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Review Article

Function and application of Soil Electrical Conductivity (EC) sensor in agriculture: A Review

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Abstract: Soil electrical conductivity (EC) denotes the ability of a solution to conduct electricity within a specific distance, serving as an indicator of the soluble salt content in the matrix, commonly referred as salinity or ion concentration. It serves as a gauge for measuring water-soluble salts in the soil, which are pivotal indicators of mineral nutrients in the topsoil readily available for plant absorption. In fact, soil salinity significantly impacts the normal growth of crops, making it essential to monitor soil EC values. By measuring EC, farmers can implement scientifically informed and reasonable water and fertilizer management strategies, promoting healthy crop growth and ultimately enhancing production and revenue. Additionally, soil water-soluble salt levels play a crucial role in determining whether salt ions in the soil pose limitations to crop growth. Imbalances in soil electrical conductivity (EC) can impede crop growth, both when the levels are too high or too low. Elevated soluble salt content, indicated by a high EC value in the substrate, can lead to the formation of reverse osmosis pressure. This pressure may displace water in the root system, causing the root tips to turn brown or dry. Moreover, an excessively high EC value raises the risk of root rot induced by cotton rot fungus. Conversely, a too-low EC value signals insufficient availability of essential nutrients. Different plants exhibit varying optimal soil EC values based on their fertilizer necessities and growth phases. Typically, the ideal EC range for optimal plant growth falls between 0.8–1.8 mS/cm, with a recommended upper limit not exceeding 2.5 mS/cm. Hence, a review on the real application and function of soil EC in agriculture is initiated to investigate its contribution towards a progressive and sustainable agriculture production.

Keywords: Soil EC; function; application; fertilizer; agriculture

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1. Introduction

Precision management of water and nutrients is crucial for crop health as superfluous nutrients can diminish yields and remaining nutrients may impact yields in subsequent seasons (Wang *et al*., 2011). Managing soil nutrients and water effectively is becoming increasingly important to sustain and optimize agricultural productivity, particularly in light of imbalances caused by climate change (Kim & Park, 2021). Therefore, soil nutrient and water management play a vital role in preserving the sustainability of agricultural land.

Smart farming practices, which utilise automation technologies such as networks connectivity and portable devices (Muangprathub *et al*., 2019), are instrumental in reducing costs and enhancing crop productivity. An automated soil water supervision system, facilitated by information and communications technology (ICT), conserves water by delivering the precise amount obligatory by crops (Abd Rahman *et al*., 2018). Moreover, this ICT-based system contributes to enhancing crop productivity and quality (Bunyamin *et al*., 2020). Particularly in outdoor smart farming setups, it is essential to regulate nutrient supply in accordance with crop growth while continuously monitoring nutrient levels using sensors (Vadalia *et al*., 2017).

Despite the availability of various sensors for monitoring agricultural environments, such as those for CO_2, light strength, temperature, humidity, soil water content, sensors for nursing soil nutrient obtainability remain underdeveloped (Ali *et al*., 2020). This limitation poses a challenge to achieving precision agriculture in open fields, as it impedes the ability to source nutrients while simultaneously monitoring soil nutrient levels.

Soil Electrical Conductivity (EC) is influenced by factors such as soil salinity, clay content, and moisture levels, and the introduction of nutrients into the soil can elevate its EC levels (Cheng *et al*., 2020; Heiniger *et al*., 2003). Heiniger *et al*. (2003) discovered that electrical conductivity (EC) measurements from soil extracts can serve as reliable indicators for predicting soil nutrient content. They observed a strong correlation between EC measurements and various soil properties, including water availability, cation exchange capacity (CEC), and soluble salts, with coefficient of determination (R^2) values extending from 0.51 to 0.75. Moreover, nutrients such as nitrogen (N) and potassium (K) directly influence the electrical conductivity (EC) of removed soil solutions (Ouyang *et al*., 1998). Therefore, predicting nutrient availability can be achieved by using soil electrical conductivity (EC). However, it is important to note that soil EC is significantly inclined to factors such as soil water content, soil texture, and organic matter (Juhos *et al*., 2019). Specifically, water content has significant effects on soil EC (Friedman, 2005). An increase in soil water content leads to a rise in soil electrical conductivity (EC) (Brevik *et al*., 2006). When soil water content is high, the soil EC increases due to the heightened solubility of ions in the soil (Adviento-Borbe *et al*., 2006).

Organic matter acting a crucial role in plant growth, complementing the nutrients presence in the soil. This is because organic matter undergoes decomposition into smaller molecules, releasing mineralised elements that can be readily absorbed by plants (Ozlu & Kumar, 2018). The presence of organic matter can increase soil electrical conductivity (EC) because it contains nutrients and salts (Gondek *et al*., 2020). When aiming to forecast soil nutrients via soil EC using sensors, it is imperative to take into account many soil features, counting soil texture and organic matter.

This write-up aims to explore, investigate, and assess the role of soil EC in agricultural practices. The integration of geospatial capacities of apparent soil particle conductivity with GPS and GIS denotes one of the most dependable techniques for delineating spatial patterns. This data will prove invaluable for developing future nutrient management strategies and assessing the sustainability of oil palm cultivation in the area.

2. Soil EC Sensor

Soil EC sensors measure the electrical conductivity of soil, an important indicator of soil salinity, moisture content and nutrient levels. These sensors assess the presence of soluble salts, also known as salinity or ion concentration, within a specific distance unit. By gauging soil water-soluble salts, these sensors provide crucial information about mineral nutrients available in the topsoil for plant uptake. Additionally, the concentration of soil water-soluble salts helps determine if salt ions in the soil may restrict crop growth.

