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IoT-Based Smart Farming Cultivation of sugarcane in Pune, Maharashtra

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Abstract—

The agricultural sector is one of the contributors towards economic stability and rural livelihoods of Maharashtra. Among the cash crops that are grown throughout the state, the cultivation of sugarcane (Saccharum officinarum) has proved crucial, especially in Pune district. Nevertheless, there are many obstacles in growing sugarcane due to the availability of unreliable water supply, soil degradation, nutrient deficiency, unpredicted climatic conditions at the micro-level, and expensive labor force. Traditional cultivation methods depend on field observation and they fail to provide real-time information for effective resource management and crop care. The present paper presents a concept of Internet of Things (IoT)-based smart farming solution for sugarcane planting in Pune District, Maharashtra. The paper suggests the use of IoT technology to measure physical parameters of soil and other environmental variables through the deployment of sensor systems, namely soil volumetric water content, soil temperature, relative humidity, soil pH level, and the presence of a water source. These data are sent wirelessly from the deployed microcontrollers to the digital dashboard for visual display purposes. Furthermore, the implementation difficulties are discussed with regards to sensors calibration, cost of IoT devices, reliability of rural power supply and cellular networks, and farmer technology adoption barriers.

Keywords—IoT, Precision Agriculture, Sugarcane, Smart Irrigation, Soil Moisture Monitoring, Sensor Calibration, Pune, Maharashtra

I. INTRODUCTION

The cultivation of agricultural produce holds an integral position in the development of Maharashtra, both economically and agriculturally, providing employment to a significant proportion of the state's rural population. Sugarcane is one of the primary cash crops of the state, which not only helps the farmers but also aids the sugar industry. Pune District falls under one of the major sugarcane-producing districts in Maharashtra; according to a district-wise statistics database, the sugarcane grown in Pune District during 2024-25 will amount to around 125.7 thousand hectares and yield around 12.9 million tonnes [2].

Sugarcane production in the district is influenced by water availability, soil quality, nutrient deficiencies, weather variability and shortage of labour. Farm management has traditionally depended on the experience of farmers, periodic visits to the field, manual observation and conventional irrigation practices. These practices remain valuable, but they do not give continuous information about changing field conditions. Soil moisture, soil temperature, atmospheric humidity, soil pH and the availability of water can change between two field visits, which makes it difficult to judge when irrigation or other measures are needed.

The Internet of Things (IoT) offers one way to reduce this information gap. In an IoT system, sensors placed in the field collect data and a controller sends it through a communication network to a digital platform, where it can be stored, visualized and analysed to support agricultural decisions. Published work indicates that IoT-based monitoring and smart irrigation systems can assist the management of water, soil and crops [1].

This paper proposes a conceptual framework for an IoT-based smart farming architecture for sugarcane cultivation in Pune District, Maharashtra. The system is described as a monitoring and decision-support architecture. It has not been built or tested, and automatic pump control is treated only as an optional extension. The remainder of the paper reviews the literature, sets out the methodology, describes the proposed architecture and its implementation requirements, examines feasibility and evaluation, discusses the framework, and outlines the validation needed in future work.

A. Background and Context of the Study

Sugarcane is a long-duration crop whose growth is commonly described in terms of early growth, grand growth and maturity, with tillering and stem elongation reported as critical phases for water [3]. Crop water demand therefore changes with crop stage, and a single fixed irrigation schedule cannot represent it. The variables most relevant to monitoring are soil moisture (the volumetric water content of the root zone), soil temperature, ambient relative humidity, soil pH and the availability of water at the source. Soil moisture and ambient relative humidity are different quantities and need different sensors.

Soils, rainfall, water sources and microclimates differ across Pune District. The framework therefore does not assume that one sensor arrangement or irrigation threshold suits every locality. Any deployment would need site-specific calibration and locally determined thresholds.

B. Statement of the Problem

Problem 1: Lack of continuous field monitoring. Periodic visits cannot capture changes in soil and environmental

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conditions between visits, so decisions may rest on outdated information.

Problem 2: Inefficient irrigation and water management. Fixed schedules or decisions based on limited observation may lead to unnecessary irrigation or insufficient water supply, affecting the efficient use of water.

