Application of Soil Testing Sensors in Agriculture: A Review

ABSTRACT

The soil whose main role is to provide nutrients in the process of plant growth is the foundation and an important part of agriculture. Soil testing is an important step for increasing agricultural production and raising farm income. Traditional soil testing methods rely on chemical processes carried out in a laboratory. Sensors play a significant role in agriculture by direct measurement of soil chemistry through tests such as pH, moisture, nutrient content, humidity and temperature. The results of soil tests are important to get high yield with good quality produce. ISE (Ion Selective Electrode) and ISEFT (ion-sensitive field effect transistor) sensors have also been used to detect the uptake of ions by plants.

Key words: pH, moisture content, nutrient content, ISE, ISEFT

1. INTRODUCTION

Agriculture depends on the soil whose major function is to supply nutrients for plant growth. Crop growth is significantly influenced by the macro and micronutrient composition of farmland. The results of the soil testing are crucial information for determining the proper application of fertilizer and soil amendments. A solid foundation for planning the appropriate application of nutrients can be formed by combining the results of soil testing with knowledge about the nutrients that are available to different crops (Hoeft *et al.,* 1996)[1]. "A typical tests will often determine the amount of available nitrogen (N), phosphorus (P), exchangeable potassium (K), calcium (Ca), and magnesium (Mg) as well as, the cation exchange capacity(CEC), pH, and the amount of lime that is needed. Additionally, certain laboratories may do tests for nitrate, salinity and organic matter (OM), sulphate, specific micronutrients and heavy metals" (Foth and Ellis, 1988)[2,35,36,37].The amount of sand, silt and clay in the soil, as well as its structure, compaction, moisture content and other physical soil attributes, have an impact on crop growth.

Soil Testing in India

For boosting the agriculture productivity and profitability, soil testing is a crucial step. Traditional soil testing techniques are based on chemical procedures carried out under laboratory conditions. These methods are generally take longer time and require more effort. On the other hand, the number of soil samples needed to be analyzed is large because of the small size of the landholdings in many parts of India. Consequently, even if soil samples are collected from different agricultural fields, timely testing of these samples is generally not possible and the test results often fail to reach farmers in a timely manner. Currently, there are around 1049 soil testing labs in the country with an annual analyzing capacity of only 10.7 million samples.The analyzing capacity of soil testing labs simply lags far behind the requirement. There is a need to repeat soil testing from time to time depending on soil types and crops. Hence, new technology has to be introduced to make soil testing-based nutrient management a reality.

Application of sensors

Direct assessment of chemical parameters such as pH, moisture, nutrient content, Humidity and temperature using sensors is significant use in agriculture. Soil testing results are crucial to obtaining a high yield with good quality. ISE (Ion Selective Electrode) and ISFET (ion-sensitive field effect transistor) sensors are used to detect the uptake of ions by plants. The rate of nutrient uptake of a crop is determined by soil nutrient content and crop growth rate. Ion-selective sensors have been developed to detect a variety of ions. ISE sensors have been using to monitor nitrogen ions in the crops and soil and crops. Hi-techequipments are in high demand to help grow high-performance crops. Scientists are using sensors to know how crops respond to different soils and weather conditions.

2. ELECTROCHEMICAL SENSORS FOR SOIL NUTRIENT DETECTION

Two types of detectors that are commonly used to know the potentiometric electrochemical sensors for soil nutrient detection are the Ion Selective Electrode (ISE) and the IonSelectiveFieldEffectTransistor(ISFET).

2.1 Ion Selective Electrode (ISE)

The Nernst equation can be used to assess the ISE method since a change in an ISE's potential relative to a reference electrode is linearly proportional to a change in the ionic activity (in logarithmic units) of the target ion.

ISEs were used to detect soil nitrate, ammonium and potassium. Until date, no detectors were employed to analyse phosphorus, however multiple studies shown that PVC-based membrane ISEs could be utilized to quantify phosphate level in biological materials.