The magnitude of the EC value is tied to the thickness of soluble salt ions in the solution. These ions primarily originate from irrigation water and fertilizer mixtures. Within a defined variety, conductivity rises with increasing liquid concentration and declines as concentration decreases. This is typically stated in units of deciSiemens per meter (dS/m) or millisieverts per centimeter (mS/cm) (Liyan, 2022).

These sensors typically consist of metal electrodes or probes that are inserted into the ground to measure its EC. Here are some key points about soil EC sensors:

1. Principle of Operation: Soil EC sensors work on the principle that electrical conductivity is directly linked to the number of ions in the soil mixture. When ions are present in the soil water, they allow electricity to flow more easily, resulting in higher electrical conductivity readings.

2. Measurement Range: Soil EC sensors are capable of measuring a wide range of electrical conductivity levels, from very low in non-saline soils to very high in highly saline soils. They are often calibrated to provide readings in units such as dS/m or mS/cm.
3. Installation: Soil EC sensors are typically installed by inserting the electrodes or probes into the soil at various depths, depending on the application. Some sensors may be installed vertically to measure soil conductivity at different soil depths, while others may be installed horizontally to cover a larger area.
4. Applications: Soil EC sensors have various applications in agriculture, environmental monitoring, and soil science. They can be used to assess soil salinity levels, monitor changes in soil moisture content, identify areas of soil compaction, and guide irrigation and fertilization practices.
5. Data Interpretation: The data collected by soil EC sensors can be interpreted to provide valuable insights into soil health and fertility. For example, high EC readings may indicate soil salinity or excess fertilizer application, while low EC readings may suggest low nutrient levels or insufficient irrigation.
6. Integration with Precision Agriculture: Soil EC sensors can be unified with other precision technologies, including GPS and remote sensing, to create detailed soil maps and guide site-specific management practices.
7. Maintenance: Proper maintenance of soil EC sensors is essential to ensure accurate and reliable measurements. This may include regular calibration, cleaning of electrodes, and protection from damage due to extreme weather or physical impact.

Overall, soil EC sensors are valuable tools for assessing soil properties and guiding management decisions in various agricultural and environmental settings. They provide real-time data on soil conductivity, which can help optimize crop production, conserve water resources, and protect soil quality.

3. Functionality of Soil EC Sensors

Soil EC sensors assess the soil's electrical conductivity, indicating its capacity to conduct electrical currents. These sensors typically comprise two or more electrodes inserted into the soil. An electrical current is transmitted between these electrodes, and the resistance encountered during its flow is gauged. Subsequently, this resistance is translated into an EC value, providing insight into the soil's conductivity (Xun, 2024).

4. Application of Soil EC Sensors

Soil EC sensors find various applications in agricultural practices such as:

1. Assessment of Soil Fertility: Soil EC sensors provide valuable insights into soil fertility by detecting levels of electrical conductivity (EC). Higher EC levels often indicate abundant dissolved nutrients, while lower levels may signal nutrient deficiencies

(Aimrun *et al*., 2011). This information helps farmers generate informed decisions on nutrient management and fertilizer routine with site-specific management (SSM) decision-making, which takes into consideration soil type at that particular area. Additionally, EC measurements at field scales can reveal important anthropogenic properties such as leaching fraction, irrigation and drainage designs, and compaction from farm apparatus. Despite occasional discrepancies, EC measurements are generally quick, reliable, and easy to obtain, making them a commonly used tool in precision agriculture scope. This allows for the spatio-temporal description of soil and environmental factors that impact crop yield (Aini *et al*., 2014; Mohad Azhan *et al*., 2021).

2. Monitoring Soil Moisture: Soil EC sensors serve in monitoring soil moisture content as well. The soil's electrical conductivity correlates directly with its moisture levels. Through regular EC measurements, farmers can ascertain the optimal irrigation schedule and prevent both under and over-watering of their crops.
3. Management of Soil Salinity: Excessive soil salinity can impede plant growth and diminish crop yields. Soil EC sensors aid farmers in pinpointing areas with heightened salinity levels, facilitating the implementation of suitable management tactics. By tracking EC values, farmers can gauge the effectiveness of salt leaching and drainage strategies.
4. Soil Health Monitoring: Soil sensors offer insights into overall soil health. Elevated EC values may indicate soil compaction, impeding root growth and nutrient absorption. By monitoring EC values, farmers can pinpoint areas with soil compaction and implement suitable measures to enhance soil health.
5. Soil pH Monitoring: Soil EC sensors can also gauge soil pH levels. Elevated EC values may signify low pH levels, detrimental to plant growth and crop yields. Through EC measurements, farmers can make informed choices regarding soil pH regulation and lime application (Aini *et al*., 2014).
6. Nutrient Management: Soil EC sensors furnish valuable data on nutrient availability and uptake. By assessing EC values, farmers can ascertain the optimal timing and dosage of fertilizer application, thereby reducing the risk of nutrient leaching and runoff (Xun, 2024).
7. Precision Agriculture: Soil EC sensors are pivotal in precision agriculture. Through the mapping of spatial variability in soil EC values, farmers can discern areas with distinct soil properties, allowing for tailored management practices. This facilitates precise application of fertilizers, water, and other inputs, optimizing resource utilization and mitigating environmental repercussions.

4. The Importance of Electrical Conductivity

An excessively high or low Soil EC level can impede crop growth. Elevated and dissolved salt content (EC value) in the soil can lead to reverse osmosis (RO) pressure, displacing water within the root system and resulting in browning or drying of the root tips. Moreover, heightened EC values increases the risk of root rot triggered by cotton rot fungus. Conversely, a low EC value indicates insufficient availability of essential nutrients.

