased microbial activity. Adding organic manure followed by mineralization raised soil nitrate levels (Ogundijo et al. 2015; Magdoff and Es 2021). Similarly, Wang et al. (2006) described that the nitrate concentration in the soil profile of a vegetable field increased substantially because of excessive manure application.

Although several processes including plant uptake, soil organisms, atmospheric N_2 fixation, mineralization, deposition, volatilization, and denitrification affect nitrate levels in the soil, nitrate concentration was related to soil EC (Table 1) (Schimel and Bennett 2004). These findings suggested that one of the potential causes of a rise in soil EC could be a high nitrate concentration in compost-fertilized soil. Exchangeable K, Ca, and Mg contents showed a similar trend to EC and nitrate in relation to different fertilizer treatments. A higher amount of basal fertilizer treatment showed higher exchangeable cations and compost fertilizer showed relatively higher exchangeable cations than other basal fertilizers (Table 1).

After two times of fertigation (66 DAT), the inorganic fertilizer treated plot showed highest water-soluble nutrients, however, exchangeable nutrients did not show consistent results according to different fertilizer applications (Supplementary Tables 2 and 3). The EC, nitrate, and water-soluble nutrients increased with increasing additional fertilizer except for compost (Supplementary Table 2). In the case of compost treatment as basal fertilizer, an increased ratio of additional fertilizer did not affect soluble nutrients, which might be related to the adsorption of cations on organic matter. According to Shin et al. (2004), the functional groups present on the surface of organic matter contributed to the greater adsorption of cations. Grimaldi et al. (2002) also observed that the

bonding forces between the surface charges of cations and the functional groups of organic matter formed the organo-mineral interaction. Soluble nutrient concentrations decreased after five times of fertigation (102 DAT) while exchangeable nutrients increased after fertigation (Supplementary Tables 2 and 3). The yield of spring onion was not significantly affected by different types of basal fertilizer and fertigation ratio, but nitrogen uptake by spring onion was decreased with increasing fertigation ratio (Lee et al. 2022).

Monitoring Of Sensor Ec

Usually, the EC of soil increased as fertilizer and water were added to the soil (Fig. 1a). In this work, according to soil water potential, water was provided by an automatic system, and water content increased by irrigation and fertigation (Fig. 1b). According to Othaman et al. (2020), the presence of water facilitates the ion liberation process and ultimately raises EC response, which is concordant with our results. Ions transport electrons and the number of ions available or capable of transporting electrons affects EC. Vitz et al. (2022) reported that soluble ions that exist in the water contribute to the passage of electrons from one electrode to another.

Inorganic fertilizer and higher fertigation ratio showed the highest followed by compost and organic fertilizer (Fig. 1a). Soil treated with inorganic fertilizer with a higher ratio of additional fertilizer (N80, K80) showed a greater EC response over to other treatment groups, which might be explained by the easy solubilization of inorganic fertilizers in water relative to other fertilizers that ultimately improve EC response. Ozlu and Kumar (2018) also reported that soil EC was increased by 33% while applying the inorganic fertilizer than manure.

The EC monitoring data were initially different among the treatments, but the difference was not significant after maturing spring onion. Lee et al. (2017) observed that after 14 days of tomato plantation, the plants started to grow rapidly, and the EC dropped quickly which signifies that EC was directly related to the amount of available ions and plant growth. However, the solubility of nutrients is highly influenced by the pH factor (Hue 1992). Therefore, pH, amount of soil organic matter, and chemical properties of the fertilizer could be responsible for the availability of a higher amount of nutrients in the soil with the addition of inorganic fertilizer.

Correlation Of Sensor Ec Value And Elemental Contents Of Different Fertilized Soils

Various fertilizers were applied to the soil in order to test if the sensor EC could correlate with soil-available nutrients. The correlation analysis revealed a positive correlation between the sensor EC and water-extracted EC values and showed a strong positive association with all the water-soluble elements except phosphorous ($p < 0.05$) (Table 2). A poor correlation between the EC and P could be due to lower mobility can result from P immobilization in soil into insoluble compounds like calcium-phosphate minerals (Carreira et al. 2005). Park and Sung (2021) described a correlation study between the EC and soil elements that exhibited a positive association with all elements excluding P, which is concordant with our results. Similar findings had also been found by Mazur et al. (2022), showing a positive correlation between EC and macronutrients, except P.

Although fertigation supplied N and K, other available nutrients such as Ca and Mg increased because of the cation exchange reaction. Water-soluble Ca and Mg were highly correlated with nitrate and exchangeable ammonium (NH_4^+). Therefore, the sum of water-soluble nutrients was also highly correlated with sensor EC (Table 2). However, the correlation between extracted EC, sensor EC, and exchangeable element contents did not show a strong correlation except NH_4^+ (Table 2). The K did not exhibit a substantial correlation with EC, which could be because K is a mobile nutrient that was exponentially absorbed by the plant (Ozkan et al. 2018). Enough amount of Ca is favorable for higher K uptake by crop roots which could be another reason for K was not correlated with EC (Adams 1986). However, the dose of fertilizer application, plant species, and irrigation all have an impact on the amount of nutrients in the top layer of soil (Zotarelli et al. 2009).