Problem 3: Inadequate timely information. Without current soil and environmental data, farmers cannot easily link crop stage, soil condition and water availability when planning field operations.

Problem 4: Sensor accuracy and reliability. Low-cost sensors need calibration and may drift or vary between units, so readings can mislead if used without checks [5], [6].

Problem 5: Affordability, maintenance, electricity and connectivity. Hardware cost, repair, unreliable power and weak network coverage can limit the use of IoT systems in rural fields.

Problem 6: Adoption barriers. Perceived cost, complexity and limited familiarity with digital tools can reduce the willingness of farmers to adopt such systems [7].

C. *Research Gap*

The reviewed literature shows that sensor-based monitoring with low-cost controllers and cloud dashboards is technically feasible [1], [4], and that low-cost soil moisture sensors can reach useful accuracy after soil-specific calibration [5], [6]. Studies on adoption in India point to cost, complexity and digital familiarity as barriers [7]. Within the sources reviewed for this paper, however, we did not find a study that brings these elements together for sugarcane in Pune District, namely crop-stage-aware monitoring, local calibration, rural connectivity, cost and maintenance, and farmer use. This statement is limited to the sources examined and is not a claim that no such study exists. The contribution of this paper is a conceptual framework that addresses these elements together and identifies what future field validation must show.

D. *Aim of the Study*

The aim of the study is to propose and critically examine a conceptual IoT-based smart farming architecture for monitoring soil and environmental conditions and supporting irrigation decisions in sugarcane cultivation in Pune District, Maharashtra.

E. *Objectives of the Study*

O1: To review existing IoT-based agricultural monitoring approaches.

O2: To identify the parameters relevant to monitoring sugarcane cultivation.

O3: To design a conceptual sensor-to-cloud architecture. O4: To develop a framework for monitoring and irrigation decision support.

O5: To assess the technical and operational feasibility of the framework.

O6: To examine affordability, reliability, connectivity and adoption constraints. O7: To identify the requirements for future field validation.

F. *Research Questions*

RQ1: What IoT-based monitoring approaches have been reported, and what do they establish for sugarcane? (O1) RQ2: Which parameters and sensors suit a sugarcane monitoring system, and what are their limits? (O2, O3) RQ3: How could sensor readings, crop stage and water availability support irrigation recommendations? (O4) RQ4: Is the proposed architecture technically and operationally feasible in Pune District? (O5) RQ5: Which cost, reliability, connectivity and adoption barriers could limit deployment? (O6) RQ6: What must field validation measure? (O7)

G. *Hypotheses of the Study*

Because this study is conceptual and uses secondary sources, no hypothesis has been statistically tested. The following are propositions for future testing. P1: Continuous soil moisture monitoring, interpreted with crop stage, provides irrigation information that periodic inspection does not. P2: Soil-specific calibration is needed before sensor readings are used for irrigation decisions. P3: Cost, connectivity and farmer familiarity will affect adoption more than sensor capability alone.

H. *Significance of the Study*

The framework may help farmers by indicating what field information could be monitored, and may help researchers and system designers by setting out sensor, calibration and connectivity issues for sugarcane in the district. Policymakers may find the feasibility and adoption discussion useful. These are expected benefits only. No water saving, yield gain or cost reduction has been measured in this study.

I. *Scope and Limitations*

The geographical focus is Pune District, Maharashtra. The paper uses secondary sources and a proposed architecture. It has no prototype and no primary field measurements. The main limitation is therefore the absence of field validation. Evidence from other regions and crops is used only to illustrate technical possibilities and is flagged where its setting differs from Pune.

II. LITERATURE REVIEW

A. *IoT in Precision Agriculture*

A survey by Waghole et al. [1] reviews IoT, artificial intelligence and machine learning (AI/ML) in agriculture. It reports that soil moisture, temperature and humidity sensors are widely used, and it discusses wireless sensor networks, edge computing, cloud platforms and data analytics. As a survey, it shows the range of architectures in use but does not report field results for a particular crop. Its architecture of sensors, a controller, wireless transmission and a mobile dashboard is the basis for the layered design proposed here.