Various plants exhibit distinct optimal soil EC values based on their fertilizer needs and growth phases. Typically, the ideal EC value for optimal plant growth falls within the range of 0.8–1.8 mS/cm, with a maximum threshold of 2.5 mS/cm (Liyan, 2022). The range of soil electrical conductivity (ECa) values is important because it provides key insights into soil properties such as texture, moisture content, and salinity, all of which directly impact crop health and productivity. Different crops have varying tolerances to soil conditions, and understanding the appropriate ECa range for specific crops helps optimize management practices (Aini *et al*., 2014).

For example, soil salinity is a key factor measured by ECa, and crops vary in their tolerance to saline conditions. Monitoring the ECa range helps in selecting appropriate crops for the given soil salinity levels.

1. Sensitive Crops (ECa < 2 mS/cm):

   Crops: Beans, carrots, strawberries.

   Importance: These crops thrive in low-salinity soils. If ECa values exceed 2 mS/cm, these crops will likely experience stunted growth and reduced yield.
2. Moderately Tolerant Crops (ECa 2–4 mS/cm):

   Crops: Corn, soybeans, alfalfa.

   Importance: These crops can tolerate moderate salinity, but their yields may start to decline as ECa values rise above this range. Careful irrigation management may be necessary to leach salts from the root zone.
3. Tolerant Crops (ECa > 4 mS/cm):

   Crops: Barley, cotton, sugar beets.

   Importance: These crops are better suited for high-ECa soils. In saline environments, they can still achieve good yields, but management practices like soil amendments may help further optimize conditions.

The table below provides the reference range of electrical conductivity (EC) values for some common crops.

Table 1. The range of electrical conductivity (EC) value for some common crops.

CROP	Soil EC	CROP	Soil EC
African Violet	1.0 - 1.2	Lavender	1.0 - 1.4
Asparagus	1.4 - 1.8	Leek	1.6 - 2.0
Anthurium	2.0 - 2.5	Lettuce - Fancy	0.3 - 0.8
Balm	1.0 - 1.4	Lettuce - Head	0.6 - 1.4
Banana	1.8 - 2.2	Melons	1.0 - 2.2
Basil	1.0 - 1.4	Mint	1.0 - 1.4
Beans	1.8 - 2.5	Mustard / Cress	1.2 - 2.4
Beetroot	1.4 - 2.2	Onion	1.8 - 2.2
Blueberry	1.8 - 2.0	Parsley	0.8 - 1.8
Broccoli	1.4 - 2.4	Passion fruit	1.6 - 2.4
Bromeliad	0.8 – 1.0	Pea	1.4 - 1.8
Brussel Sprout	1.8 - 2.4	Pumpkin	1.4 - 2.4
Cabbage	1.4 - 2.4	Radish	1.2 - 2.2
Capsicum	2.0 - 2.7	Rhubarb	1.6 - 2.0
Carrot	1.4 - 2.2	Roses	1.8 - 2.6
Cauliflower	1.4 - 2.4	Sage	1.0 - 1.6
Celery	1.5 - 2.4	Spinach	1.8 - 3.5
Chives	1.2 - 2.2	Silver-beet	1.8 - 2.4
Cucumber	1.6 - 2.4	Squash	1.8 - 2.4
Roses	1.8 - 2.2	Strawberry	1.8 - 2.5
Eggplant	1.8 - 2.2	Thyme	1.2 - 1.6
Endive	0.8 - 1.5	Tomato	2.2 - 2.8
Fennel	1.0 - 1.4	Turnip, Parsnip	1.8 - 2.4
Garlic	1.4 – 1.8	Watercress	0.4 - 1.8

Note: The units for soil EC value is mS/cm. (Source: Liyan, 2022)

For oil palm, the EC value is ranged from 0.5–2.5 milliSiemens per centimeter (mS/cm). However, it's important to note that optimal EC levels may vary depending on specific soil and environmental conditions, and regular monitoring is necessary to ensure soil health and crop productivity (Mohad Azhan *et al*., 2021).

5. Factors Affecting the Electrical Conductivity of the Soil

Soil EC is influenced by various factors, including crop cultivation, irrigation practices, land management, and the application of fertilizers, manure, and compound fertilizers. Additionally, intrinsic factors such as soil minerals, climate, and soil texture play a role in determining EC levels.

Excessive fertilization is prevalent in contemporary agricultural practices, leading to soil salinity issues that significantly impede crop growth. Therefore, it is imperative to monitor soil EC levels attentively. Assessing the EC value enables farmers to implement scientifically sound adjustments to water and fertilizer usage, promoting the robust growth of crops and ultimately enhancing productivity and income (Liyan, 2022).