ISEs were used to detect soil nutrients in two directions:

(1) Currently, soil sampling is done manuallyinfields to detect nitrogen variability in soil nutrients by using visible/ ultraviolent spectroscopy. Therefore, soil nutrient 1350 Injection Analysis systems (FIA)

(2) vehicle-based soil sensing systems. A vehicle based soil sensing system uses sensors like radar, laser or ultrasonic sensors to exchange information between a server and vehicles about the surrounding area.

Limitation:

ISEs may notbe suitable for real-time sensing applications due to their longer processing time.

2.2 Ion Selective Field Effect Transistor (ISFET)

ISFET is the combination of an ISE and a field effect transistor (FET). The ion selective membrane is placed on top of the insulator layer of the FET structure, allowing for chemical modulation of the threshold voltage. This results infast response, low output impedance high signal-to-noise ratio and multi-ISFET integration on a single chip.

ISFETs have been used to detect soil ammonia, nitrate and potassium. An automated technique for mapping soil pH was successfully tested in the field.

Limitation

However, due to their expensive cost and poor reproducibility, ISFETs are not widely used in practical systems.

Both ISFETs and ISEs respond selectively to a specific ion in solution using a logarithmic relationship between ionic activity and electric potential. ISFETs and ISEs require recognition elements, such as ion selective membranes, which, when paired with a reference electrode, turn the chemical response (ion concentration) into a signal (electric potential). Numerous ion-selective membranes have been produced in many areas of applied analytical chemistry as a result of rising demand for new ion measurement and enormous breakthroughs in the electronic technology necessary to produce multiple channel ISFETs.

2.3 Soil NPK estimation by optical measurements

The optical soil measurement methods describes six different types. Soil nutrients are measured by using inductively coupled plasma spectroscopy, Visible–infrared (*Vis* – IR) spectroscopy, fluorescence spectroscopy and colorimetric methods.

2.3.1 Vis–IR spectroscopy

Vis-IR spectroscopy is a fast, accurate, repeatable, physical nondestructive method that costs nothing and is used to characterize materials by measuring how much energy they absorb between 700 and 1 nm in wavelength. The unique spectral lengths of each soil nutrient make it easier to detect them in the soil. It's a non-liquid nutrient testing technique that's at the forefront of soil analysis. Because the approach involves minimal to no sample preparation, it is very practical and portable. IR spectra require the creation of a calibration curve utilizing multivariate approaches in order to extract quantitative information from them. Plotting the spectrum's intensity against the known concentration yields the calibration curve, which is used to estimate a solution's unknown concentration.Thus, spectroscopic approaches for soil analysis are more straightforward and advantageous than other methods. The method's sole constraint is the creation of a comparable database and soil mapping. Since 1960, IR spectroscopy has been extensively explored in soil to ascertain the amount of carbon and nitrogen present. Soil phosphorus and potassium levels are determined by Vis-IR spectroscopy.

2.3.2 Reflectance spectroscopy

There are three categories for reflectance spectra: diffuse reflectance, internal reflectance, and specular reflectance. Diffuse reflectance is the foundation for almost all nutrient detection. Guidelines for assessing soil nitrogen using diffuse reflectance techniques were developed by Du *et al.* (2019) [3] using near-infrared reflection spectroscopy. They produced a nitrogen detector that is portable. For data collection and spectrum analysis, they used a compact Fourier transform infrared (FTIR) coupled spectroscope with software. The wavelengths of soil nitrogen for nitrogen-containing groups were found to be 1500–1850 nm and 2000–2400 nm, respectively.Hu *et al*. (2016) [4] examined the impact of using a restricted wavelength range of 1100-2450 nm to sense potassium and phosphorus in soil and found that having a smaller detecting range is beneficial for sensor development. A Vis-NIR diffuse reflectance spectroscopy-based sensor for determining NPK in soil extracts was designed by Mukherjee and Laskar (2019) [5].

