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Monitoring of soil EC for the prediction of soil nutrient regime under different soil water and organic matter contents

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Abstract

Smart farms and precision agriculture require automatic monitoring and supply of water and nutrients for crops, but sensors to monitor plant available nutrients in soil are not available. Soil electrical conductivity (EC) is related to nutrients in soil solution, which can be affected by soil organic matter, soil texture, temperature, and water content. Therefore, the objective of this study is to evaluate factors influencing soil EC sensor values by monitoring EC under different soil organic matter and water contents. Ten soil samples with various sand and clay contents, EC, pH, and organic matter contents were selected and saturated with water. Volumetric water content and EC of the soil were monitored while drying the soil. Humic acid and manure were added to soils in order to evaluate the effect of organic matter on soil EC. Soil EC values linearly increased with increasing water content at 10–25% which is favorable water content for plant growth. The EC increased when organic matter was added to soils, which was related to ions released from the organic matter. Soil EC calibration factor for soil water content increased when EC of the soil was high and organic matter was added. The sensor EC values in sandy loam and loam soils was related to the ion contents in pore water, and exchangeable ions in soil, respectively. Sensor EC values were highly correlated with organic matter and K contents in soil and can be used as an indicator for plant available nutrients in soil. Therefore, the sensor EC at optimal soil water content for plant growth can be used to monitor changes in plant available nutrients in soil.

Keywords Precision agriculture, Humic acid, Soil texture, Sensor, Nutrients

Introduction

Precision supply of essential water and nutrients is important for crops because excess nutrients can reduce crop yields and residual nutrients can positively or negatively affect yields in the following year [53]. Importance of effectively managing soil nutrients and water to sustain and optimize agricultural productivity in changing environmental conditions is emerging due to imbalances in nutrients and water caused by recent climate changes [31]. Therefore, soil nutrient and water management are important to maintain the sustainability of agricultural land.

Smart farms reduce costs and improve crop productivity by monitoring and controlling the agricultural environment through integration of automation technologies such as networks and mobile devices [37]. Automatic soil water management system using information and communications technology (ICT) helps in saving water by supplying desired amount of water required by the crops [1]. In addition, the ICT-based water management system contributes to the improvement of crop productivity and quality [16]. Especially, in outdoor smart farms, it is necessary to control the

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supply of nutrients according to crop growth while monitoring nutrients in real time using sensors [50]. Although there are various sensors for monitoring agricultural environment such as CO_2, light intensity, temperature, humidity, and soil water content, sensors for monitoring nutrient availability in soil are still not fully developed [5]. Therefore, it is difficult to supply nutrients while monitoring soil nutrient levels, which is obstacle to precision agriculture in open field.

Soil EC is affected by soil salinity, clay and water content, and adding nutrients to the soil increases the soil EC [17, 26]. Heiniger et al. [27] found that EC measurements of soil extracts could be used to predict soil nutrient content and are highly correlated with soil properties such as water content, cation exchange capacity (CEC), and soluble salts (R^2 ranging from 0.51 to 0.75). In addition, nutrients such as N and K directly affect the EC of extracted soil solutions [40]. Therefore, nutrient content can be predicted by monitoring soil EC, but soil EC is highly influenced by soil water, soil texture, and organic matter [29]. In particular, the water content has significant effects on soil EC [22]. Increasing soil water content increased soil EC [14]. When the water content in soil was high, the soil EC increased as a result of the increased solubility of ions in soil [4].

Organic matter is important for plant growth along with nutrients in the soil because it is decomposed into smaller molecules and mineralized elements are absorbed by plants [41]. Organic matter can increase the soil EC due to the nutrients and salts included in organic matter [24]. However, the effect of soil organic matter on EC was not fully understood. To predict soil nutrients through soil EC monitoring using sensor, various soil characteristics including soil texture and organic matter affecting EC should be considered.