Several factors influence the soil apparent electrical conductivity (ECa), which reflects the soil's ability to conduct electrical current. These factors include:

1. Soil Moisture Content: Moisture content is one of the most significant factors affecting soil ECa. As water increases in soil, it enhances the movement of ions, improving conductivity. Wet soils exhibit higher ECa compared to dry soils.
2. Soil Texture: Fine-textured soils, such as clay, tend to have higher ECa values due to their higher surface area and water-holding capacity. Coarse-textured soils (e.g., sandy soils), with larger particles and less water retention, generally exhibit lower ECa.
3. Soil Salinity: Salts in the soil increase the number of charged particles (ions), which enhances electrical conductivity. Higher soil salinity, therefore, increases soil ECa, which is often used to monitor saline conditions.
4. Soil Bulk Density: Higher bulk density, often caused by compaction, reduces pore space and increases soil particle contact, improving conductivity. Compacted soils generally have higher ECa values.
5. Soil Temperature: Electrical conductivity increases with temperature due to increased ion mobility. Colder soils tend to have lower ECa values, while warmer soils show higher values.
6. Soil Organic Matter: Soils with higher organic matter typically have lower ECa values. Organic matter increases soil porosity and retains less water compared to mineral-rich soils, which reduces conductivity.
7. Soil Depth: ECa varies with depth as different soil layers have varying textures, moisture, and salinity. Deeper layers may have different ECa values compared to the topsoil, depending on compaction, moisture, and other factors.
8. Ionic Composition of Soil Solution: The type and concentration of dissolved ions in the soil solution affect conductivity. Higher ion concentrations (e.g., calcium, magnesium, sodium) improve the soil's ability to conduct electricity, leading to higher ECa values.
9. Soil Structure: Well-structured soils with larger aggregates and more pore space may exhibit lower ECa, while poorly structured soils with more compacted or tightly packed particles may show higher ECa.
10. Cation Exchange Capacity (CEC): Soils with a high CEC (e.g., clays and organic-rich soils) can hold more cations and thus show higher ECa values due to the presence of more exchangeable ions.

Furthermore, in term of application, it is important to acknowledge the absence of quantitative data or specific examples to illustrate their impacts. Integrating case studies and data points can greatly enhance understanding and provide tangible evidence of how these factors influence ECa in practical settings. There are several case studies that support the statement, including:

1. Soil Moisture Content

Studies have shown that a 10% increase in soil moisture can lead to a 2- to 4-fold increase in soil ECa, depending on soil texture. In a study of sandy loam soils in the U.S. Midwest, Kitchen *et al*. (2003) observed a significant rise in ECa values after heavy rainfall, confirming that soil moisture content strongly correlates with ECa measurements.

2. Soil Texture

In a loamy soil field, researchers recorded ECa values of 20 mS/m for sandy areas and up to 60 mS/m for clay-rich areas, highlighting the texture's effect on conductivity. Lesch and Corwin (2003) conducted a study on an irrigated almond orchard in California, where clay soils exhibited ECa values nearly three times higher than sandy soils due to greater ion exchange and water retention in clay.

3. Soil Salinity

A salinity increases of 1 dS/m resulted in a 10% rise in ECa in a saline field near the San Joaquin Valley (Corwin & Plant, 2005). In saline soils of Texas, a study showed that ECa values of over 120 mS/m were detected in highly saline patches, while non-saline areas had ECa values below 40 mS/m, demonstrating the link between salinity and conductivity (Corwin & Lesch, 2005). Aini *et al*. (2014) reported that the soil ECa has a relationship with soil pH in oil palm plantations at three different depths, with the final result showing an R^2 value of approximately 0.484.

4. Soil Bulk Density

Quantitative Example: Soil compaction in a cornfield resulted in an increase in ECa values from 30 mS/m to 50 mS/m as bulk density increased by 0.4 g/cm³. Sudduth *et al*. (2001) observed this in a precision agriculture study where compacted soils showed consistently higher ECa due to reduced pore space and increased particle contact.

4. Soil Temperature

ECa in a loam soil increased by 5% for every 5°C rise in temperature during a field study. Evett *et al*. (2006) demonstrated this temperature-ECa relationship during a growing season in Colorado, where soil temperature fluctuations contributed to varying ECa readings.

These factors strengthen the important of the soil ECa for the technology's effectiveness in agricultural and environmental applications.

5. Techniques to measure soil EC

Various methods are available for testing soil EC values (Figure 1) (Liyan, 2022):

a) Handheld EC Meter: This device is a straightforward tool for measuring soil extract EC values. It comprises of a probe implanted into the soil excerpt, with the reading showed on a digital screen.

