



Calibration and Validation of Integrated Sensors System with Low-Cost Data Acquisition System for Measuring Soil Compaction and Electrical Conductivity of Soil in Central Plane Zone of Punjab

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Abstract: In the present study, an experimental analysis was carried out to find the calibration curves for the S-type load cell used for measuring soil compaction and electrical conductivity measuring sensor based on the Wenner Array method and integrate the sensor's calibrated output corresponding to different depth intervals by using ultrasonic depth sensor after its calibration. The data acquisition system was designed with the help of an Arduino Uno Microcontroller based on ATmega 328P which was equipped with high-performance AVR technology. The monochrome graphic flat panel display Module with 4 Pin was used for displaying the sensor's output data in real-time. A data logger was used for recording and saving the pre-calibrated data from all the integrated sensors in Excel format for accurate calibration of all the integrated sensors. The developed dual soil sensor was validated in the field in three types of tillage treatments in sandy loam soil. The accuracy of the developed dual soil sensor measuring soil compaction and soil electrical conductivity was 95.4 and 73.42 %, respectively.

Keywords: S-type load cell, Electrical conductivity, Ultrasonic depth sensor, Arduino Uno, Calibration, Soil sensors

In India, the majority of people rely on agriculture for their living. Soil conditions have a significant impact on cost-effective and efficient farm production. In order to evaluate the fertility status or the physical and chemical characteristics that affect a soil's suitability for growing plants, soil testing is a crucial technique to carry out. Over time, various soil assessment techniques have been used. In precision agriculture, the lack of soil data that is pertinent, trustworthy, economical, readily accessible, and adequately precise continues to be a major concern. In order to practice precision agriculture, it is necessary to have access to timely, affordable, and accurate soil data (Kumar and Masrat Mohi 2024, Kumar 2024a). Usually, soil sampling and subsequent laboratory analysis, which is very time-consuming and labor-intensive, yield the most crucial soil properties. If performed on a fine grid, soil sampling, and laboratory analysis take a long time and become prohibitively expensive. Testing the soil directly in the field, such as by using real-time soil sensors, may be an alternative to or a supplement to laboratory soil analyses (Adamchuk 2011).

Due to their robust nature, which makes them reliable and suitable for field applications, soil sensors continue to be widely used as the foundation of precision agriculture for mapping soil variability. Before releasing any method for use in practice, these types of sensors need careful calibration and a well-designed validation. Calibration refers to the evaluation of testing equipment (sensors) against the pre-

known values by developing the correlation between the actual values and measured values to reduce error in the sensors' measurement. The difference between the expected and measured values of a sensor is called structural error. During the calibration process the set of adjustments performed on a sensor or instrument to make that instrument function as accurately, or error-free, as possible (Soni et al 2017).

In India, soil compaction (MPa or kPa) and electrical conductivity (mSm^{-1}) are measured by penetrometer and laboratory methods, respectively. Soil compaction is commonly used as a measure of soil strength as determined by a cone penetrometer in terms of cone index. There are three different types of electrical conductivity measuring sensors based on the principle of the soil sensor: electromagnetic induction (EMI), time-domain reflectometry (TDR), and direct contact method (ERM). One of the basic elements of electrical conductivity measurement is the electrode array, which characterizes the configuration settings of the electrode sensor used to measure current or voltage. Furthermore, soil sensors based on the electrical resistivity principle such as the Wenner array method are affordable and easy to use (Kumar 2023, Kumar 2024b). Many researchers are working on the development of new improved penetrometers with the incorporation of electronic instruments to monitor the penetration resistance simultaneously with electrical conductivity by employing load

cell, electrical conductivity measuring sensors, and penetration depth using ultrasonic depth sensors. Gradually data loggers and control panels are also introduced in new editions of penetrometers by different researchers (Kumar and Bector 2022).