In this study, we hypothesized that organic matter increases EC of the soil by releasing nutrients and affects EC by adsorption of ions. Conducting correlation analyses between EC and organic matter can offer insights into setting nutrient supply corresponding to EC values monitored by sensors for soils with different characteristics [46, 51]. Based on the relationship of soil organic matter and EC, the sensor EC values should be calibrated. Calibration of EC based on these correlations can enhance the accuracy of nutrient supply recommendations and improve the efficiency of soil management practices [39, 51]. Therefore, the objectives of this study were to monitor nutrients using EC sensors in soils with different clay and sand composition, water content and organic matter content and evaluate the effect of water content and organic matter on soil EC in different soils.

Materials and methods

Soil characterization

Soils with different characteristics were collected from different agricultural lands in Korea, dried at room temperature, and sieved to a particle size of less than 2 mm using a stainless-steel sieve. The sand, silt and clay content of the soil was determined by Stoke's law [23]. Soil pH and EC were measured using pH and EC meter after extracting 5 g of soil with 25 mL of deionized water for 30 min. The Walkley–Black method was used to determine the amount of soil organic matter [52]. Two grams of soil and 20 mL of 1 M NH_4CH_3COOH solution at pH 7 were shaken for 30 min and filtered through 0.45 μm syringe filter. Filtered solution was acidified and elements were analyzed using inductively coupled plasma optical emission spectroscopy (ICP-OES, Perkin Elmer, Avio 500). The soil CEC was calculated with Ca, Mg, K, and Na [47]. Ammonium (NH_4^+) and nitrate (NO_3^-) in the soil were measured using the indophenol-blue method and the vanadium (III) reduction method, respectively, after extracting 5 g soil with 25 mL of 2 M KCl solution [19, 20]. For NH_4^+ analysis, 0.125 mL EDTA, 2 mL phenol/nitroprusside (PNP), and 1 mL NaOH/hypochlorite were mixed with 1 mL of the extract. The mixture was incubated at 37 °C for 20 min and absorbance of the solution was measured at 630 nm using a UV–VIS spectrometer (Orion AquaMate 7000, Thermo-Fisher Scientific, USA) [20]. For NO_3^- analysis, 20 μL of soil extract was mixed with 1 mL of the reagent prepared by dissolving 0.4 g of VCl_3 in 50 mL of 1 M HCl and mixing with 0.2 g of sulfanilamide and 0.01 g of N-(1-Naphthyl)-ethylendiamine-dihydrochloride (NEDD) in 400 mL of de-ionized water. Absorbance of the solution was measured at 540 nm using a UV–VIS spectrometer after 18 h at 25 °C to determine soil NO_3^- concentration [19]. Table 1 shows the physicochemical properties of soils used.

Soil EC and water content monitoring

Air dried soil (1.5 L) was packed in a 2.2 L square container. For organic matter treatment, 40 g of compost manure were added to silty clay loam soil, 30 g of humic acid were added to loam soil, and 50 g of compost manure were added to sandy loam soil. Soils after adding organic matter were also characterized to evaluate effect of organic matter on sensor EC (Table 1). To monitor EC and water content, an EC sensor (Teros 12, METER Group, USA) was placed in soil to a depth of about 10 cm in an incubator at 20 °C. The Teros 12 sensor measures EC, volumetric water content, and temperature in soil at the same time. Water (900 mL) was added to the soil for saturation and the EC and water content were monitored until the soil water content evaporated to be less than