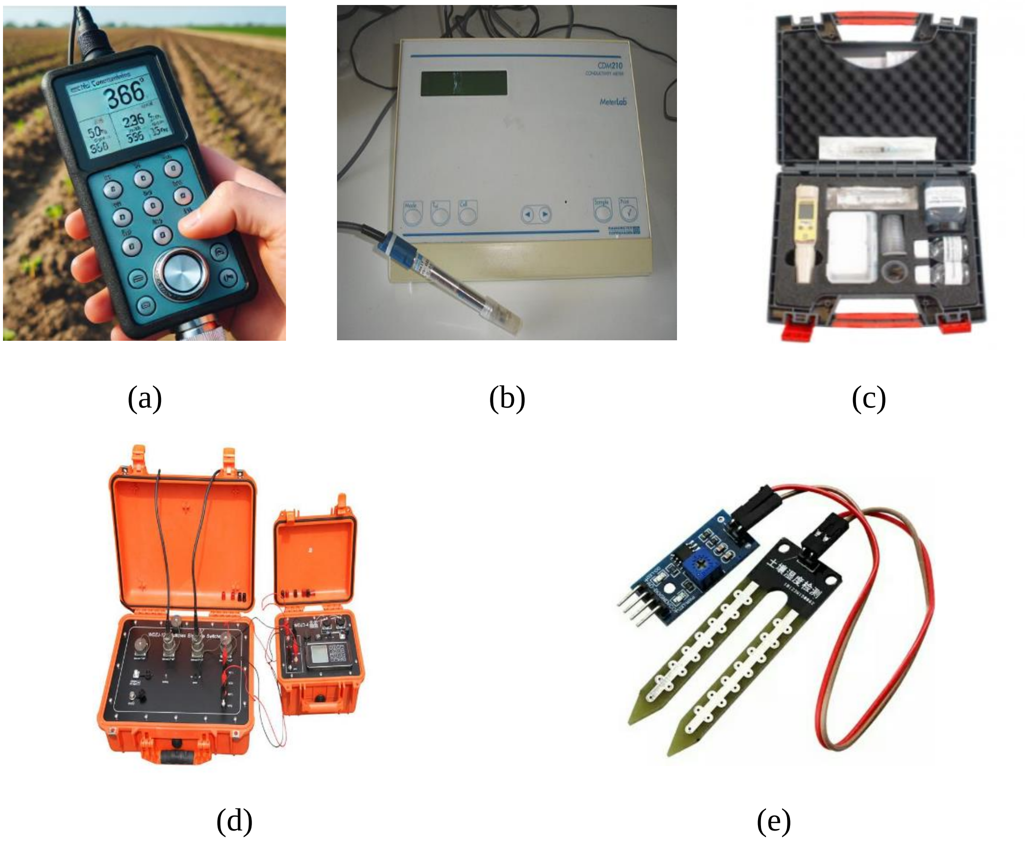

Figure 1. Different methods for testing soil EC values, including: a) Handheld EC meter, b) Conductivity meter, c) Soluble Salt test Strips, d) Electrical Resistivity Imaging (ERI) and e) Soil moisture sensor.

b) Laboratory Analysis: Soil samples can undergo laboratory analysis, where a conductivity meter measures the EC value. While this method yields precise results, it can be time-intensive and costly.

c) Soluble Salt Test Strips: These paper strips are immersed in a soil excerpt. The strip's colour vicissitudes according to the soil extract's EC value, enabling comparison with a color chart for identification (Hardie & Doyle, 2012).

d) Electrical Resistivity Imaging (ERI): It is a geophysical technique, employs electrodes to gauge soil electrical resistivity. By assessing resistivity, the soil's EC value can be estimated.

e) Soil Moisture Sensor: Widely utilized in smart agriculture, soil moisture sensors aid farmers in real-time and remote soil EC monitoring, ensuring ideal plant growth.

According to research done by Mohad Azhan *et al*. (2021), a soil EC mapping coordination using intelligence sensor at young oil palm planted area was carried out at Melaka by operating an auto-pilot system and Veris 3100 (Figure 2). The Veris 3100 has revolutionized soil EC measurement for farmers, enabling them to generate soil EC maps with precision. Veris, integrated with GPS technology, accurately locates the device before transforming the data into map format. However, any GPS malfunction can lead to data inaccuracies. Nevertheless, Veris 3100 is a reliable technology known for its ability to identify areas with specific soil properties using soil EC.

Figure 2. Veris 3100.

There are two methods for measuring EC with Veris 3100. Firstly, it employs a direct contact sensor that interfaces directly with the soil, measuring at two different depths: shallow (0–30 cm) and deep (0–90 cm). Using three pairs of electrodes, one pair injects electrical current into the soil while the others measure voltage changes. While the coulter-electrodes only penetrate the soil a few inches, the Veris system's electrical ranges carefully evaluate the soil's properties. During data collection, it's crucial to maintain GPS readiness and minimize movement to prevent connection loss, which could disrupt the process. Once the cart traverses the soil, a distinctive line appears, signifying direct contact as Veris 3100 establishes EC measurements with the soil. Soil compactness correlates positively with EC readings, highlighting the importance of soil structure for accurate EC assessment.

From the study, it was revealed that by utilizing Veris 3100 allows for the determination of EC levels at the study location, aiding in the identification of soil properties and texture, whether it's sandy, clayish, or silt. Understanding the soil texture enables the assessment of crucial basics such as water holding capacity, CEC and porosity. Precision agriculture (PA) promotes improved management routines, leading to enhanced operational efficiency, higher yields, reduced inputs, and environmental conservation (Mohad Azhan *et al*., 2021).

Another study by Aini *et al*. (2014) on the relationship between soil apparent electrical conductivity and pH values in the Jawa series within oil palm plantations resulted in maintaining the appropriate pH level is essential for robust plant growth as it influences nutrient availability. This research aimed to assess soil pH levels in oil palm plantations using the EC parameter calculated by soil sensors. Soil samples were composed at three depths: 0–15 cm, 15–30 cm, and 30–45 cm, and EC was recorded using sensors within the oil palm plantation. The findings revealed a significant negative correlation between EC and soil pH, particularly evident in deep EC at a depth of 15–30 cm, with an R^2 value of 0.484.

In the U.S. Midwest, soil EC sensors have been effectively used to monitor soil salinity and moisture in corn and soybean fields. A notable case is the use of Veris EC mapping systems to guide variable rate irrigation (VRI) and fertilizer applications. The sensors helped identify zones with differing soil properties, enabling precise nutrient and water management. As a result, crop yields improved by up to 15%, and input costs were reduced by 10%. This case demonstrates the practical benefits of integrating soil EC sensors into large-scale farming operations.

In California's wine-producing regions, soil EC sensors have been employed to manage moisture levels and salinity in vineyards. Given the sensitivity of grapevines to salinity and drought, multi-depth EC sensors were installed to monitor soil moisture and salt accumulation. This data was combined with remote sensing and weather data to optimize irrigation scheduling. As a result, vineyards reported higher-quality grapes and a reduction in water usage by up to 20%. This case highlights the advantages of combining EC sensors with other smart farming technologies, such as drones and satellite imaging.

