Desarrollo De Un Sistema Inteligente Para El Monitoreo De Fertilizantes Y Biofertilizantes Mediante Sensores E Integración De Una API

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INTRODUCTION

Climate change and population growth have increased dramatically, and with them, food needs—requiring a 60% increase in agricultural production in the coming years. In response, technological solutions for data analysis and demand forecasting have become widespread on a global scale. (Precision Fertilization). However, agricultural production with its intensified use of land—as well as water quality issues, causes pollution and degradation of water bodies and soil, in addition to eutrophication, which depletes oxygen and leads to the decline of aquatic life.

Among the variables considered in agricultural analysis are hydrogen ion concentration (pH), soil temperature, and ambient relative humidity, as well as nutrients such as nitrogen, phosphorus, and potassium. These elements are essential for agricultural development; a deviation in their levels can cause nutrient depletion of between 30% and 50%, accelerating soil degradation.

With Agriculture 4.0 and the Internet of Things, it is possible to collect soil data for real-time analysis; however, to optimize the agricultural sector, precision techniques are needed to identify strategies for the efficient use of resources while reducing environmental impact (Ortiz et al., 2025). Although there are many strategies and proposals, smart agriculture paves the way for achieving specific sustainable development goals. Sometimes, these strategies rely on complex applications or fail to adapt to specific uses; in response, the proposed technological architecture addresses the need for use across all environments.

To achieve these objectives, applications such as Progressive Web Apps (PWAs), supported by full-stack architectures, represent a low-cost, cross-platform alternative. They run on both mobile and desktop devices, facilitating field monitoring.

In light of this challenge, this paper illustrates the design and implementation of a comprehensive IoT and PWA system for the continuous monitoring of soil pH and temperature, based on microcontrollers for soil readings, which are transmitted to an application that integrates soil condition assessment and the generation of real-time recommendations.

This project was designed to provide a cost-optimized technological architecture that reduces soil degradation and depletion, ensuring safe use and providing real-time recommendations. In light of this, the overall objective will be to evaluate the integration of the API, as well as the responsiveness of the monitoring system for pH and temperature.

LITERATURE REVIEW

Using the PRISMA methodology, a literature review was conducted to identify keywords, including: sensors, IoT, biofertilizer, and agriculture, while limiting the time frame to articles published after 2020 and consulting reliable sources such as Scielo and Redalyc, among others; In addition, an analysis was conducted of forty articles, from which were selected as the most relevant to the project. The information was organized into the following table for presentation.

Table 1 Literature Review

Title	Objective	Methods	Results	Limitations
A two-port microwave sensor for real-time liquid fertilizer concentration measurement system with Internet of Things.	Design an IoT-integrated microwave sensor to measure and monitor the concentration of liquid urea fertilizer in real time.	Design of a planar microwave sensor using CST Microwave Studio. Urea solutions with different concentrations were prepared, the sensor's response was evaluated, and a Wi-Fi connection was integrated to display the data in the cloud.	A sensitivity of 3.20 dB/(g/mL) was obtained at 2.37 GHz. The measurement model achieved an R^2 of 0.9689 and an RMSE of 0.0433. Real-time concentration monitoring was achieved using IoT.	The study focuses on urea solutions; therefore, its results cannot be directly extrapolated to biofertilizers with complex compositions. The sensor requires a specialized electronic design and calibration for each type of solution.
Characterization of bioles from the anaerobic fermentation of cattle and swine excreta.	To characterize the physicochemical properties of bio-fertilizers obtained through the anaerobic fermentation of bovine and swine manure, in order to evaluate their potential as fertilizers.	Daily monitoring over a two-month period. Measurements of pH, temperature, electrical conductivity, dissolved oxygen, oxidation-reduction potential, moisture, solids, and nutrients. A pH meter, multiparameter analyzer, gravimetric methods, a nutrient analyzer, and atomic absorption spectrophotometry were used. A one-way ANOVA was performed.	Differences were identified between bovine and porcine biols. The bovine biol had an electrical conductivity (EC) of 8.94 mS/cm, while the porcine biol had an EC of 8.4 mS/cm. Concentrations of ammoniacal nitrogen, phosphates, and potassium were also determined. The authors found that the systems were stable under mesophilic conditions.	Monitoring was conducted using conventional measurement and analysis equipment, not through an integrated IoT architecture. Some nutrients require specialized equipment and laboratory procedures, which makes it difficult to measure them continuously and cost-effectively.
Portable internet of things-based soil nutrients monitoring for precision and efficient smart farming.	Design and implement a portable IoT-based system to monitor NPK nutrients and provide information to support decisions regarding fertilization and agricultural management.	Development of a portable device with NPK sensors and wireless communication. A quantitative evaluation was conducted, and ANOVA was applied to compare the device's measurements with those of industrial reference equipment.	The system made it possible to collect and transmit nutrient data online. The ANOVA revealed differences in phosphorus and potassium measurements compared to the industrial equipment, but not in nitrogen measurements.	The system is designed for soil analysis, not for the direct measurement of liquid fertilizers or biofertilizers. Furthermore, the differences observed in P and K highlight the need to improve the calibration and accuracy of the sensors.
Characterization of Biofertilizers Used in the Guasave Agricultural Valley, Sinaloa, Mexico.	To determine the physicochemical and microbiological characteristics of various organic fertilizers for use as quality indicators.	Evaluation of seven organic fertilizer treatments, with four replicates. pH and electrical conductivity were measured using a YSI multiparameter probe; organic matter was measured using the Walkley-Black method; and nutrients were measured using spectrophotometry. Statistical analyses and comparison tests were performed.	pH values ranging from 3.3 to 8.28 were found, as well as differences in electrical conductivity among the fertilizers. A positive correlation was identified between EC and nutrients. Differences in product characteristics were also detected depending on the source materials.	The study is based on laboratory analyses and one-time measurements; it does not develop an automated monitoring system or IoT data transmission. Nor does it establish an intelligent classification model to continuously assess the condition of biofertilizers.