The S-type load cell is a transducer that can measure force and weight by converting tensile and compressive forces in the form of electrical signals. When the force is applied to the load cell, the shape of the wire is slightly distorted and returns to its original shape, unless it is overloaded, resulting in a change in resistance. This change in resistance is proportional to the pressure of the applied force. The maximum pressure that it can withstand is called the capacity of the load cell (θ). The ultrasonic depth sensor triggers an ultrasonic wave from the transmitter at a frequency of 40Hz and the receiver module receives the returned wave signals. Once the wave returns after being reflected by any object, at the same time the Echo pin makes a transition from low to high level for a specified period, which is equivalent to the time it takes for the wave to return to the sensor. The distance is calculated from the speed and time travelled by the wave (Carrara 2014). These sensors are generally interfaced with a microcontroller that monitors such as Arduino Uno, performs transformation, and makes decisions on the sensor's input and output signals. It functions as a small computer, accepting inputs and controlling outputs for various electronic devices (Anonymous 2015). The accuracy of calibration and validation of the sensors in well-designed ecosystems is a key factor in determining the validity of these sensors that are interfaced with the microcontroller. Consequently, objective was to precisely calibrate and validate the integrated sensor system in the actual field using established standard laboratory techniques in real-world settings.

MATERIAL AND METHODS

The major sensors selected for the development of the sensor-based integrated system for measuring soil compaction and electrical conductivity of the soil were an S-type load cell, an ultrasonic depth sensor, and electrical conductivity measuring sensor based on the Wenner Array method. The detailed procedure for the calibration of the integrated sensors systems is presented under the following sub-heading:

Load cell calibration: The S-type load cell of 500 kg capacity was calibrated by applying known dead weight (kg) load vertically under a static load experiment set on the top of the load cell in two phases and the output was recorded in millivolt (Fig. 1). Initially the dead weight ranged from 5 to 50 kg at an interval of 5kg and in the second phase the dead weight ranged from 1 to 50 kg at an interval of 1 kg (Fig. 2, 3). The same procedure for calibration was followed by Rahai (2013), Anonymous (2014), and Anonymous (2017). The signals generated from the load cell were very low and were not able to work with the microprocessor therefore, a signal amplifier cum signal conditioning module (HX711 amplifier module) was used. The signal amplifier provided well-controlled regulated excited voltage to the circuit of the load cell and in addition, it includes noise signal filtering, amplification, and output signal manipulation.

The S-type load cell was connected to the recording unit via a voltage amplifier module (HX711 amplifier module) powered with the 12-volt DC battery. The output measured data without load on the load cell was set at zero and the corresponding output data was recorded with gradually loading and unloading the dead weight on the top of the load cell. The analog to digital (A/D) converted output of the load cell was recorded manually as displayed on the OLED screen. The output of the amplified signals from the load cell



Fig. 1. Experimental setup for load cell calibration with loading and unloading known dead weights

was programmed by using the linear regression equation (1) to express the load from millivolt to kilogram and the basic program of the converted output of the penetration resistance or soil compaction (Cone index), was expressed in megapascal by using the standard equation (2) which states that the cone index is the force (N) that is applied on the base area of the cone. The relationship between the actual load in kilogram and measured output average mean of loading and unloading in millivolt was found to be highly linear at their respective interval and the linear regression line was fitted to the measured output data with R² value of 0.99 (Table 1).

$$\text{Weight (kg)} = 2.24028 \times (X) + \text{constant}$$

PR = Penetration resistance
 X = Analog to digital converted output (mV)
 Constant = 0.628

$$\text{Cone index (MPa)} = \frac{\text{Weight (kg)} \times 9.8}{\text{Cone base area (mn}^2\text{)}}$$

