ADVANCED TECHNIQUES FOR SOIL HEALTH AND NUTRIENT MANAGEMENT

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Soil health encompasses structure, fertility, and biodiversity. Structurally, a good soil supports the infiltration of water, the development of roots, and the exchange of gases. Soil fertility is related to the availability of sufficient amounts of essential nutrients in soils for the growth and development of plants. Soil health often get deteriorated due to alteration in the soil ecosystem cause by climatic factors, erosion, poor land use practices, excessive tilling, excessive application of chemical fertilizers, and improper crop rotation.

The four basic components of soil are mineral matter, organic matter, soil water, and soil air. Mineral matter that constitutes a greater part of the soil comprises very fine particles from the weathering of rocks and minerals. It provides various nutrients to plants and helps building of soil. Organic matter contains organic carbon plays a key role in promoting soil health through improving the soil structure, water-holding capacity, soil biodiversity and nutrient availability. Texture and structure affect the amount of soil water, a vital requirement for plants. Soil air is required for root respiration and it is one of the most critical factors which supports soil structure.

Technological advancement made the measurement of soil physical and chemical properties faster than ever since they allow real-time field testing of soil properties.

ARTIFICIAL INTELLIGENCE APPLICATIONS TO MEASURE SOIL HEALTH

Artificial Intelligence (AI) applications enable monitoring of soil health in real-time with the help of sensors (Figure 1 & 2). Sensors assist crop managers to assess soil properties without physical soil sampling. Some of the sensors used to measure soil parameters are as follows

1. **Nutrient Sensors**: Measures the levels of nutrient elements in the soil and helps to calculate dose of fertilizers required for crop growth.
2. **Moisture Sensors:** Monitor the soil moisture and helps in the proper scheduling of irrigation.
3. **pH Sensors:** Helps in measuring the acidity or alkalinity of soils. Soils with a pH between 5.5 and 7.5 promote better plant growth.
4. **Organic Matter Sensors:** Helps in assessing the content of organic matter in soils.
5. **Temperature Sensor:** Monitor soil temperature and help farmers to understand how fluctuations in soil temperatures affect plant growth.
6. **Tensiometers:** Used for measuring the soil water suction (negative pressure) that is equivalent to the force or energy plant need to exert to extract water from the soil.

7. **Airflow sensors:** It quantifies the permeability of air through the soil. It is the pressure which must be exerted to compress a given volume of air into the soil at some same depth.

8. **Neutron Probe:** This measures the exact quantity of soil water by sensing the time delay of fast neutrons on hitting the water molecules of the soil.

9. **Electrochemical Sensors:** These sensors help measurement off soil nutrient levels and pH using ion selective electrodes.

10. **Electromagnetic Sensors:** Used for measuring texture, CEC, salinity, organic matter, and subsoil characteristics. It measures the charge in the conductivity of soil particles using electric circuits

11. **Electrical Resistance Sensors:** Helps in the measurement of soil tension through electrical conductivity.

12. **Time Domain Reflectometer (TDR) Sensors:** Measures the volumetric water content voltage pulse reflection.

The soil sensors could fine-tune the use of fertilizers and water to prevent the waste of water on agriculture and avoid polluting water sources, in addition to restoring effective soil moisture.