Table 1 Physicochemical properties of soil samples used for EC monitoring

Samples	Texture	Sand (%)	Clay (%)	Silt (%)	pH	EC (dS/cm)		OM (g/kg)		CEC (cmol_c/kg)	
						without OM	with OM	without OM	with OM	without OM	with OM
SiCL	Silt clay loam	13.5	33.3	53.2	5.66	0.071	0.76	0.09	0.13	9.6	14.9
L-1	Loam	33.6	18.6	47.7	5.87	0.068	1.59	0.25	0.34	7.5	8.4
L-2	Loam	46.4	19.0	34.7	6.62	0.147	3.22	0.06	0.22	9.8	10.9
L-3	Loam	42.1	23.0	34.9	6.58	0.055	1.06	0.13	0.19	9.2	9.5
L-4	Loam	54.5	16.2	29.3	6.35	0.066	0.90	0.21	0.22	6.7	7.5
L-5	Loam	32.2	17.4	50.4	4.95	0.076	3.16	0.30	0.32	11.0	12.9
SL-1	Sandy loam	65.8	16.2	17.9	7.24	0.058	0.51	0.15	0.16	16.2	22.2
SL-2	Sandy loam	72.0	13.4	14.6	5.46	0.147	0.57	0.13	0.21	11.9	18.4
SL-3	Sandy loam	66.9	14.0	19.1	7.63	0.138	1.22	0.29	0.33	6.4	9.7
SL-4	Sandy loam	60.8	13.2	26.1	6.50	0.054	0.86	0.11	0.16	7.8	10.0

10% (v/v). Soil EC sensors were connected to ZL6 logger (METER Group, USA) and soil bulk EC (mS/cm), temperature (°C) and volumetric soil water content (m^3/m^3) were recorded every 15 min. Soils with added organic matter (manure and humic acid) were also monitored for soil EC and water content in the same manner.

Analysis of ion contents in soil pore water

Rhizon sampler (Rhizosphere Research Products, Netherlands) was inserted into the soil to a depth of about 10 cm and pressure was applied to collect pore water in the soil at 25% water content. The pH and EC of the pore water were measured and element contents in the pore water were analyzed using ICP-OES after filtration using 0.45 μm syringe filter. Ammonium and NO_3^- contents of the pore water were also analyzed using the indophenol-blue method and the vanadium (III) reduction method, respectively. Soil samples were taken after monitoring EC, dried, and mixed with 1 M NH_4CH_3COOH solution (pH 7) at a soil to solution ratio of 1:10 for 30 min. The solution was filtered through 0.45 μm syringe filter and exchangeable ion concentrations in the soil were analyzed using ICP-OES. Soluble NH_4^+ and NO_3^- in the soil before drying were extracted with de-ionized water and analyzed using a UV–vis spectrometer following the indophenol-blue method and the vanadium (III) reduction method, respectively.

Statistical analysis

Analyses were conducted in triplicate and presented as mean and standard deviation. The correlation among sensor EC, soil organic matter (SOM), EC calibration factor for water content, soil clay and sand contents, pH, and exchangeable elements was analyzed using Xlstat (Addinsoft). Principal component analysis (PCA) was conducted to evaluate relationship among the parameters including sensor EC values and SOM contents (Xlstat, Addinsoft). For PCA, soil sensor EC values were selected

Table 2 Calibration factor of soil EC for soil water content without and with added organic matter

Samples	Soil texture	No treatment			Added organic matter		
		Calibration factor	Intercept	Correlation coefficient	Calibration factor	Intercept	Correlation coefficient
SiCL	Silt clay loam	0.81	– 0.06	0.97	2.00	– 0.17	0.99
L-1	Loam	0.63	– 0.01	0.99	1.10	– 0.07	0.99
L-2	Loam	1.32	– 0.02	0.99	2.08	– 0.16	0.99
L-3	Loam	0.57	– 0.02	0.99	1.61	– 0.14	0.99
L-4	Loam	0.77	– 0.04	0.99	2.40	– 0.17	0.99
L-5	Loam	1.56	– 0.12	0.99	1.48	– 0.13	0.99
SL-1	Sandy loam	0.75	– 0.04	0.99	2.91	– 0.22	0.99
SL-2	Sandy loam	0.74	– 0.03	0.99	2.41	– 0.18	0.99
SL-3	Sandy loam	0.72	– 0.02	0.98	3.92	– 0.12	0.99
SL-4	Sandy loam	0.57	– 0.00	0.99	2.09	– 0.18	0.99