In rice production, particularly in regions like Southeast Asia, soil EC sensors have been used to monitor salinity and manage waterlogging, both of which are critical for rice health. By deploying EC sensors in paddy fields, farmers were able to prevent salinity buildup during irrigation and drainage cycles. In one example from Thailand, the integration of EC sensors with automated water gates led to a 30% reduction in yield loss due to salinity, demonstrating the value of sensor data in managing challenging environmental conditions.

As part of soil EC functionalities, by adapting this sensor, several technological advancements are expanding to the next level of continuous improvement. Recent advancements in soil EC sensors have focused on enhancing accuracy by reducing interference from temperature fluctuations and soil texture variations. Modern sensors now come equipped with temperature compensation features, which allow them to provide more reliable readings across a variety of environmental conditions. This improvement has expanded their applicability across different soil types and climates, making them useful for precision farming in diverse regions. The durability of soil EC sensors has significantly improved with the use of more robust materials and better sealing against moisture and chemical exposure. Newer sensors are designed to withstand harsh agricultural environments, including exposure to fertilizers, pesticides, and prolonged moisture. This increased durability reduces the frequency of sensor replacement and maintenance, making the technology more cost-effective for long-term use. By integration with Smart Farming Technologies, the most important advancements are the integration of soil EC sensors with the GPS-guided tractors, drones, and automated irrigation systems. Many modern sensors are equipped with wireless capabilities, enabling real-time data transmission to cloud-based platforms. This integration allows farmers to access data remotely, analyze it using machine learning algorithms, and make immediate adjustments to irrigation and fertilization systems. The ability to combine soil EC data with other datasets, such as weather forecasts and satellite imagery will enhances decision-making and enables precision agriculture practices at a larger scale (Ali *et al*. 2020 and Bunyamin *et al*. 2020).

7. Economic Benefits

The economic benefits of using soil EC sensors in precision agriculture are substantial, especially in terms of cost savings and yield improvements. Below is a detailed discussion of these benefits, supported by quantitative data from real-world applications.

7.1 Cost Savings

a. Reduced input costs

Soil EC sensors enable farmers to apply fertilizers, water, and other inputs only where they are most needed. By creating management zones based on soil properties, farmers can tailor input applications, leading to significant cost reductions. Studies have shown that precision agriculture techniques using soil EC data can reduce fertilizer usage by 15% to 30%. In a study conducted on corn and soybean fields in Iowa, the reduction in fertilizer application due to soil EC mapping saved around USD25 per acre, equating to USD2,500 for a 100-acre farm. In irrigated crops, variable rate irrigation (VRI) guided by soil EC data has been shown to reduce water use by 20%. For example, in vineyards in California, where water is a precious resource, farmers saved approximately 15% on water costs, translating to hundreds of dollars in savings per acre each growing season.

b. Decreased fuel and labor costs

With accurate soil EC maps, farmers can reduce the number of passes required for tilling, planting, and spraying. This not only saves fuel but also reduces labor costs. For instance, by using precision agriculture practices like variable rate application (VRA), a 15% reduction in field passes was reported in several cases, which saved approximately USD5 to USD8 per acre in fuel costs.

c. Reduced environmental impact and regulatory compliance

By optimizing input application, precision farming reduces the environmental footprint of agriculture, leading to potential savings in penalties or fines related to overuse of fertilizers or pesticides. Additionally, more efficient use of water can help farmers comply with local water regulations and avoid fines.

7.2 Yield Improvements

a. Better nutrient management

Soil EC sensors provide critical information about soil texture, salinity, and organic matter content, allowing for precise nutrient management. In a study conducted in the U.S. Midwest, fields that implemented variable rate fertilization based on soil EC data saw yield increases of 5% to 10% in corn and soybeans. The yield increase translated to an additional 8 to 10 bushels per acre, which, at a market price of USD4 per bushel, equals an additional USD32 to USD40 per acre in profit.

b. Improved irrigation efficiency

In regions with water scarcity, soil EC sensors help optimize irrigation schedules, preventing over- or under-watering. For example, rice fields in Southeast Asia using soil EC data for irrigation control reported yield increases of 10% to 15% by maintaining optimal soil moisture levels. Given that rice yields can range from 3,000 to 7,000 kg per hectare, these increases could result in hundreds of additional kilograms of rice per hectare, translating into significant financial gains for farmers.

c. Enhanced pest and disease management

Soil EC sensors also help identify areas of stress in crops, which may be linked to pest or disease outbreaks. By identifying these zones early, farmers can apply pesticides or fungicides only where needed, reducing crop loss and input costs. Cotton farmers in Australia using soil EC mapping reported yield increases of up to 12% due to improved management of pest-prone areas, resulting in several hundred dollars per hectare in additional revenue.

7.3 Quantitative Economic Benefits Summary

It is crucial to demonstrate the value of economic benefits from adapting the soil EC in agriculture, as illustrated below:

Table 2. Economic benefits of using soil EC sensors in agriculture

Benefits	Cost Savings/ Yield Improvement
Fertilizer Savings	USD25 per acre (15%–30% reduction)
Water Savings	15%–20% reduction, e.g., USD300 per acre for vineyards
Fuel and Labor Savings	USD5–USD8 per acre (15% reduction in field passes)
Yield Increases	5%–15% increase (e.g., 8–10 bushels/acre for corn/soy)
Pest and Disease Management	Up to 12% yield improvement in crops like cotton

(Source: Xun, 2024)

The adoption of soil EC sensors in precision agriculture delivers notable economic benefits. From Table 2, fertilizer costs can be reduced by 15%–30%, translating into savings of approximately USD5 per acre. Water usage sees a reduction of 15%–20%, leading to savings of up to USD300 per acre, particularly in high-value crops like vineyards. Fuel and labor expenses decrease by USD5–USD8 per acre due to fewer field operations. In terms of productivity, yield improvements of 5%–15% are common, with crops like corn and soy benefiting from an additional 8–10 bushels per acre. Furthermore, enhanced pest and disease management enabled by these sensors can boost yields by up to 12% in crops such as cotton. These economic gains, through more efficient resource use and increased crop productivity, underscore the transformative potential of soil EC sensors in precision farming.