2.3.3 Raman spectroscopy

Raman spectroscopy is a quick way to test soil nutrients. It illuminates the material with a powerful visible or ultraviolet light beam and collects scattered Raman spectra.The Raman spectrum signature, which is based on the vibrations and rotations of radiation excited molecules, can reveal structural information that can be utilized to identify a sample. The sensor is meant to detect and quantify soil nutrients such as nitrogen, phosphorus, and potassium.

2.3.4 Colorimetric

According to McCoy and Donohue (1979)[6], soil testing kits detect soil nutrients quickly, approximatileyand on the spot. These kits make use of colorimetric techniques to assess soil nutrients. The colour change of the solution is compared to calibrated reference colour charts using colorimetric methods. A concentration range is represented by the hue of the colour chart. By relating the colour of the solution to the concentration of nutrients in it, the colorimetric method determines the nutritional fertility (NPK) of soil.

2.3.5 Optical imaging

Chen *et al*. (2019)[7] investigateda novel approach for assessing nutritional status in plants. According to them analyzing photographs of plant leaves could aid in predicting potassium deficit in plants. The data was analyzed using support-vector machines (SVM) and a calibration model from Matrix laboratory (MATLAB) software to determine the potassium level in the leaf image. Li, Jia, and Le (2019)[8] measured the total nitrogen content of soil at wavelengths between 900 and 1700 nm using a hyperspectral imaging system.

3.Soil moisture Sensors

There is a water shortage in the world right now, which is limiting agricultural growth and eventually, food production. Given that water is limited in the majority of India, conservation of water is essential, and optimal use of water in agriculture is necessary (Munoth*et al.,* 2016)[9]. A crop's ideal water requirements are largely dependent on the moisture content of the soil (Schroder, 2006)[10]. The two most prevalent ways for measuring soil moisture are indirect methods utilizing meters and sensors (such as TDRs, FDRs, soil moisture blocks, etc.) and direct methods such as feel and appearance method, gravimetric method, and hand-push probe(Evans *et al.,*1996)[11]. For assessing crop growth and detecting soil moisture, soil moisture sensors are incredibly helpful tools (Scherer *et al.,* 2013)[12]. Soil moisture sensors are a useful tool for a variety of applications, including domestic gardens, landscapes, rainfall monitoring, environmental testing, hydrology, and precision agriculture (Skierucha*et al.,* 2010)[13]. They also detect the quantity of water content in the root zone. The market is filled with many kinds of soil moisture sensors.

TYPES OF SENSORS

3.1 Tensiometer

The porous ceramic cup is inserted into the soil, allowingsoilwater pressure to be transmitted to the tensiometer which is read by pressure sensing devices mounted on it.This instrument monitors soil water tension rather than soil moisture content directly. Tensiometers usually reply within two to three hours (Zazueta *et al.,* 1994)[14]. Tensiometers are available and can be used to automate an irrigation system with the help of pressure gauges.

Table 1. Differences in soil water tension between various soil types

Soil type	Soil moisture tension (centibars)
Sandy or loamy soils	40-50
Sandy loam	50-70
Loam	60-90

Clay loam	90-120

(Source: Hanson *et al*., 2002)[15]

Advantages

a)Tensiometers are quick, simple, cheap, and easy to use (Enciso-Medina *et al.,* 2007)[16].

b) "Various liquids, such as ethylene glycol solution, can be utilized to collect data under freezing and thawing circumstances" (Schmugge*et al.,* 1979)[17].

c) In sandy loam or light-textured soils, use a tensiometer.

Disadvantages

a) "Periodic maintenance is essential because air bubbles form during normal use" (Hensley *et al.,* 1999)[18].

b) It is prone to damage from freezing temperatures.

c) "Multiple tensiometers are required for measurement since they only detect soil water potential near the tensiometer" (Goodwin, 2009)[19].

d) "The usable range is limited to 0-85 centibars of tension, after which the gauge will malfunction" (Werner, 2002) [20].