Table 3 Exchangeable ion contents in soil without and with added organic matter

Samples	Ca (mg/kg)		K (mg/kg)		Mg (mg/kg)		Na (mg/kg)		P (mg/kg)		S (mg/kg)	
	without OM	with OM	without OM	with OM	without OM	with OM	without OM	with OM	without OM	with OM	without OM	with OM
SiCL	1181.2 ± 0.4	1704.5 ± 2.7	177.6 ± 0.3	289.1 ± 7.1	378.6 ± 0.6	598.6 ± 1.2	38.8 ± 0.3	168.7 ± 0.3	14.6 ± 0.0	26.3 ± 0.7	64.8 ± 0.4	71.2 ± 0.1
L-1	1159.5 ± 1.6	1316.9 ± 11.2	199.8 ± 2.4	200.0 ± 19.5	106.9 ± 2.1	126.3 ± 1.1	71.0 ± 0.4	74.1 ± 0.5	1.3 ± 0.4	3.4 ± 0.1	54.5 ± 0.7	159.3 ± 1.1
L-2	1265.8 ± 2.3	1442.0 ± 17.6	199.4 ± 1.9	239.2 ± 48.4	317.4 ± 1.0	336.3 ± 3.5	75.4 ± 1.2	824 ± 0.6	1.6 ± 0.0	4.9 ± 0.2	61.0 ± 3.4	133.6 ± 2.5
L-3	1291.7 ± 0.2	1315.4 ± 3.7	264.8 ± 0.5	292.6 ± 4.0	217.0 ± 0.1	231.1 ± 0.6	58.3 ± 0.1	58.5 ± 0.1	3.6 ± 0.2	5.3 ± 0.1	18.0 ± 0.2	92.2 ± 0.0
L-4	812.6 ± 1.3	929.4 ± 8.7	335.2 ± 5.9	406.3 ± 111.6	170.1 ± 1.9	173.0 ± 1.7	78.5 ± 1.4	82.8 ± 0.5	4.1 ± 0.7	4.7 ± 0.1	20.1 ± 1.6	150.0 ± 0.4
L-5	1435.0 ± 15.7	1629.6 ± 120.4	226.8 ± 9.9	504.6 ± 85.4	354.4 ± 6.1	373.8 ± 14.7	72.1 ± 2.3	85.7 ± 4.5	13.2 ± 1.2	13.4 ± 3.0	75.1 ± 4.1	167.0 ± 6.1
SL-1	2724.2 ± 11.1	3506.6 ± 50.0	144.2 ± 7.3	146.7 ± 4.3	261.8 ± 2.5	427.6 ± 1.5	19.0 ± 0.3	185.8 ± 0.3	53.8 ± 0.6	75.4 ± 0.8	49.8 ± 2.3	98.8 ± 1.5
SL-2	1891.3 ± 2.9	2748.7 ± 19.2	82.4 ± 1.1	136.3 ± 2.8	261.6 ± 1.0	436.3 ± 1.0	26.2 ± 0.5	165.0 ± 0.2	24.4 ± 0.2	32.1 ± 0.2	18.4 ± 1.1	108.8 ± 0.7
SL-3	840.1 ± 3.1	1161.4 ± 11.6	272.4 ± 40.9	399.2 ± 3.8	173.8 ± 2.8	275.7 ± 1.6	15.0 ± 0.9	149.4 ± 0.3	28.5 ± 2.8	52.5 ± 1.3	36.0 ± 1.3	68.3 ± 0.4
SL-4	1276.7 ± 1.3	1477.8 ± 57.6	202.2 ± 1.4	293.0 ± 7.4	103.1 ± 0.7	155.3 ± 1.2	17.6 ± 0.8	133.2 ± 0.3	23.3 ± 0.2	28.1 ± 0.2	32.8 ± 0.7	34.3 ± 0.5