Ultrasonic depth sensor calibration: The ultrasonic depth sensor selected was an electronic device that was sensitive to changes under different environmental conditions and thus produce undesirable outputs under abrupt changes. To reduce the error in the measured output and expected output, the sensor was calibrated. The two pins (tripper and echo) were connected to the I/O pins of the microcontroller (Arduino Uno) and readings were displayed on the OLED screen integrated with the circuitry of the ultrasonic sensor and microprocessor (Arduino Uno). The output reading of the

ultrasonic sensor displayed on the screen was manually recorded against the actual reading on the measuring tape by placing a target plate (obstacle) in parallel and gradually moving the targeted plate from 0 to 60cm at an interval of 2 cm. The inbuilt circuitry of the ultrasonic sensor automatically calculated the distance by measuring the time taken by the ultrasonic wave when triggered by the trigger pin at 40 Hz and receiving the return wave reflected by the obstacle plate attached parallel to the ultrasonic sensor. The average data from the output values against the actual value at each respective interval indicated almost excellent linearity (Fig. 4, Table 2). The experimental results of the depth sensor showed negligible error as compared to the actual distance. Since the error was very small, therefore it was easily

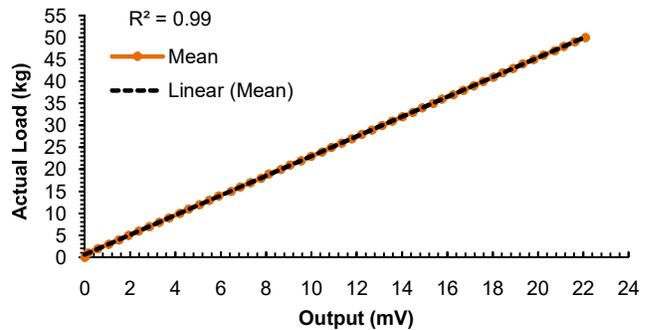


Fig. 3. Calibration of the S-type load cell with loading and unloading known dead weights (1kg interval)

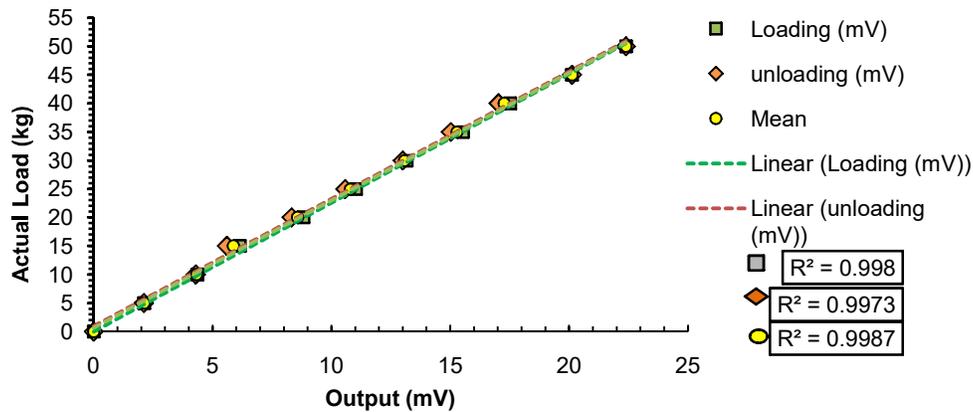


Fig. 2. Calibration of the S-type load cell with loading and unloading known dead weights (5kg interval)

Table 1. Model summary of regression correlation between input and output of actual and measured values of the load cell

Statistical parameters	Load cell range (5-50 kg) at 5 intervals (Actual input value vs output mean)	Load cell range (1-50 kg) at 1 interval (Actual input value vs output mean)
R ² value (correlation)	0.999	0.999
R ² value (coefficient of determination)	0.9987	0.999
Adjusted R ²	0.9986	0.999
Standard error of the estimate RMSE	0.3912	0.1086
Linear equation, Y	y = 2.2322x + 0.6836	Y = 2.2402x+0.628

corrected in the programming code.

Electrical conductivity measuring sensor calibration:

The electrical conductivity of the soil is directly proportional to the concentration of salt in the soil. High concentrations of ions increase conductivity in which current is transported via ions within the soil. Similarly, the lower the salt concentration, the higher the resistance, and vice versa. For calibrating the developed soil EC sensor, a total of 45 samples of the soil were collected from three different types of locations with different soil textures up to 60 cm at an interval of 20 cm and the samples were air dried (Table 3). The electrical conductivity of each sample was measured as per the standard laboratory process which served as a reference point for calibrating the developed integrated soil sensor system.