Applicability

The tensiometers can be used in any horticulture crop that requires watering. (Goodwin, 2009)[19].

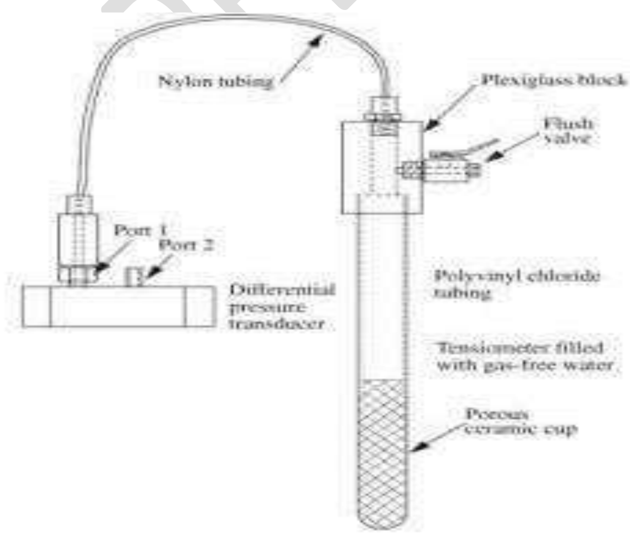

Fig 1. Soil water tensiometer

(Source: Freeman *et al.,* 2004)[21]

3.2 Granular Matrix Sensor (GMS)

As shown in Figure 2, the granular matrix sensor consists of an interior matrix structure with two electrodes and a porous ceramic external shell. Above the gypsum wafer, in the granular fill layer, are embedded the electrodes of the GMS. The difference in electrical resistance between two electrodes in the sensor continuously indicates changes in the water conditions in the granular matrix, which are correlated with variations in the corresponding water conditions in the soil. The relationship between soil water and this resistance between the electrodes is inverse.

Advantages

a) GMS is less expensive and requires less maintenance than tensiometers.

b) Irrigation in fields can be automated.

c) Sensor performance varies insignificantly with soil temperature.

Disadvantages

a) It shows different responses based on the soil types.

b) Poor contact between the soil and the sensor might cause high m values, which is especially common in heavy soils.

c) It is less sensitive to small rains.

d) Because of the greater particle size in sandy soils, it has limited accuracy.

Applicability

"The GMS is used to assess soil moisture in crops such as potato,onion, cotton, urbanized landscapes, and corndrip irrigated vegetable crop" (Thompson *et al*., 2005)[22]. Because the soil particle size is comparable to that of the transmission materialwhich has the consistency of fine sand trapped in a porous membranethe GMS performs well in medium-to-fine soils.