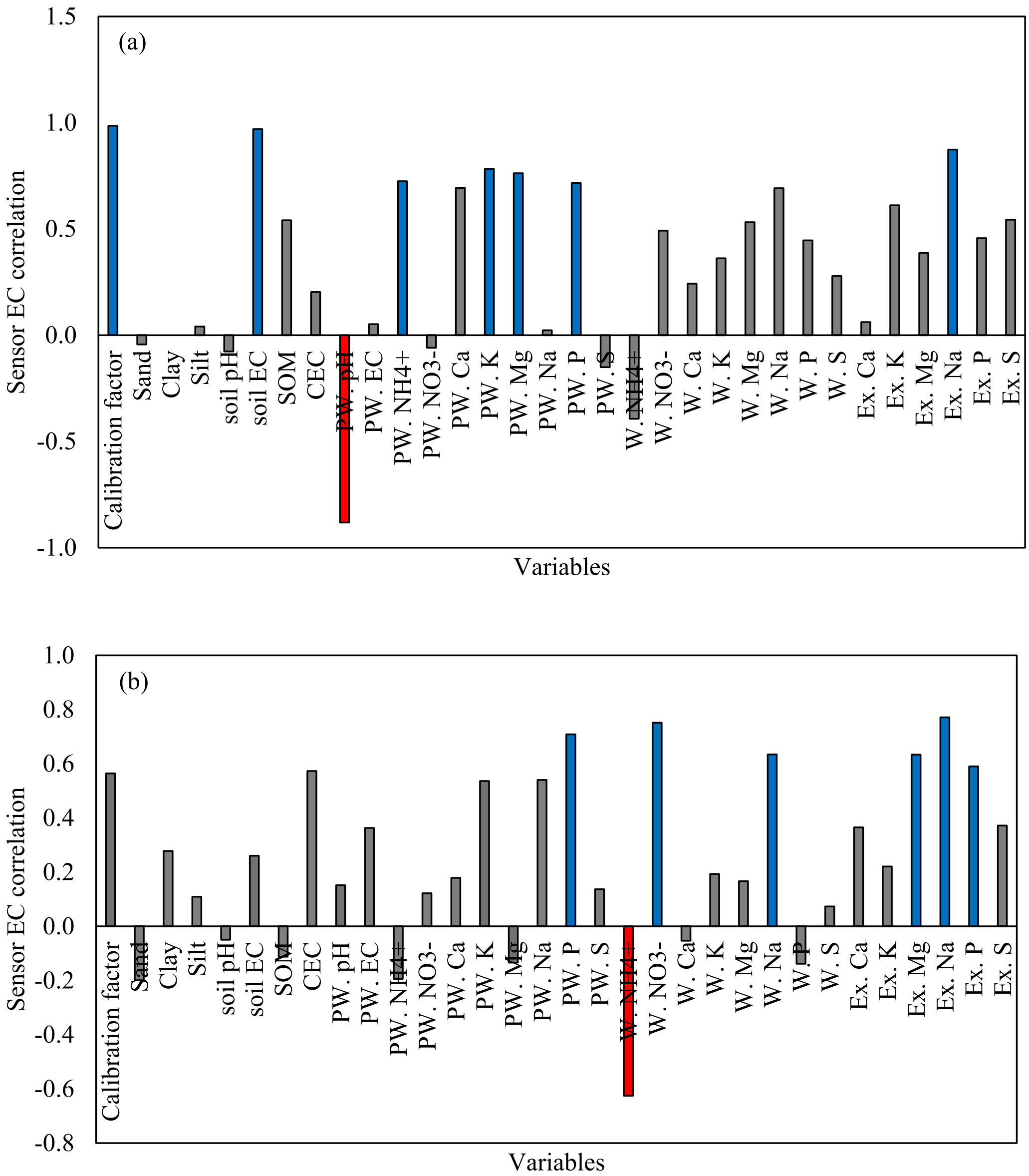

Fig. 1 Correlation of sensor EC with soil properties and ion contents of sandy loam (**a**) and loam (**b**) (PW. pore water, W. water soluble ion, Ex. exchangeable ion)

at water content of 30.9%, 22.5% and 17.0% v/v for silt clay loam, loam and sandy loam soils, respectively.