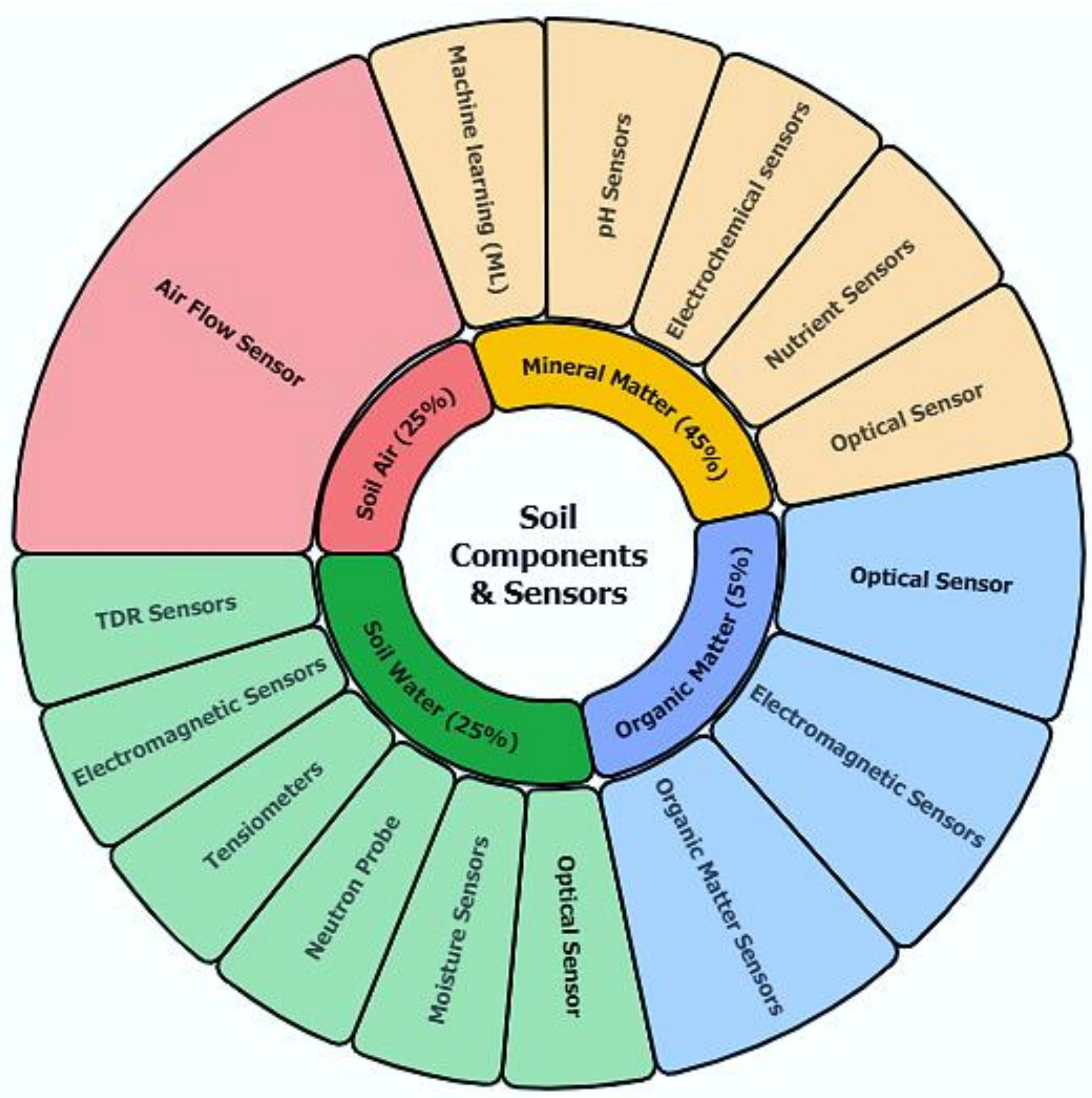

Figure 1. An outline of different sensors used in the measurement of the four soil components (Source: Authors' compilation)