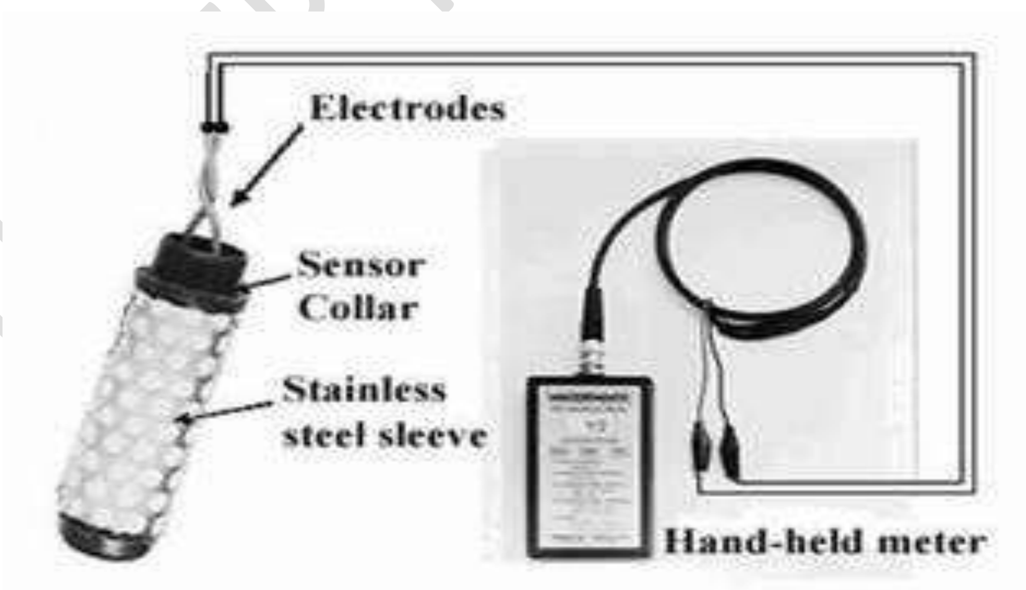

Fig 2. Granular matrix sensor (GMS)(Model 200SS) (Source: Irmak *et al.,* 2006)[23]

3.3 Time Domain Reflectrometry (TDR)

A radio frequency energy pulse is injected into a transmission line in time domain reflectrometry and the velocity of the pulse is determined by detecting the reflected pulse at the end of the line. The dielectric constant affects this velocity. The time it takes for the reflected pulse to return is used to calculate the amount of moisture (Cepuder*et al.,* 2008)[24]. TDRs react in roughly 28 seconds.

Advantages

a) TDR respond fastly to changing soil moistures levels.

b) It accurately measures moisture (± 2%) in all soil types.

c) A single probe can be used to measure soil moisture at multiple depths.

d) There is little or no disruption to the test site during the testing.

Disadvantages

a) Calibration is crucial for accurately measuring pulse recovery time.

b) This unit is more costs than other measuring methods

c) TDR applications are limited due to expensive costs.

d) TDR detect the soil moisture only in the area of the sensor

Applicability

TDR is mostly used in areas having mineral crops and crops grown on organic soils. The crops planted on sandy soils that can benefit from TDR include sweet corn, green bell peppers, and others, according to Dukes *et al.* (2010)[25].

Fig 3. Time Domain Reflectrometry

(Source: labmodules.soilweb.ca)

3.4 Frequency Domain Reflectrometry (FDR)

FDR sensor is made up of two metal rings that operate as capacitors, with the soil sample serving as the dielectric. Soil volumetric content can be measured directly using the electrical sensor capacitance. It works on a similar concept as a TDR sensor.

Advantages

a) Proper calibration ensures high accuracy (±1%).

b) Unlike TDR, it is tolerant to high soil salinity.

c) With FDR, measurements to be taken simultaneously at various depths.

d) It is more expensive than TDR.

Disadvantages

a) Soil specific calibration is necessary

b) To avoid air gaps in FDR, make sure there is appropriate contact between soil and sensor.

c) It can only detect moisture within the sensor's range.

Fig 4. Frequency Domain Reflectrometry

(Source: www.experimental-hydrology.net)

3.5 VH400 Soil Moisture Sensor

"VH400, a resistive-based soil moisture sensor, monitors the dielectric constant of soil" (Salih *et al.,* 2013)[26]. "It facilitates the accurate and cost-effective soil water content monitoring. It has a fast response time, can collect readings in less than a second and is extremely sensitive at increasing volumetric water content" (Ravi *et al.,* 2011)[27]. "Inserting the soil moisture probe into the earth is best done horizontally at the root level. This sensor is tiny in size, sturdy, waterproof, and requires little power.