Results and discussion

Response of soil EC sensor in relation to soil water content

Soil EC showed a linear correlation with water content at water content of 10–25% for loam and sandy loam soils and at water content of 10–40% for silty clay loam soil (Table 2). The water content range having linear relationship with EC was suitable water content for plant growth [11]. The linear correlation between soil water content and EC in the range of soil water content appropriate for plant growth indicates that soil EC can be used for nutrient monitoring regardless of soil moisture content by calibrating EC values for soil water content. Soil EC can be calibrated for desired water content because it is linearly proportional to water content. Other studies also reported that soil EC linearly increased with soil water content [14, 25, 54]. Sensor EC value decreased with decreasing water content in soil because the mobile fractions of ions decreased [18, 55]. In addition, water containing ions is a conductor of electricity and water content was closely related to EC [33]. Sudduth et al. [48] also reported that EC could be explained by water content and bulk density of soil. However, at higher water content, the relationship between EC and water content

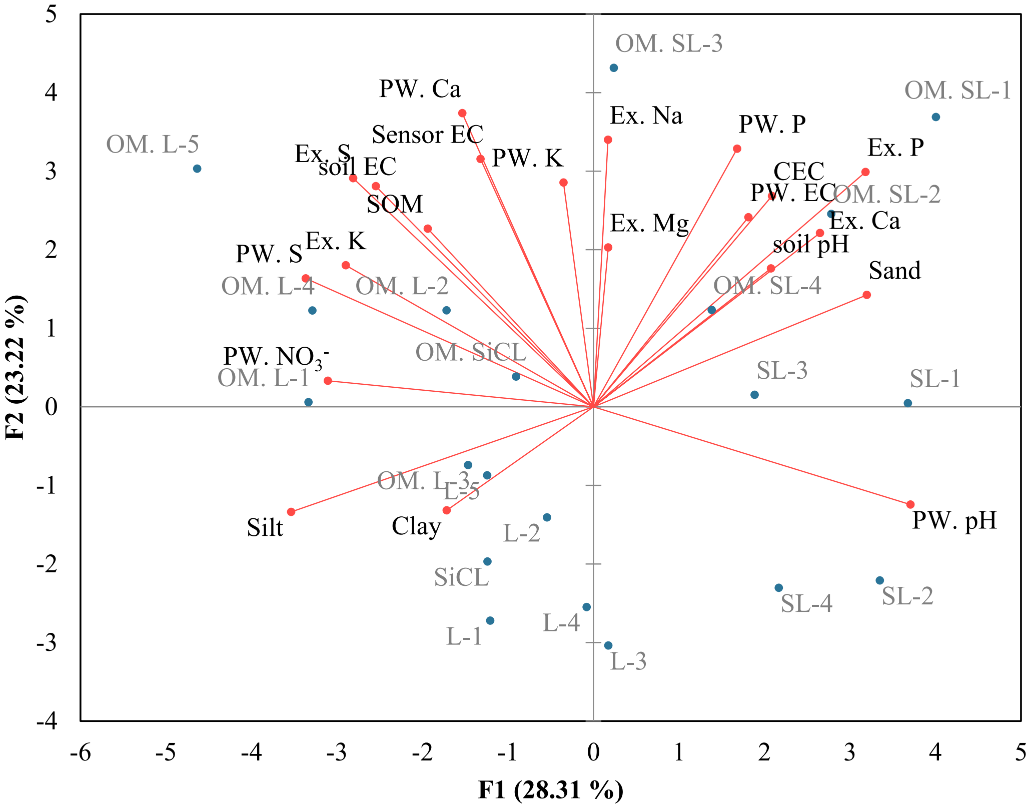

Fig. 2 Biplots of PC1 and PC2 for sensor EC monitoring values by soil characteristics and ion content and organic matter treatment (OM. organic matter added soil, PW. pore water, Ex. exchangeable ion)

was not linear, which was also reported by Rusydi [44]. When soil water is more than optimum water content, the relationship becomes nonlinear, wherein further increase of water content does not linearly raise EC due to saturation and mobility constraints [44].