B. *IoT-Based Soil and Environmental Monitoring*

The monitoring architecture described in [1] combines a soil moisture sensor, a DHT11 sensor for air temperature and humidity and an ultrasonic sensor for water level with an ESP8266 NodeMCU controller, which sends readings over Wi-Fi to the Blynk application. Another study by Pinto et al. is reported to use an ESP32 controller with soil moisture and DHT11 sensors [reference details to be supplied by the authors]. The DHT11 measures air temperature and humidity, not soil conditions, so soil temperature needs a separate probe suited to soil. The architecture in [1] does not centre on soil pH, which this proposal also requires.

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C. Smart Irrigation and Water Management

The survey [1] describes a system in which a relay and motor start irrigation in response to sensor readings, and its summary of earlier studies includes threshold-based irrigation and wireless sensor networks for remote irrigation management. Threshold rules are simple to implement, but their agronomic validity depends on the crop, soil and growth stage. Water savings reported in individual studies should not be assumed to transfer to Pune without local validation.

D. IoT Applications in Sugarcane Cultivation

Mehdizadeh et al. [4] describe an energy-autonomous wireless sensor network for sugarcane that tracks soil moisture, plant temperature, environmental conditions, groundwater level and crop height, processes data locally, and sends it to a cloud server for irrigation decisions based on the Crop Water Stress Index. The authors report a soil moisture correlation of R-squared 0.96 against gravimetric measurement, 98.7 percent data transmission reliability and 15 percent water saving. These figures are the authors' own results from their study setting and cannot be taken as expected results in Pune. The study is useful because it shows sugarcane-specific monitoring that combines sensing, local processing and cloud decision support, and because it reports reliability and accuracy measures that a Pune study should also report.

E. Wireless Sensor Networks and Cloud-Based Agriculture

Wi-Fi with a low-cost controller and a hosted dashboard is the most common arrangement in the studies reviewed [1]. Wi-Fi needs a nearby access point, which large rural fields may lack, and cellular links add recurring cost. The choice of link, and of a cloud service, therefore depends on field coverage and cost. This paper does not treat any one platform as proven for sugarcane.

F. Sensor Reliability, Calibration, and Data Quality

Several research articles have investigated the role of calibration in inexpensive soil moisture sensors. For example, González-Teruel et al. [5] developed and calibrated a low-cost capacitive soil moisture sensor in three different soils and observed reduced yet cost-effective accuracy in comparison to commercial soil moisture sensors along with an effect of temperature on the sensor reading. Another study by Nagahage et al. [6] compared a low-cost capacitive soil moisture sensor with gravimetric method and a commercial soil moisture sensor and applied a soil-specific calibration function for using it in automatic monitoring of soil moisture. Neither of these studies was conducted in sugarcane fields in Pune.

G. Economic Feasibility and Farmer Adoption

An analysis involving dryland farmers in Anantapur district of Andhra Pradesh through a survey of 100 farmers and binary logistic regression has found that factors like perceived usefulness, perceived ease of use, innovativeness, and facilitating conditions increased the probability of adoption of IoT solutions, whereas perceived cost and decision-making complexity reduced it [7]. This is a different context from Pune, and there might be variations in the response of sugarcane farmers in Pune; however, it suggests usability and cost as important design considerations..

H. Critical Synthesis and Research Gap

Table I compares the studies discussed. Together they show that monitoring architectures, sugarcane-specific sensing, calibration methods and adoption factors have each been studied, mostly in separate papers and in settings other than Pune. The gap addressed here is their combination for sugarcane in Pune District, with attention to local calibration, connectivity, cost and use by farmers.

TABLE I. QUALITATIVE COMPARISON OF SELECTED STUDIES

Study	What it establishes	Main limitation for this work
Waghole et al. [1]	Survey of IoT sensing, controllers, wireless links and dashboards in agriculture	Review, not crop-specific; no Pune field data
Mehdizadeh et al. [4]	Sugarcane IoT network with local processing and cloud irrigation decisions; reports accuracy and reliability measures	Different setting; reported results not transferable to Pune
González-Teruel et al. [5]	Low-cost capacitive sensor needs soil-specific calibration; temperature affects readings	Not tested on sugarcane fields
Nagahage et al. [6]	Soil-specific calibration of a low-cost sensor against gravimetric and commercial references	Not tested on sugarcane fields
Adoption study [7]	Usefulness and ease of use raise, cost and complexity lower, adoption likelihood	Andhra Pradesh dryland farmers, not Pune

III. RESEARCH METHODOLOGY

A. Research Design

The study is conceptual and literature-based. It uses secondary sources to develop a proposed architecture and an evaluation framework. It is not experimental, and no primary data were collected.