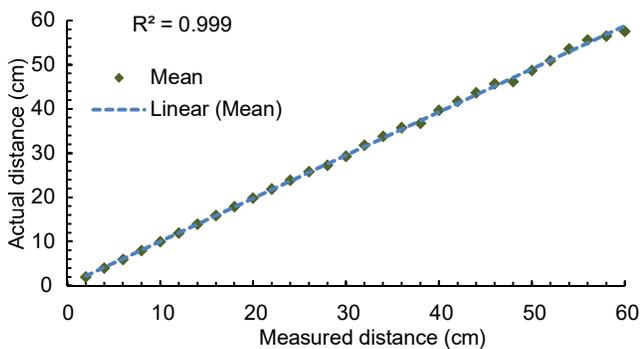


Fig. 4. Calibration graph of the ultrasonic depth sensor



Fig. 5. Measurement of output data of the developed probe sensor

Similarly, the soil electrical resistance was measured from the same location at each point of sample collection for the same soil at an interval of 20 cm up to 60 cm (Fig. 5). The relationship was developed between the electrical conductivity (dSm^{-1}) measured by the standard laboratory methods and the developed sensor's voltage (mV) (Fig. 6 a,b,c). The relationship was also developed from the corresponding output of all the samples with the laboratory methods to establish the overall correlation with all the three types of soil (Fig. 6 d, Table 4). The regression showed an inverse relation between the laboratory method and output from the developed sensing system which was analysis-backed Ohm's law. The same procedures were followed by many researchers (Park et al 2016, Jusoh and Osman 2017). The developed sensor with the microprocessor (Arduino Uno) set up was carried out for the determination of soil

Table 2. Model summary of regression correlation between input and output of actual and measured values of the ultrasonic depth sensor

Statistical parameters	Actual measurement vs output measurement
R^2 value (correlation)	0.9996
R^2 value (coefficient of determination)	0.9992
Adjusted R^2	0.9992
Standard error of the estimate RMSE	0.4662
Linear equation, Y	$Y = 0.9764x + 0.255$

Table 3. Physical characteristics of selected soil and location of plots

Particulars	Soil type-I	Soil type-II	Soil type-III
Texture class	Sandy silt loam	Sandy loam soil	Sandy Clay loam
Composition of soil texture (Sand, Silt & Clay %)	37.98, 45.61, 16.41	61.07, 27.13, 11.80	70, 13.8, 21.2
Location	L1: Research farm of DFMPE, Near PRSC, Gate no.6, PAU, Ludhiana	L2: Research farm of DFMPE, Near Gate no.4, PAU, Ludhiana	L3: Soil research farm of DSS, Near Gate no.8, PAU, Ludhiana
GPS Coordinates	75° 48'45.06" E, 30° 54'41.04" N	75° 49'08.19" E, 30° 54'38.78" N	75° 52'.10" E, 30° 56'.04" N

electrical conductivity in terms of voltage. This developed system was powered by a portable 12 V battery to make it convenient to handle independently. The sensor produced an output voltage according to the change in the resistance offered by the soil within the soil profile which was recorded manually from the display on the OLED screen. The best-fit regression curve from the regression analysis was drawn which was used for calibrating the soil sensor.

Field evaluation of the integrated soil sensor system :

The developed soil sensor system (DSS) was evaluated in three types of tillage treatments (T1, T2, T3). The total percentage of accuracy between the parameters, measured by the developed soil sensor, and the reference parameters measured by the manual hand-held cone penetrometer for cone index (MPa), and laboratory analysis for electrical conductivity of soil (dS/m), was determined by making suitable assumptions that the reference/controlled methods of measuring CI and EC are 100 % accurate. However, the comparison of the data values of CI and EC obtained from the soil sensor developed can be done with values obtained from any other selected method.