Soil EC is related to soil texture, water content, organic matter, etc., and varies with soil properties [30]. Therefore, it is necessary to calculate the calibration factor considering the soil properties and apply it to calibrate the EC sensor value against soil water content. Sensor EC values were plotted against soil water contents and the slope of linear regression was defined as calibration factor. Higher calibration factor indicates that EC changes more with water content variation. Calibration factor derived from the slope of the linear relationship between soil EC and water content serves as a valuable metric [39]. This coefficient aids in predicting soil EC based on water content variations, which in turn can offer insights into nutrient contents and other essential soil properties [21]. Calibration factor for each soil was calculated in the range of available water content of each soil and the correlation coefficient was to be higher than 0.97 (Table 2). In comparison to the soil without organic matter, the calibration factor was higher when organic matter was added to the soil (Table 2). The increased calibration factor is because of adding organic matter to the soil and increases in exchangeable ions and nutrients (Table 3). Soil organic matter increased nutrient contents and finally increased soil EC [2, 28, 49]. When the ion contents of the soil are high, more dispersal occurs with the higher water content, which might be attributed to higher calibration factor with organic matter [42]. In addition, since sensitivity of the EC sensor increases as the water content increases, the calibration factor can be higher when organic matter and water are added to the soil [12]. Therefore, higher the soil nutrient content, the greater increase in soil EC by water content.

Changes in soil ion contents by addition of organic matter

The concentration of exchangeable ions such as K, and Ca in the soil increased when organic matter was added in the soil because of dissolution of minerals containing K and exchangeable Ca by organic acids (Table 3). Initially manure compost was added as organic matter, but it increased EC and humic acid was added as organic matter for loam soil to avoid effect of salts released from added organic matter. However, both organic matters increased available nutrient concentrations increasing

Table 4 Factor loadings based on correlations matrix and total variance explained by the principal components (OM.: added organic matter, PW.: pore water, Ex.: exchangeable ion)

	PC1	PC2	PC3	PC4
Sensor EC	– 0.290	**0.628**	0.326	0.450
Sand	**0.702**	0.283	– 0.543	-0.163
Clay	– 0.377	– 0.262	**0.708**	0.294
Silt	– 0.777	-0.266	0.421	0.092
soil pH	0.456	0.351	– 0.061	– 0.365
soil EC	– 0.559	**0.559**	– 0.028	– 0.291
SOM	– 0.426	0.451	– 0.437	0.032
CEC	0.459	**0.534**	**0.628**	– 0.266
PW. pH	**0.815**	– 0.248	0.058	– 0.259
PW. EC	0.398	0.480	– 0.305	– 0.069
PW. NO_3^-	– 0.683	0.066	– 0.005	– 0.355
PW. Ca	– 0.337	**0.744**	– 0.165	– 0.360
PW. K	– 0.077	**0.568**	– 0.428	**0.657**
PW. P	0.369	**0.654**	– 0.202	**0.507**
PW. S	– 0.740	0.325	– 0.178	– 0.478
Ex. Ca	**0.582**	0.440	0.495	– 0.391
Ex. K	– 0.637	0.359	– 0.316	0.264
Ex. Mg	0.038	0.404	**0.808**	0.108
Ex. Na	0.037	**0.676**	0.429	0.310
Ex. P	**0.699**	**0.595**	0.111	0.103
Ex. S	– 0.618	**0.579**	0.130	– 0.421
Variability (%)	28.307	23.223	15.517	11.319
Cumulative (%)	28.307	51.530	67.047	78.365

The bold value indicates a loading > 0.5

soil EC. Adding organic matter to the soil increased the content of N, C and S etc., which were included in manure compost and humic acid [3, 15, 38]. In addition, Bader et al. [7] reported that K concentration was significantly increased by the amount of organic matter. This is because some soil minerals that contain K are dissolved by organic acids (humic and fulvic) as a result of the decomposition of organic fertilizer [6]. Exchangeable Ca content was also related to soil organic carbon because Ca protects soil organic carbon from microbial degradation [45]. As a result, while monitoring soil EC with sensors, it is important to consider organic matter which influence the ion contents in the soil.