8. Data Interpretation of Soil EC Readings

Expanding data interpretation for soil electrical conductivity (EC) readings can significantly enhance their utility in precision agriculture. There are several important scopes to be highlighted during soil EC application, such as follows (Aimrun *et al*., 2011):

8.1 Understanding EC Values

1. Low EC Readings (<0.5 mS/cm): Indicate low salinity and generally favorable conditions for crop growth. Management decisions may include ensuring adequate nutrient application since nutrient availability may also be low.
2. Moderate EC Readings (0.5–1.5 mS/cm): Suggest a balanced salinity level. While many crops tolerate this range, monitoring is essential to prevent salinity accumulation. This is a good time to adjust irrigation practices to avoid excess salts.
3. High EC Readings (>1.5 mS/cm): Indicate potential salinity stress. Management decisions may involve implementing leaching strategies, selecting salt-tolerant crop varieties, or improving drainage to mitigate excess salts.

8.2 Spatial Variability

By using EC maps to identify spatial variability within fields, areas with consistently high EC can be managed with different management strategies, such as targeted irrigation or nutrient applications, compared to low EC zones. Part of that, by integrating EC data with variable rate technology (VRT), to apply fertilizers, water, and other inputs, the works are more precisely in response to the specific needs of different areas within the field.

8.3 Crop Management Decisions

Interpreting soil EC readings provides valuable insights for effective nutrient management, irrigation scheduling, and crop selection. Higher EC levels often indicate increased salinity and nutrient concentration, allowing farmers to integrate soil test results with EC data to fine-tune fertilizer applications according to specific crop needs. Additionally, adjusting irrigation practices based on EC readings can help manage soil moisture effectively; for example, elevated EC levels may necessitate more frequent but smaller irrigation events to leach excess salts without oversaturating the soil. Furthermore, selecting appropriate crop varieties based on specific EC conditions is crucial for optimizing yield potential—planting salt-tolerant varieties in high salinity areas can enhance resilience, while more sensitive crops can thrive in low-salinity zones. This tailored approach allows for better adaptation to varying soil conditions, ultimately promoting healthier crop growth and improved productivity (Ali *et al*., 2020).

8.4 Long-term Monitoring and Trends

Tracking changes in soil EC over time is essential for evaluating the effectiveness of management practices, as regular readings can reveal trends that may necessitate adjustments in irrigation or fertilization strategies. For instance, a rising trend in EC levels could indicate an accumulation of salts or nutrients, prompting farmers to reconsider their current practices. Additionally, incorporating EC data into a broader soil health monitoring program that includes metrics such as organic matter content, pH, and microbial activity provides a more holistic view of soil conditions. This comprehensive approach enables better-informed soil management decisions, ultimately enhancing soil health and promoting sustainable agricultural practices (Brevik *et al*., 2006).

9. Discussion

Soil EC plays a crucial role in determining crop performance, particularly in terms of yield. Measuring soil EC allows for the valuation of various soil properties, such as texture, including sand, silt, and clay. The electrical conductivity of sandy soil typically ranges from 0 to 8 millisiemens, while silt registers between 8 and 50 millisiemens, and clay exhibits levels between 10 and 1000 millisiemens. Notably, sand demonstrates lower conductivity, silt falls within the medium range, and clay exhibits higher conductivity levels (Mohad Azhan *et al*., 2021).

The connection between electrical conductivity and other soil properties significantly influences field output. In this investigation, the Veris 3100 functions as a direct interaction sensor, conducting measurements at two distinct depths: shallow (0–30 cm) and deep (0–90 cm). Each depth provides insights into varying levels of EC within the soil. According to Aini *et al*. (2014), deep EC measurements can serve as an approximation for soil pH compared to shallow measurements.

According to Aimrun *et al*. (2011), careful consideration of management operations and agrichemical inputs is essential for implementing SSM or precision farming, which involves dividing fields into different management zones. The study characterized the physico-chemical properties of moist tropical paddy soils after zoning based on apparent EC. In some cases, grid-soil sampling and nutrient mapping are the most suitable approach for management operations. Soil EC zoning can serve as a consistent gauge of yield potential and a valuable tool for evaluating site-specific management feasibility. Based on his study in the Tanjung Karang Rice Irrigation Scheme in Kuala Selangor and Sabak Bernam, Malaysia, the results indicated that zone 1 of shallow EC showed significantly lower levels of EC, Calcium (Ca), Potassium (K), and Iron (Fe), but higher fine sand and sand contents. Zone 1 of deep EC resulted in significantly lower levels of Magnesium (Mg), Sodium (Na), and total cations. The lower Na levels in zone 1 may be attributed to the deep soil profile reaching marine clay parent material. The high fine sand and sand content were consistently observed in zone 1 across all seasons. These findings suggest that field-scale EC surveys can delineate distinct soil condition zones with varying nutrient levels, providing a basis for effective zone-based soil sampling and aiding farmers in implementing variable rate application strategies. Furthermore, Jung *et al*. (2005) demonstrated that soil EC serves as an indicator of soil quality and productivity. Their study revealed a correlation between EC, soil properties, and crop yield, with some dependency on precipitation rates. As such, soil EC sensors are valuable tools for mapping various soil properties in specific areas due to their ability to quickly measure EC with precision location data. Besides, measurements conducted at four sites in oil palm plantation in Indonesia have demonstrated that high productivity can be achieved even in soils at low pH levels. Furthermore, implementing a good management practice has been shown to have the potential to raise pH levels in soils initially characterized by low pH values (Aini *et al*., 2014).