RESULTS AND DISCUSSION

Validation of the integrated soil sensor system with a manual cone penetrometer:

The accuracy of the sensor was 95.4 %. Similar trends in the data obtained using a manual cone penetrometer as a control method and the integrated soil sensor system's measurements of soil compaction were observed. The highest and lowest mean cone index that the designed integrated soil sensor system measured were 4.0604 and 0.8212 MPa, respectively whereas the highest and lowest mean cone index measured with the hand-held cone penetrometer was 0.9184 and 3.6627 MPa, respectively (Fig. 7). There was a non-significant difference between the soil compaction measured by the developed soil sensor DSS and the manual cone penetrometer (CI MCP) in sandy loam soil (Fig. 8). The R² value (correlation) was 0.83 and the coefficient of variation was 12.20, whereas the standard error of the estimate RMSE was 0.322. A box and whisker plot was plotted for displaying the distribution of soil compaction patterns in all three treatments with the developed soil sensor (CI DSS) and the manual hand-held con penetrometer (CI MCP) (Fig. 9).

Validation of the integrated soil sensor system with laboratory methods (EC):

The developed soil sensor (EC DSS) was evaluated in three types of tillage treatments (T1, T2, T3) and compared with the laboratory method (EC Lab/control method) in sandy loam soil. Similar trends between data (EC) obtained using a laboratory approach (control method) and data obtained using the developed

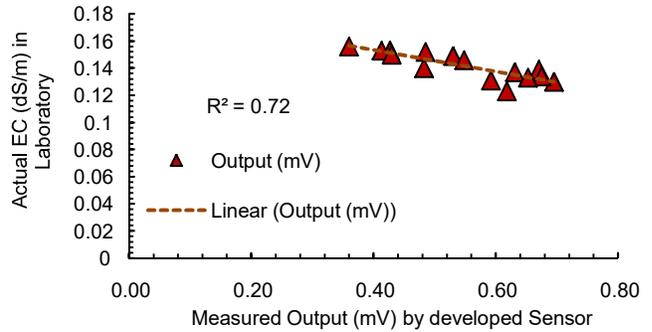


Fig. 6a. Calibration graph for EC measurement at Research Farm of FMPE, PAU, Ludhiana (L1)

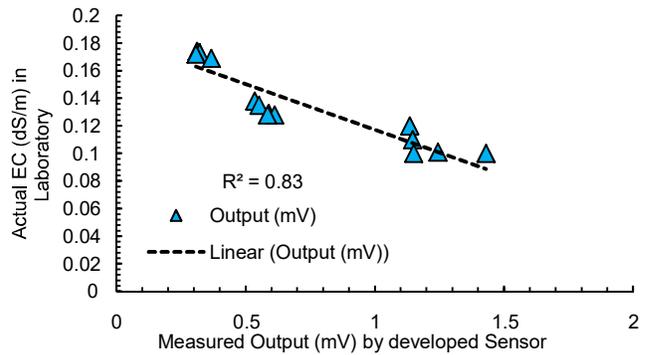


Fig. 6b. Calibration graph for EC measurement at Research Farm of FMPE, PAU, Ludhiana (L2)

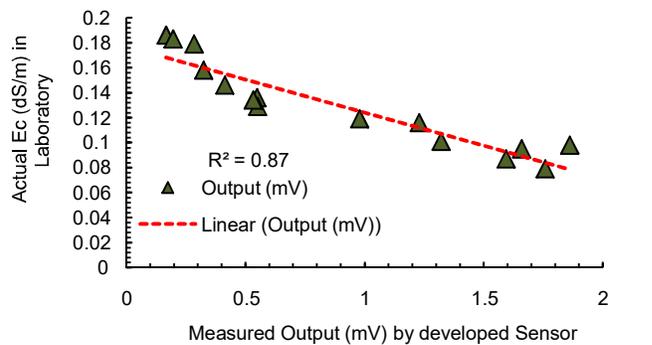


Fig. 6c. Calibration graph EC measurement at Research Farm of Dept. of soil science, Ludhiana (L3)