B. Study Area

The study area is Pune District, Maharashtra, where sugarcane is a significant crop [2]. Soils, rainfall, water sources and microclimates vary within the district, so the framework is described at a level that allows local adaptation. A detailed agro-climatic description from official sources is not included here and should be added by the authors from district agricultural records.

C. Data Sources

The sources are peer-reviewed articles and conference or repository records [1], [3]-[6], a published adoption study [7] and a district-wise agricultural statistics dataset [2]. Technical statements about sensors that are not drawn from these sources are general engineering considerations, and manufacturer documentation should be consulted before any hardware is chosen.

D. Literature Selection and Review Procedure

Sources were found through targeted web searches using terms such as IoT sugarcane irrigation monitoring, low-cost capacitive soil moisture sensor calibration, IoT adoption by farmers in India, and sugarcane water requirement by growth stage. Each source was checked against its publisher, journal or repository record, and sources whose bibliographic details could not be confirmed were excluded or flagged. Publications from 2019 to 2026 were mainly considered. This was a targeted search, not a systematic review, and it may have missed relevant studies.

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E. Proposed System Design Method

Design requirements were derived from the problems stated in Section I and from the literature. Parameters were chosen for their relevance to irrigation and soil condition, and each was matched to a sensor type, a controller interface and a data path to a dashboard. Constraints on cost, power, connectivity and maintenance were applied as design limits.

F. Sensor Selection and Measurement Parameters

Table II lists the monitored parameters. Ranges and accuracy figures are not given because they depend on the chosen sensor model and must be taken from its datasheet and from calibration.

TABLE II. MONITORED PARAMETERS AND SENSOR CONSIDERATIONS

Parameter	Measured by	Key limitation
Soil moisture (volumetric water content)	Capacitive soil moisture probe	Needs soil-specific calibration [5], [6]; sensor-to-sensor variation
Soil temperature	Probe suited to soil	Air-temperature sensors do not measure soil
Ambient relative humidity	Air humidity sensor (for example DHT11 [1])	Measures air, not soil moisture; limited accuracy of low-cost types
Soil pH	pH probe	Needs buffer-solution calibration; drift and care in long-term use
Water source level	Ultrasonic or pressure level sensor	Level does not give usable volume or irrigation demand

G. Data Processing and Analysis

The literature is analysed qualitatively, by comparing the purpose, method, findings and limits of each study (Table I). No numerical analysis of primary data is performed and no results are computed.

H. Validation Plan

A future field trial on representative sugarcane plots would calibrate sensors against gravimetric soil sampling, compare readings with reference instruments, log communication success and data gaps, and compare irrigation recommendations with existing farmer practice across crop stages. None of this has been done in the present study.

IV. PROPOSED IOT-BASED SMART FARMING ARCHITECTURE

A. Overall System Architecture

The architecture has five layers (Fig. 1): a field sensing layer, a controller layer, a communication layer, a cloud layer with dashboard, and a farmer decision-support layer. Data flows from sensors to the controller, over a wireless link to the cloud, and to the farmer. The farmer remains the decision maker. Optional pump control is kept separate from core monitoring.