Soil electrical conductivity EC holds significant importance in agriculture due to its multifaceted functions and applications. In term of Soil Fertility Assessment, soil EC assists in determining of soil fertility by reflecting the concentration of dissolved salts in the soil. High EC values may suggest the presence of abundant dissolved nutrients, while low values could indicate nutrient deficiencies. By measuring soil EC, farmers can gain insights into soil fertility status and make informed decisions regarding nutrient management and fertilization practices. Besides, irrigation management is closely linked to soil moisture content. Monitoring changes in EC levels can help farmers optimise irrigation practices by determining when and how much water to apply. This ensures that crops receive adequate moisture without risking waterlogging or leaching of nutrients. Furthermore, salinity Management indicated that soil salinity can negatively influence crop development and yield. Soil EC measurements enable farmers to identify areas with high salinity levels and implement appropriate management strategies, such as leaching or selecting salt-tolerant crop varieties. According to Aimrun *et al*. (2007) and Razali *et al*. (2012), soil EC is closely associated with salinity levels. Increased absorptions of salts in soil water result in higher soil EC readings. However, excessive salt accumulation is not advisable as it can lead to soil acidity. In Precision Agriculture scope, Soil EC mapping allows for the identification of spatial changeability in soil possessions within a field. By creating EC maps, farmers can delineate zones with different soil characteristics and tailor management practices, such as fertilization and irrigation, to specific areas. This facilitates precision agriculture, optimizing resource use and improving crop productivity. As for soil health monitoring, the changes in soil EC can indicate alterations in soil health, such as compaction or organic matter content. Continuous monitoring of soil EC helps farmers assess soil health conditions and take corrective actions to maintain soil fertility and structure. In addition, the Soil EC data can inform crop management decisions, such as selecting suitable crop varieties based on soil salinity tolerance or adjusting fertilizer application rates according to soil nutrient availability. This ensures that crops receive optimal growing conditions, leading to improved yields and quality.

Several factors affect soil electrical conductivity EC. Firstly, the soil's pore structure plays a significant role. When soil pores are saturated with water, they become more compact, allowing them to conduct electricity more efficiently. Additionally, soils with higher clay content typically exhibit better conductivity compared to sandy soils.

According to studies by Islam *et al*. (2012) and Corwin and Lesch (2005), the high EC values are associated with increased water holding capacity, while lower EC values indicate lower water retention capabilities.

As a way forward, a proper sensor calibration is essential for accurate readings, yet it can be complicated by soil variability and changing conditions, such as moisture levels and temperature. Regular maintenance of the sensors is also necessary to ensure long-term functionality and precision, especially in harsh field environments. Environmental factors like soil texture, organic matter, and salinity can affect the accuracy of EC readings, requiring adjustments or the development of more robust sensor technologies. Future research could focus on improving sensor durability, automating calibration processes, and enhancing the integration of EC data with other smart farming technologies to provide more precise and reliable measurements across diverse agricultural conditions.

Expanding geographic and crop-specific studies is essential to fully demonstrate the flexibility and potential of soil EC sensors across diverse agricultural environments. Soil electrical conductivity (EC) is influenced by a wide range of factors, including soil type, moisture content, temperature, and salinity, all of which vary significantly across different geographic regions and climatic conditions. By conducting studies in varied locations, researchers can gather data on how these environmental variables impact EC readings and refine sensor calibration for specific conditions. For instance, arid regions may show a higher sensitivity to soil salinity, while tropical climates may require adjustments due to fluctuations in soil moisture levels. Understanding these regional differences is critical for improving the accuracy and reliability of EC sensors.

In the context of oil palm cultivation, expanding geographic and crop-specific studies involving soil EC sensors would be particularly valuable due to the unique challenges this crop presents. Oil palm plantations are often spread across a wide range of climates and soil types, including tropical regions with high rainfall and sometimes poorly drained soils. Soil EC sensors could play a critical role in managing the specific nutrient and moisture requirements of oil palm trees, improving both productivity and sustainability. This type of research also helps in understanding how EC readings interact with other agronomic factors such as soil organic matter, pH, and microbial activity. By examining a wider range of geographic and crop conditions, scientists and farmers can build more robust models that integrate EC data into comprehensive soil health monitoring systems.

Ultimately, these expanded studies would demonstrate the adaptability of soil EC sensors to different farming systems, enabling more precise nutrient management, irrigation scheduling, and crop selection based on local conditions. This would foster greater adoption of soil EC sensors globally, providing farmers with actionable insights to improve yields, reduce input costs, and enhance sustainability across a wide variety of environments and agricultural practices.

10. Conclusions

Overall, soil EC serves as a valuable tool for enhancing agricultural productivity, sustainability, and environmental stewardship by providing insights into soil fertility, moisture status, salinity levels, and overall soil health. Employing this technology facilitates optimal management practices for farmers. Through mapping systems, farmers can easily delineate management zones tailored to specific crop requirements, as each area exhibits varying levels of EC. Precision agriculture holds great potential for implementation in Malaysia.

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