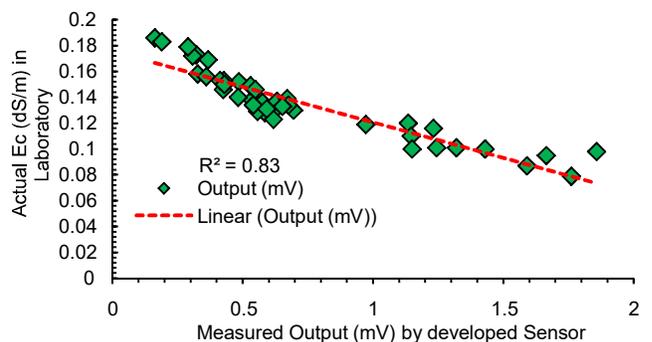


Fig. 6d. Calibration graph of EC measurement output of all three textures of soil at PAU, Ludhiana (L1:L2:L3)

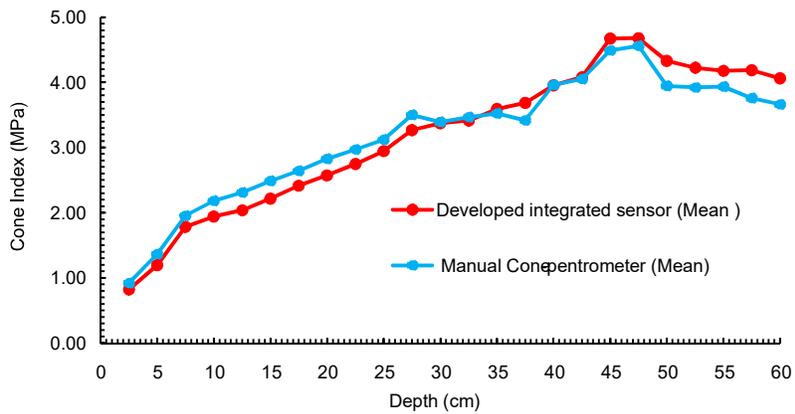


Fig. 7. Measurement of soil compaction

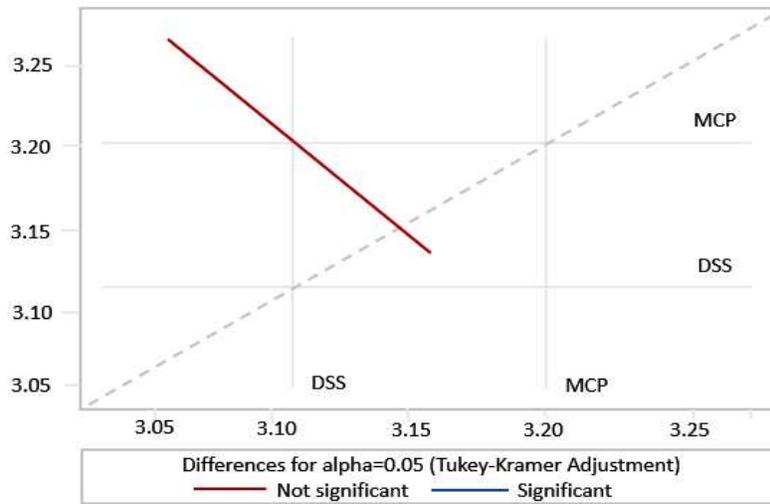


Fig. 8. Diffogram for the effect of methods of measuring soil compaction (DSS and MCP) in sandy loam soil