It is also insensitive to water salinity, does not corrode with time, and responds to even tiny changes in water content. This sort of sensor is sensitive to temperature changes in moist environments, therefore temperature measurements are constantly required" (Bitella*et al.,* 2014)[28]. In order to create a wireless sensor network, which is frequently employed in smart irrigation and precision agriculture, the probe is normally connected to a soil moisture reading device (Khriji*et al.,* 2014)[29]. A soil moisture data recorder is one such gadget that displays moisture content readings on a computer screen. The system can communicate with the remote user in two ways: first, by sending the readings over the GSM network via Short Messaging Service (SMS); second, by storing the readings on a memory card and transferring them to a computer for analysis. The sensor's specifications

Fig 5. A VH400 sensor; its Data logger

List 1: The sensor's specifications are as follows:

Power consumption	< 7 Ma
Supply voltage	3.5 - 20 V (DC)
Temperature	-40◦C to 85 ◦ C
Accuracy at 25◦ C	± 2%
Out put	0 - 3 V related to moisture content

Applications

Agronomy, Hydrology, Soil physics,Sprinkler systems,Phenotyping,Plant physiology,Environmental monitoring,Irrigation, Root ecologyand Rain monitoring.

3.5 Neutron Scattering

"The theory at the core of the neutron scattering technique is based on the tendency for hydrogen nuclei to slow (thermalize) high-energy (2–4 MeV) neutrons to approach the characteristic speed of particles at ambient temperature with corresponding energies of about 0.03 eV. A typical NP consists of a radioactive neutron source (americium-241 and beryllium) and a detector to determine the flux of thermalized neutrons that form a cloud of nearly constant density near the probe. Neutrons lose different amounts of energy when colliding with various atomic nuclei. The greatest energy loss is due to collisions with particles of similar mass, such as hydrogen. The quantity of hydrogen in the soil is largely dependent on the amount of water and to a lesser extent on the amount of organic matter and clay minerals" (Babaeian et al., 2018)[32]

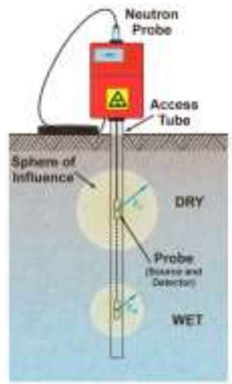

Fig : 6 Schematic of a portable neutron probe. (Babaeian et al., 2018)[32]

3.6 Cosmic rays neutron sensor

This is an innovative method for measuring soil moisture. It has a horizontal scale of 10-100 m and can work at depths of 10-100 m. It is a non-invasive and non-contact method that allows broad coverage to an extent of 20 hectares. The sensor produces fast neutrons in the ground. These neutrons are slowed through elastic collisions with nuclei, i.e., hydrogen, which leads to the loss of energy and eventually becoming thermalized. The decrease in energy depends on hydrogen content in the soil, and it reflects the amount of moisture content in a given area. .(Rundan et al. 2023)[35]

4. SOIL TEMPERATURE SENSORS

"In the case of soil temperature sensor, there is no much work. For example a bent-stem soil thermometer is used to measure soil temperature between the ground surface and a depth of 20 cm underground, and has a bend between the bulb and the scale"(WMO 2010). "But this thermometer has many problems. Problems of this thermometer is: it is exposed to external factors like sunlight, cold etc., it requires removal of it from the installed place during harsh season. The following figure shows the various types of temperature sensors"(Kedzierski 1993)[30].