Principal component analysis was performed with averaged sensor EC value of the sampling day and soil chemical properties analyzed for different fertilizer-treated soils, and the projections of the cases with two principal components were imaged in Fig. 2. PC1 and PC2 accounted for 59.17% and 19.94% of the total variation, respectively. Sensor EC was strongly associated with nitrate and soluble Ca and Na and negatively related to soil pH. PC1 was strongly associated with soluble nutrients while PC2 was related to exchangeable nutrients. (Table 3, Fig. 2). The application of inorganic fertilizers was substantially correlated with sensor EC, soluble Na, Ca, Mg, and nitrate among the variables.

Table 3
Principal component loadings and variance explained by the first four principal components

	PC1	PC2	PC3
Sensor EC	0.906	0.064	0.175
pH	-0.566	-0.015	0.763
Soil EC	0.971	-0.162	0.119
Sol. Ca	0.989	-0.046	0.078
Sol. K	0.602	0.629	0.029
Sol. Mg	0.978	-0.166	-0.069
Sol. Na	0.929	0.163	0.117
Sol. P	-0.633	-0.482	0.216
Sol. S	0.874	-0.421	-0.053
NO ₃ -N	0.973	0.094	0.048
Ex. Ca	-0.493	0.816	-0.039
Ex. K	-0.379	0.856	-0.158
Ex. Mg	0.325	0.582	0.579
Ex. Na	0.672	0.576	-0.197
Ex. NH ₄ -N	0.760	-0.146	0.029
Eigenvalue	8.876	2.992	1.105
Variability (%)	59.172	19.943	7.369
Cumulative %	59.172	79.116	86.485
The bold value indicates a loading > 0.5.			

Overall work revealed that the amounts of soluble nutrients and N had a significant impact on variations in EC response and it was positively correlated with sensor EC values. The results imply a strong correlation between extracted values of elemental contents and sensor EC values, suggesting that EC sensors can monitor soil nutrients, particularly N. Measurement of soil EC is a key marker for determining soil fertility. According to Gajda et al. (2000), measuring soil electrical conductivity might be a valuable indicator for determining available N in the soil. However, factors such as cropping, irrigation systems, land usage, and various fertilizers have different effects on soil EC. Therefore, different soil factors should be considered to apply soil EC sensors for monitoring nutrient levels in other soils.

Conclusion

EC sensor has been successfully implemented in the field for monitoring soil nutrients. In comparison to other fertilizer groups, inorganic fertilizer raised the soil EC response in this study, which was also represented by an EC sensor value and showed a strong positive correlation with soluble nutrient contents. Therefore, the monitoring of EC values using soil sensors could be used to estimate the amount of fertilizer needed in the field. Additionally, it has also been found that the fertilizer application rate, soil moisture, and pH, all significantly affect the EC response. Overall research has demonstrated that soil nutrients, particularly N greatly affect EC sensor response suggesting that EC sensor technology could be prominently adopted for monitoring soil nutrients to promote crop development and reduces the probable risk of environmental pollution.

Declarations

Conflicts of interest

The authors declared no conflict of interest.

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Authors contribution

The study design, conceptualization, and supervision were done by Jin Hee Park. The original draft, methods, and material collection was contributed by Govind Vyavahare. Yejin Lee contributed to material preparation, methodology and revised the manuscript. Yeong Ju Seok and Hanna Kim contributed to the

material collection and methodology. Jwakyung Sung revised the manuscript. All authors read and approved the final manuscript.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and/or its supplementary materials.