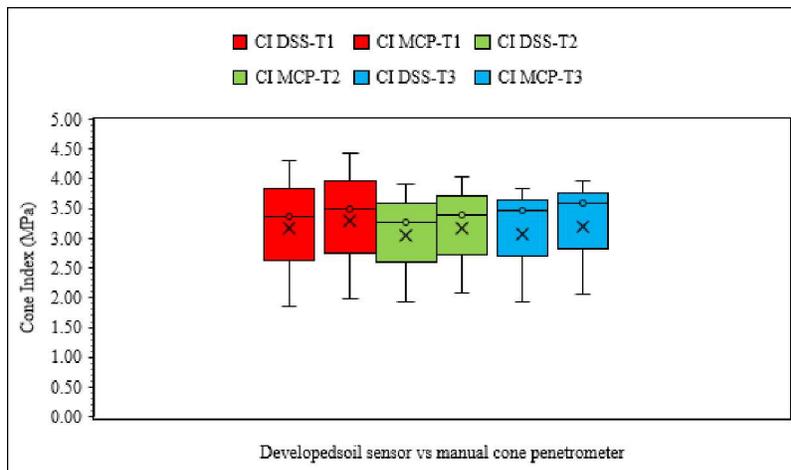


Fig. 9. Whisker's boxplot chart for soil compaction distribution by developed soil sensor (DSS) and manual control penetrometer (MCP) in T1, T2, and T3

integrated soil sensor. The mean of electrical conductivity measured using the developed integrated soil sensor system was 0.0904, 0.0862, and 0.0784 dS/m from 0-20 cm, 20-40

cm, and 40-60 cm, respectively. The electrical conductivity measured using the laboratory method was 0.1276, 0.1150, and 0.1045 dS/m from 0-20 cm, 20-40 cm, and 40-60 cm, respectively (Fig. 10). The accuracy of the sensor was 73.42 %. However, most of the literature revealed the accuracy of real-time EC sensors between 55 to 70 % (Liu et al 2017, Salam et al 2017). There was a significant difference between the soil compaction measured by the developed soil sensor (EC DSS) and the laboratory/control method (EC Lab) in sandy loam soil (Fig. 11). The R^2 value (correlation) was 0.93 and the coefficient of variation was 7.380, whereas the standard error of the estimate RMSE was 0.0074. A box and whisker plot was plotted for displaying the distribution of soil electrical conductivity pattern in all three treatments with the developed soil sensor (EC DSS) and the laboratory method (EC Lab) (Fig. 12).