The sensor EC value of sandy loam soil was highly correlated with the ion content in pore water, and the sensor EC value of loam soil was highly correlated with exchangeable ions (Fig. 1). Generally, loam soil has a higher adsorption capacity than sandy soil because it has a higher clay content than sandy loam [35]. Since sandy loam has a low water and ion holding capacity, the sensor EC value was highly correlated with ion content of the pore water (Fig. 1a, [10]). In addition, loam soil has a higher ion holding capacity than sandy loam, so the sensor EC value showed significant correlation with NO_3^- and Na which are soluble in water and with exchangeable cations that are relatively less soluble in water (Fig. 1b, [56]).

The pH of the pore water and the sensor EC value were negatively correlated (Fig. 1a). Luce et al. [36] explained that the negative correlation between soil EC and pH was associated with microbial mineralization and nitrification processes in the soil.

Relationship between sensor EC values and soil properties

PCA was performed to evaluate the relationship between sensor EC values and soil properties with soil samples before and after adding organic matter. PCA is used to identify the variables that are related to associations among samples [13]. The PC1, PC2, PC3 and PC4 accounted for 28.3%, 23.2%, 15.5% and 11.3% of the total variation, respectively (Table 4). The four PCs explained more than 78% of cumulative variance. The first PC showed positive correlations with sand content, pore water pH, and exchangeable Ca and P. The second PC was correlated with sensor EC, soil EC, CEC, pore water Ca, K, and P, and exchangeable Na, P and S, which were parameters contributing EC. The third PC was correlated with clay, CEC and exchangeable Mg, which were related to adsorption of cations.

The sensor EC monitoring values showed a high correlation with the contents of NO_3^-, K, S and Ca in the pore water (Fig. 2). Since pore water exists between soil particles, ion content in pore water reflects plant available nutrients which increases EC [9, 43]. Nitrate is water soluble and increasing the mobility of ions increased the EC [8]. In addition, increased mobility of adsorbed K increased EC [34]. Since soil nutrients such as N and K are closely related to EC, which can be monitored using soil EC sensor.

The close correlation between sensor EC and SOM was found because increased organic matter in the soil increased the ion contents and finally increased the soil EC (Fig. 2). In particular, samples with additional organic matter were clearly separated from samples without added organic matter. Samples with added organic matter were distributed along soluble and exchangeable nutrients on PC1 and PC2 (Fig. 2). Soils with different texture were also well differentiated indicating that texture and organic matter affect available nutrients and sensor EC. Since the soil sensor EC values are related to the soluble ion contents in sandy loam and the exchangeable ion contents in loam soil, soil texture should be considered in the interpretation of sensor EC for the prediction of nutrient levels in soil.

In addition, soil sensor EC values are highly correlated with N, K and SOM, which are important for plant growth. Therefore, when monitoring nutrient levels in soil using EC sensor, organic matter and soil texture need to be considered. If organic matter and water content are considered, the sensor EC can be used as an indicator of the nutrients available to plants in the soil. Conclusively, at optimal soil water content for plant growth, EC can be used to monitor changes in plant-available nutrients in the soil.

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Author contributions
JHP contributed to the study conception and design. Material preparation, data collection and analysis were performed by HNK and JHP. The first draft of the manuscript was written by HNK and JHP commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The data that support the findings of this study are available from the corresponding author, [J.H. Park], upon reasonable request.

Declarations

Ethics approval and consent to participate
The manuscript does not have potential conflicts of interest. The research does not involve human participants or animals.

Competing interests
The authors have no relevant financial or non-financial interests to disclose.

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