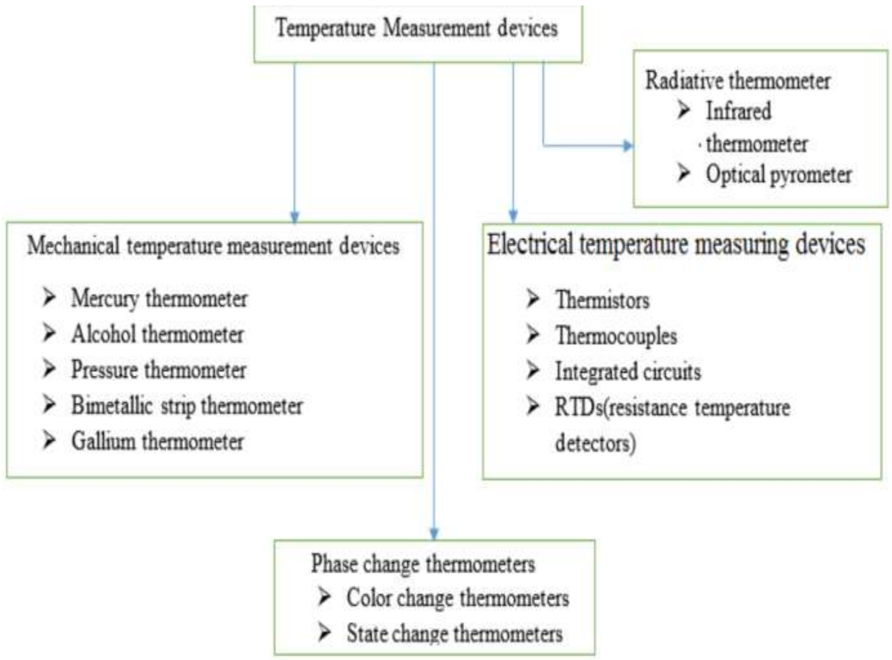

Fig 7. Classification of temperature sensors

All temperature sensors have nonlinear transfer functions, Except for IC sensors, indicating that the temperature dependence of the physical parameter under examination (e.g. voltage output, resistance etc.) is not linear (Feteira 2009) [31].

4.1 LM35: The LM35 is a type of sensor that is used to measure temperature with an electrical output that is directly proportional to the temperature. This type of sensor is mostly used in greenhouses to maintain an optimal temperature for healthy plant growth.(Rundan et al. 2023)[35]

Advantages:

There is no need to calibrate it and it maintains accuracy of ± 0.4°C under room temperature and ± 0.8 ºC over a range of 0 ºC to +100 ºC. The temperature varies linearly with variations in the output voltage. When the desired value is reached, the temperature is modified with the help of foggers or misters, and sometimes heaters are also used to increase the temperature in temperate countries

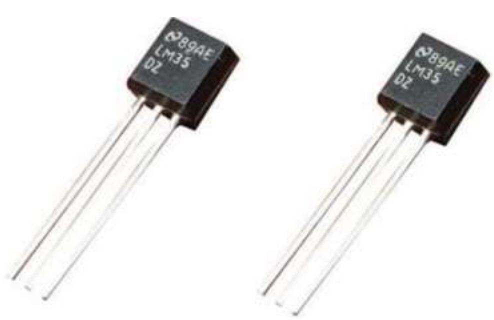

Fig 8. **Temperature Sensor LM35**

5.Conclusion

Soil nutrient detection depends on variations in soil and environmental factors resulting in poor detection accuracy.Using pretreatment methods and various calibration methods will help to resolve this issue.The primary issue with spectroscopic approaches is that most spectrometers are big and expensive, and they require site-specific calibration. Colorimetric methods used for developing a portable, cost effective optical sensor for detecting macronutrients in soil. In general, the colorimetric technique doesn'trequire expensive equipment and ideal measuring conditions or good database or advanced analytic methods. Additional research on colorimeter-based soil nutrient detection can be conducted in order to develop a portable sensor that is reasonably priced. Research findings suggest that the solution-based soil extractant can be replaced with ion-selective membranes, making the colorimeter-based sensor more compact and convenient.Using of Imaging techniques are the most recent trend in the field of nutrient testing.Despite extensive study in the optical sensing field, there is still no cost-effective portable soil NPK sensor available in the Indian market.Soil moisture sensors help growers schedule irrigation by indicating when to irrigate their crops.Because there are so many soil moisture sensors on the market, selecting one for a particular application or soil type can be a time-consuming process. The benefits and drawbacks of sensors must be considered as selection criteria because each type of sensor's operating principle changes depending on its application and soil type.

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