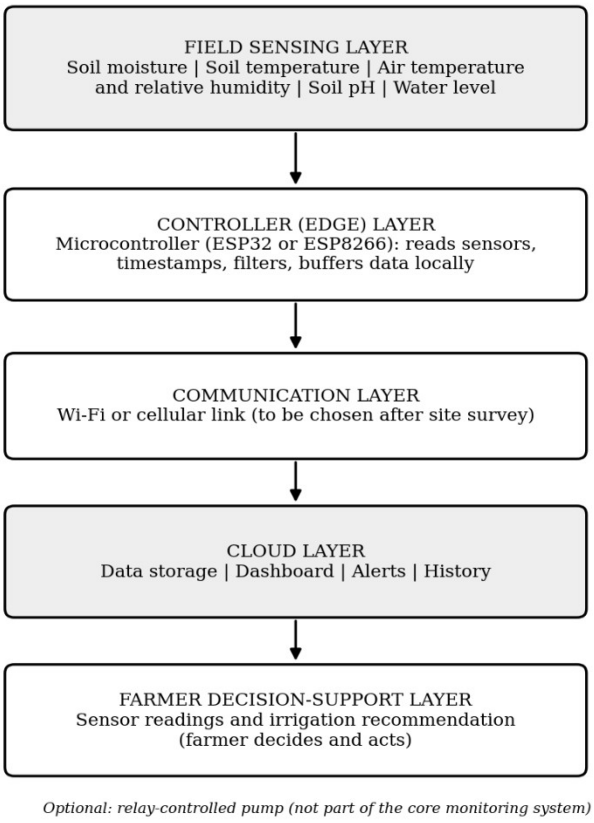


Fig. 1. Conceptual sensor-to-cloud architecture of the proposed system (not implemented). Optional pump control is shown separately from core monitoring.

B. Soil Moisture Monitoring

Soil moisture would be measured as volumetric water content in the root zone. Probes would be placed at more than one depth and in more than one location in a plot, because moisture varies with depth and position. Each probe needs soil-specific calibration [5], [6], and readings should be interpreted with crop stage.

C. Soil Temperature and Ambient Relative Humidity

Soil temperature is measured with a probe in the soil. Air temperature and ambient relative humidity are measured above the canopy or at a sheltered point. Neither describes soil water, and the two should not be mixed in the dashboard or in decision logic.

D. Soil pH Monitoring

Soil pH helps to assess soil condition, but it changes slowly and its sensors need regular calibration with buffer solutions. Readings would be treated as indicative and checked by laboratory soil testing. Interpretation of pH for sugarcane needs agronomic advice and is outside this paper.

E. Water Source Availability Monitoring

The level in a tank or reservoir could be monitored with an ultrasonic or pressure sensor [1]. Level alone does not give the volume available or the irrigation requirement, and the geometry of the source must be known to estimate volume.

F. Microcontroller and Sensor Integration

An ESP32 or ESP8266-based controller, as in the studies reviewed [1], can read analogue and digital sensors, add

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timestamps, filter noise and send data over Wi-Fi. Analogue sensors need suitable conversion and power arrangements. The choice between the two controllers depends on the number of sensor inputs and power use, to be checked against their datasheets.

G. Wireless Communication

Wi-Fi is low in cost but depends on an access point near the field. Cellular links give wider coverage at a recurring cost. Other low-power long-range links may also suit large fields. The choice should follow a site survey of coverage, cost and energy use.

H. Cloud Dashboard and Data Storage

The cloud layer stores timestamped readings, shows current values and history, and sends alerts, for example for a sensor fault or a low water level. User access should be limited to the farmer and authorised helpers. Dashboards should be simple enough for farmers with limited digital experience [7].

I. Irrigation Decision-Support Logic

The logic would compare soil moisture with a locally determined range for the current crop stage, check that readings are plausible, check water availability, and show a recommendation to irrigate or wait. Universal thresholds are not given because they are not supported by the evidence reviewed. Thresholds should come from agronomic advice and local trials.

J. System Workflow

The workflow is: (1) sensors measure at set intervals; (2) the controller reads, timestamps and checks the values; (3) data are sent over the wireless link, or buffered if the link is down; (4) the cloud stores the data and updates the dashboard; (5) the decision logic produces a recommendation or alert; (6) the farmer reviews it and acts, and records the action for later analysis.

K. Proposed Architecture Diagram

Fig. 1 shows the layers and the direction of data flow. It is a conceptual diagram and does not represent a built system.

V. Hardware, Software, and Implementation Requirements

A. Hardware Components

Required items are the sensors in Table II, a microcontroller board, a communication module or router, a power supply, and weatherproof enclosures and cable protection. A relay and pump are needed only if automatic control is later added.

B. Software Components

Software includes controller firmware for reading and sending data, a messaging protocol, a hosted dashboard and database, and alert rules. Hosted services in the studies reviewed include Blynk [1]. The selection of services should consider cost, data ownership and long-term availability.