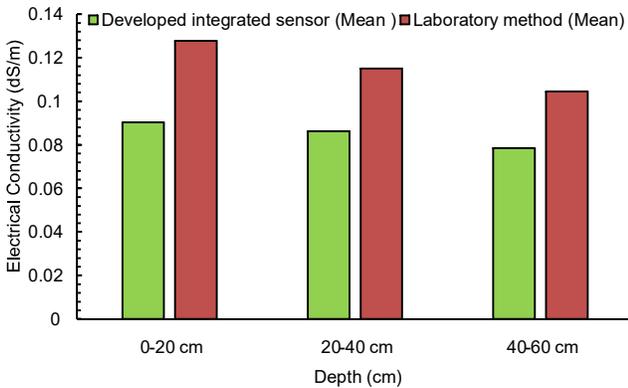


Fig. 10. Measurement of soil electrical conductivity

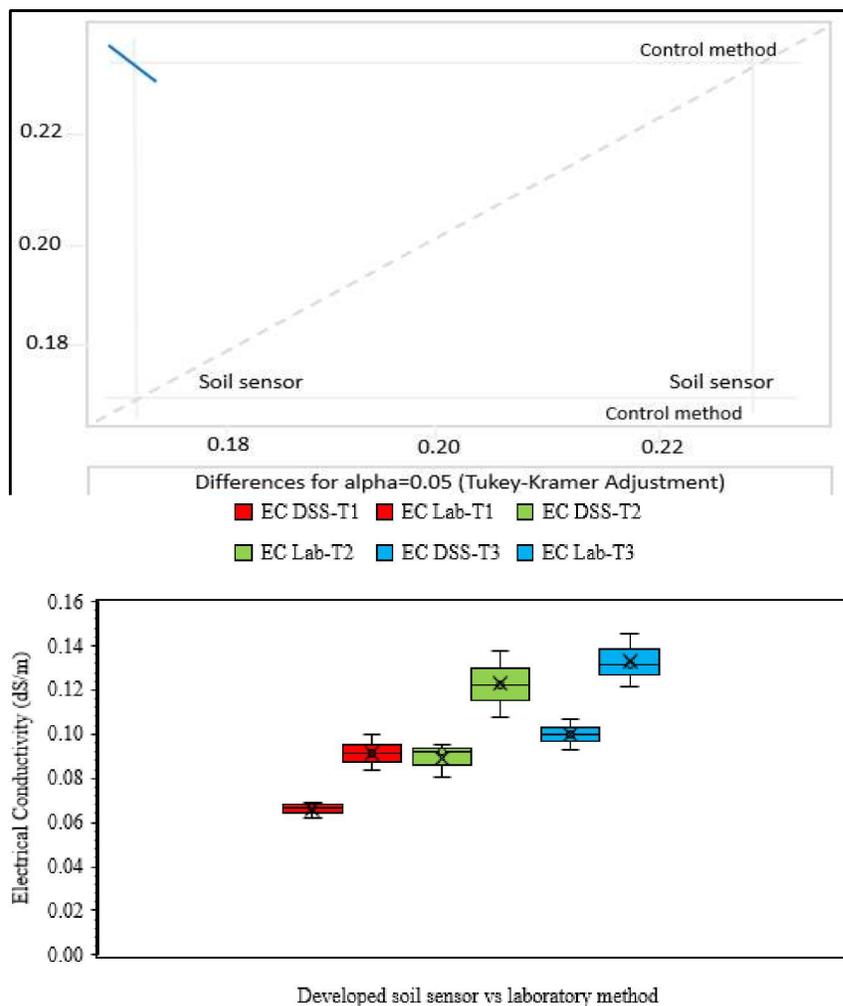


Fig. 12. Whisker's boxplot chart for soil electrical conductivity distribution by developed soil sensor (EC DSS) and laboratory method (EC Lab) in T1, T2, and T3

Table 4. Model summary of regression correlation between three different types of soil

Statistical parameters	Lab test vs measured output			
	Research farm of DFMPPE, Near Gate no.4, PAU, Ludhiana	Research farm of DFMPPE, Near PRSC, Gate no.6, PAU, Ludhiana	Soil research farm of DSS, Near Gate no. 8, PAU, Ludhiana	Corresponding output result of all textures
R ² value (correlation)	0.91	0.85	0.93	0.91
R ² value (coefficient of determination)	0.83	0.73	0.87	0.83
Adjusted R ²	0.81	0.72	0.87	0.83
Standard error of the estimate RMSE	0.0118	0.005	0.0123	0.011
Linear equation, Y	$y = -0.0662x + 0.1835$	$y = -0.0793x + 0.1851$	$y = -0.0532x + 0.1775$	$y = -0.055x + 0.1755$

CONCLUSION

The calibration of the S-type load cell, depth sensor, and electrical conductivity sensors interfaced with the microcontroller was successful, as demonstrated by the calibration results. The regression models indicated a strong correlation and a low standard error of estimate for the load cell calibration. The ultrasonic depth sensor also showed excellent calibration results, with an R² value of 0.99 when compared to manual distance measurements using a tape measure. Similarly, the electrical conductivity sensor exhibited a strong correlation (R²=0.99) with laboratory EC measurement methods.

The integrated soil sensor system demonstrated an impressive accuracy exceeding 95% in measuring soil compaction during field evaluations, closely matching the results obtained through standard laboratory methods. In contrast, the assessment of soil electrical conductivity yielded an average accuracy of 75% when compared to laboratory techniques, indicating a moderate level of reliability in this measurement. Future enhancements to the accuracy of the EC sensor could be achieved through the implementation of a non-contact sensor or by redesigning the system to incorporate four probes instead of one. Overall, the results from the integrated soil sensor system confirmed that the sensors were effectively calibrated, validating the system's suitability for real-time monitoring of electrical conductivity and soil compaction, which is essential for preserving soil health.

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