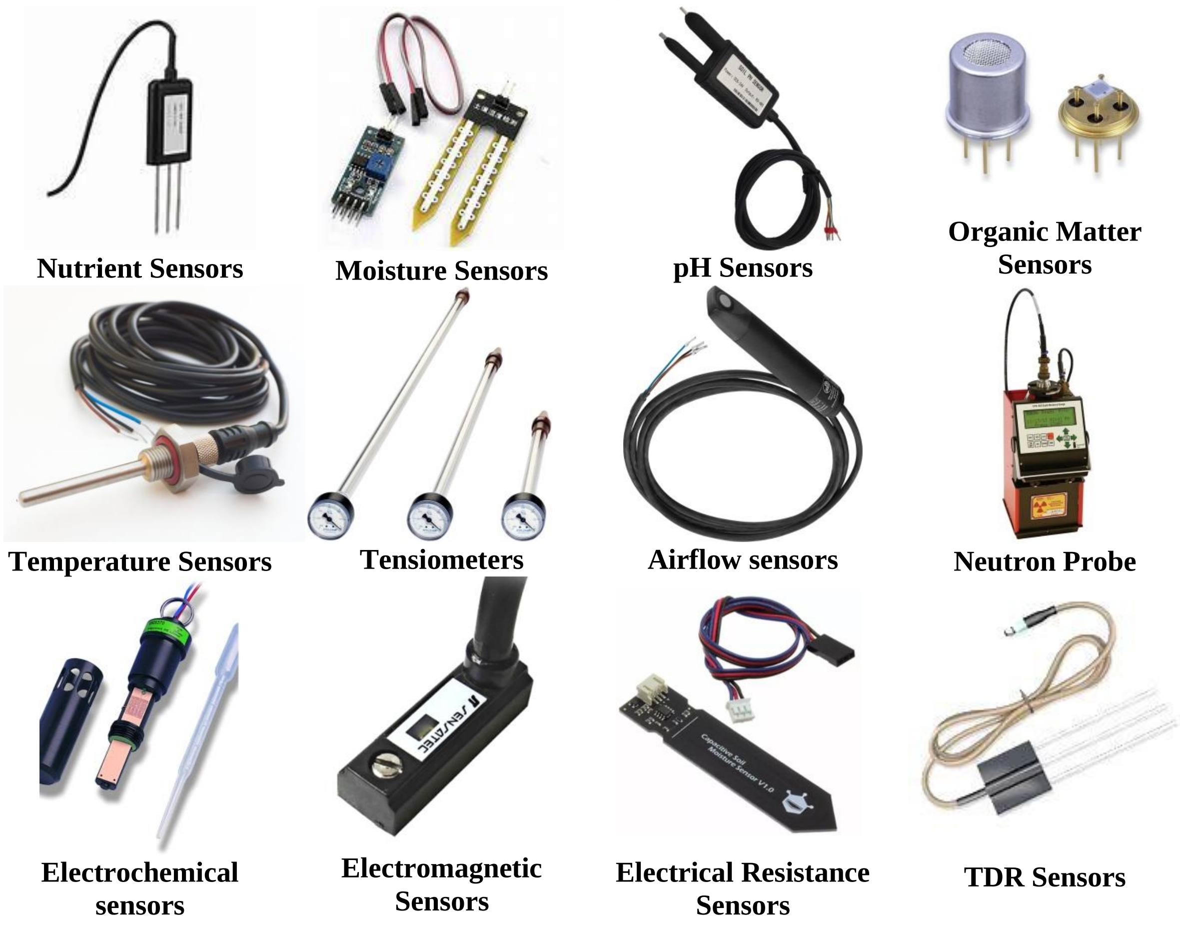

Figure 2. Soil sensors (Source: Authors' compilation)

AI/IoT-ENABLED NUTRIENT MANAGEMENT

Nutrient status in the soil accounts for the variation in crop yield to a large extent hence, management of their levels in soil is essential to improve the quality of crops. This makes the soil nutrient level prediction an important aspect of sustainable crop production and food security. Machine learning (ML) is used to develop decision-support tools for modern farming systems. IoT-enabled soil nutrient real-time monitoring devices, using sensor data and ML algorithms have techniques for running field data or RGB/hyperspectral photos in NPK management systems. Figure 3 describes the key septs included in the AI-enabled soil nutrient management process.

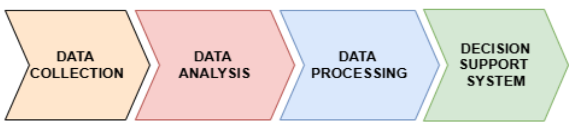

Figure 3. Steps for IoT/AI-ML model for Nutrient Management

Data Collection: *Soil sensors* can be used to detect several different properties, including pH, soil moisture, temperature, and levels of various nutrients like nitrogen, phosphorus and potassium. *Remote sensing* techniques utilize satellite images, drones, and aerial photography to electronically monitor vast land tracts, enabling the monitoring of soil conditions and cropping health over such areas. *IoT Devices*: IoT enabled devices for data collection in real-time.

Data Analysis and Processing: *Model development:* ML models from the harvested data should predict nutrient deficiencies and determine the best fertilizer types, and quantity. *BIG DATA Analytics:* Big data analytics will be applied to massive datasets from various sources – like weather data, historical crop performance, and soil data.

Decision Support Systems: *Prescription mapping:* generate the specific application maps which will illustrate the locations and the relative quantities of fertilizer to be used in specific parts of the farm field. *Notifications:* in the form of mobile or web-based automated recommendations.

Precision Agriculture Techniques: *Variable Rate Technology (VRT):* VRT is data-driven insight used to change the rate of application of fertilizer across the field, depending on specific nutrient needs, soil properties, and crop requirements, by prescription map. *Site-Specific Nutrient Management (SSNM):* SSNM is an advanced approach that optimizes nutrient application to crops based on specific field conditions, ensuring that plants receive the right amount of nutrients at the right time.

FUTURE DIRECTIONS/ RECOMMENDATIONS

The future of soil health and nutrient management will likely depend on advanced AI-IoT technologies. Among the available precision agriculture tools, VRT, remote sensing, AI and, IoT can greatly optimise the use of inputs like seeds and agricultural chemicals, reduce waste generation as well as the potential impacts of agriculture on environment. Further, cultivators should give more emphasis to eco-friendly agricultural practices such as use of organic nutrient inputs, growing cover crops, crop rotation, and management practices those enhance soil organic matter and biodiversity. For this, the governments need to invest in training farmers and giving them the appropriate infrastructure for ease of adoption. Long-term soil health and agricultural productivity demand collaborative efforts.

CONCLUSION

Adoption of sustainable agriculture practices such as soil test based balanced fertilizer application and conservation agriculture practices are essential for long-term food security and conservation of scares natural resources like soil and water used in crop production. The AI-IoT fusion is most powerful technology; to be imbibed in soil technology will revolutionize agriculture with precise insights that will inform farmers toward better decisions for enhance soil health, reduce the environmental impact of agriculture, and ensure the food and nutrient security for the rapidly growing population. With the never-ending development of technology, AI-IoT here holds endless possibilities, and numerous other innovations in the area of food production are waiting to be discovered.

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