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Figures

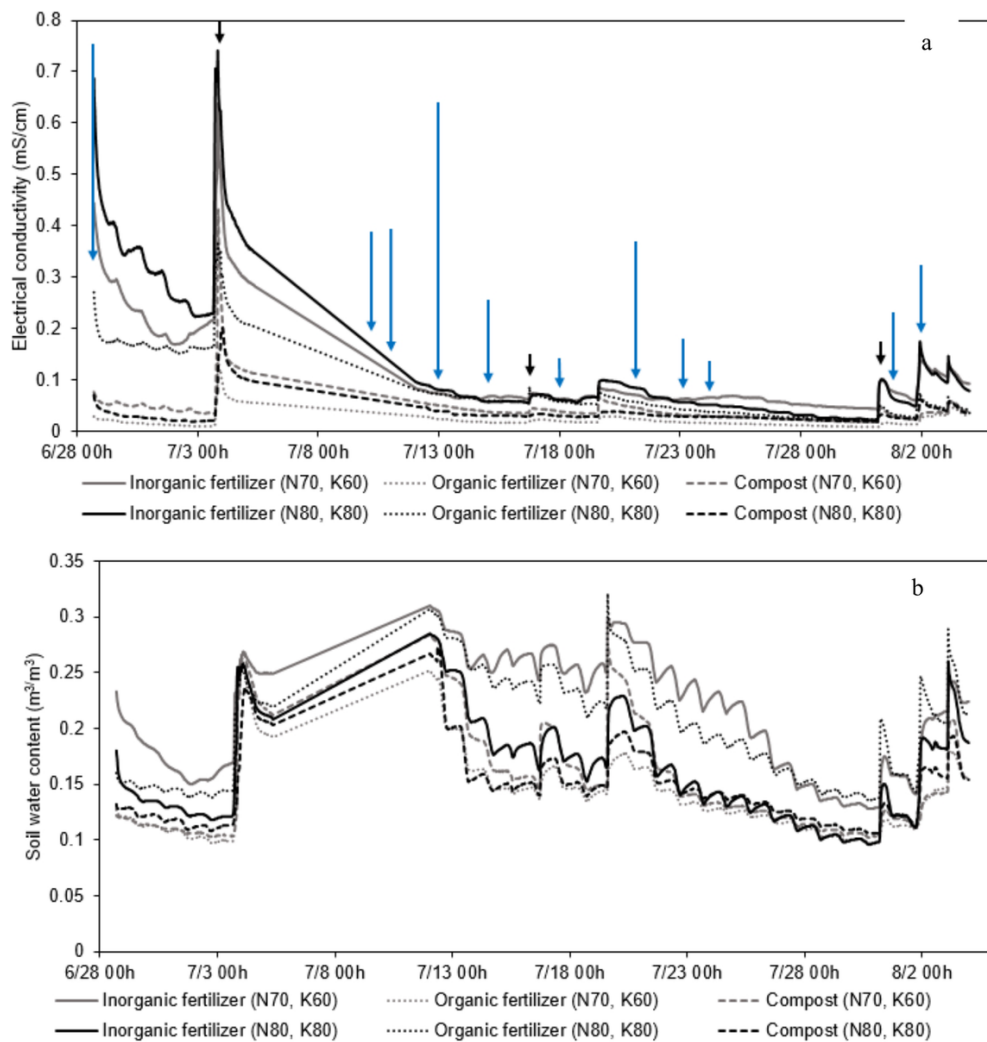


Figure 1
Effect of different fertilizers on soil EC response (a), the water potential of different fertilized soil (b) (Black arrows indicate fertigation treatment and blue arrows indicate rainfall. Length of the blue arrows is related to the amount of rainfall)

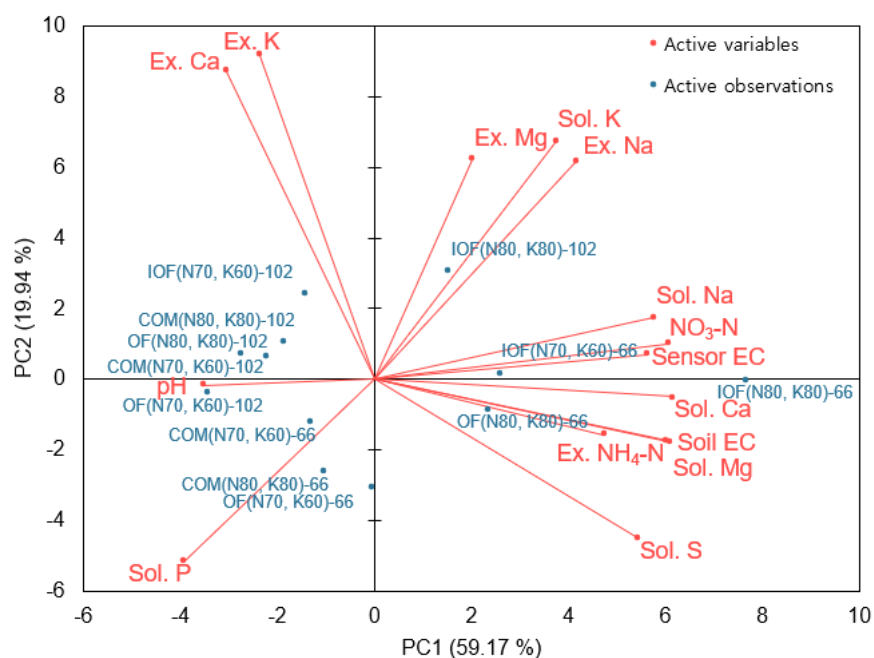


Figure 2

Biplot of the principal component analysis for sensor EC, pH, water-soluble and exchangeable elements of different fertilizer-treated soils. (IOF: inorganic fertilizer, OF: organic fertilizer, COM: compost, 66: sampled at 66 DAT, 102: sampled at 102 DAT)

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