C. Calibration and Maintenance

Soil moisture probes should be calibrated for each soil type [5], [6], and re-checked at intervals. pH probes need buffer-solution calibration. Probes need cleaning, inspection for corrosion and cable damage, and replacement when faulty. Fault detection should flag readings that are constant, out of range or missing.

D. Power Management

Mains power may be unreliable in rural fields. Battery operation with duty-cycled sensing, or a solar panel with a battery, are possible options. Mehdizadeh et al. [4] report an energy-autonomous design for sugarcane, but its performance cannot be assumed for Pune.

E. Connectivity and Offline Operation

The controller should store readings locally when the network is down and send them later with their original timestamps. The dashboard should show the age of the latest reading so that farmers do not rely on stale data.

F. Security and Data Privacy

The system should use authenticated access, encrypted transmission, regular backups, and limited sharing of farm data. Farm and farmer information should be handled with the owner's consent.

G. Scalability and Interoperability

The design could be extended by adding controller nodes per plot, with a common data format and device identifiers. Scalability has not been demonstrated, and larger deployments would raise new issues of coverage, cost and maintenance.

VI. Feasibility and Evaluation Framework

A. Technical Feasibility

The components are available and are used together in the studies reviewed [1], [4]. Feasibility in Pune depends on sensor suitability for local soils, protection from weather and irrigation water, and communication reliability, none of which has been tested here.

B. Economic Feasibility

Costs include sensors, controllers, enclosures, power, connectivity, installation, repair and replacement. Verified prices were not collected for this paper, so no cost figures are given. The authors should add dated prices and stated assumptions before drawing any conclusion on affordability.

C. Operational Feasibility

Operation depends on easy installation, a dashboard that farmers can read, basic training, and a route for field servicing and support. Adoption studies point to ease of use and perceived cost as important factors [7].

D. Environmental Relevance

Better information on soil moisture and water availability may support more informed water use. Whether it reduces water use in Pune can only be shown by measurement.

E. Risk Analysis

Main risks are sensor failure or drift, false readings, network interruptions, power loss, data loss, and inappropriate irrigation advice from wrong thresholds. Mitigations are calibration, plausibility checks, local buffering, backups, and keeping the farmer as the final decision maker.

F. Evaluation Metrics

Proposed measures are sensor measurement error against a reference, data availability, communication success rate, alert delay, water use per unit area, and usability as rated by farmers. All of them require future field testing.

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VII. Results, Analysis, and Proposed Outcomes

No prototype was built and no field data were collected, so there are no experimental results. The outputs of this study are the proposed architecture (Fig. 1), the parameter and sensor considerations (Table II), the qualitative comparison of earlier work (Table I), and the evaluation measures in Section VI. The expected contribution is a structured basis for a Pune sugarcane field study. Any benefit, such as water saving or better decisions, is an expected outcome and has not been measured.

VIII. Discussion

The literature supports the technical feasibility of sensor-to-cloud monitoring [1], [4] but also shows that its usefulness depends on calibration [5], [6] and on adoption factors [7]. For sugarcane, crop-stage-aware interpretation is needed because water sensitivity changes through the crop cycle [3]. The framework therefore recommends monitoring first and treating automatic irrigation as a later step once thresholds and reliability are established.

Choices carry trade-offs. Wi-Fi is cheap but limited in range. More probes improve spatial coverage but raise cost and maintenance. Solar power helps in remote fields but adds cost. These points follow from the cited evidence and from the authors' analysis, and they have not been tested in Pune.

IX. Conclusion

This paper proposed a conceptual IoT-based architecture for monitoring soil and environmental conditions and supporting irrigation decisions in sugarcane cultivation in Pune District. The literature indicates that such monitoring is technically feasible, that low-cost soil moisture sensors need soil-specific calibration, and that cost, complexity and familiarity affect adoption. The framework addresses these issues together, but it is conceptual: no prototype was built and no water saving, yield gain or cost reduction has been shown. Field validation is the necessary next step.

X. Future Scope

The future research should include implementation of the developed model to several representative sugarcane fields. It will include calibration and validation of the sensors in relation to the local soil/weather environment. Data gathering will be carried out seasonally and a comparison between the efficiency of the system and conventional methods will be made taking into account water consumption and crop productivity andother parameters.

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