Soil Nutrient Monitoring Technologies for Sustainable Agriculture: A Systematic Review.	Analyze the technologies used to monitor nutrients and evaluate their application in sustainable agriculture, including sensors, the Internet of Things (IoT), and artificial intelligence.	Systematic review conducted according to the PRISMA guidelines. A total of 93 articles were analyzed, and the technologies were classified into traditional methods, remote sensing, IoT and intelligent systems, in situ sensors, and artificial intelligence models.	Five main technological approaches were identified, along with a growing trend toward the integration of sensors, IoT, and machine learning to obtain real-time information. System validation and accuracy techniques were also analyzed.	This is a review focused on soil nutrients, not an experimental study of direct fertilizer monitoring. It does not validate a specific prototype or establish universal physicochemical ranges for biofertilizers.
"Biol" Biofertilizer: Physical, Chemical, and Microbiological Characterizatio n.	To evaluate the physicochemical and microbiological characteristics of a liquid biofertilizer (Biol) produced from cattle manure.	A laboratory characterization was performed using a previously calibrated conductivity meter and pH meter. Atomic absorption spectroscopy, the reactive phosphorus method, and the Kjeldahl method were used to determine nutrient levels. Sulfides and microorganisms were also assessed using the methylene blue method and the Most Probable Number (MPN) method.	A conductivity (EC) of 16.32 mS/cm and a pH of 6.90 were obtained. Concentrations of N were determined to be 290 mg/L, P 17.78 mg/L, K 111.7 mg/L, and Mg 153.2 mg/L. The absence of total and fecal coliforms was also reported, with levels below 1.8 NMP/100 mL.	The characterization was performed using conventional laboratory procedures and spot measurements. It does not incorporate connected sensors, continuous monitoring, IoT storage, or artificial intelligence models. Measuring nutrients and metals requires specialized equipment.
Characterizatio n of biofilms from the anaerobic fermentation of bovine and swine manure	To characterize and compare the physicochemical properties of bio-fertilizers obtained through the anaerobic fermentation of bovine and swine manure, in order to determine their potential as fertilizers.	A two-month monitoring period was conducted, with daily measurements. The following parameters were evaluated: pH, temperature, EC, dissolved oxygen, oxidation-reduction potential, total dissolved solids, moisture, and nutrients. A HANNA HI-255 pH meter, a HACH HQ40d multiparameter analyzer, a HANNA HI-83215 nutrient analyzer, and atomic absorption spectrophotometry were used. A one-way ANOVA was applied, and the analyses were performed in duplicate.	Differences were identified between the bovine and porcine bioli, particularly in calcium and magnesium. The bovine biol had an electrical conductivity (EC) of approximately 8.94 mS/cm, while the porcine biol had an EC of 8.4 mS/cm. Concentrations of ammonium, phosphates, and potassium were also determined. The fermentation systems showed stability under mesophilic conditions.	Although numerous variables are monitored daily, the measurements were taken using laboratory instruments rather than an automated IoT system. Nutrient analyses require specialized equipment, and no intelligent classification system has been developed.
The Internet of Things for Monitoring Agricultural Environmental Factors: A Systematic Review.	Analyze how IoT technologies have been applied to monitor environmental factors in agricultural production during the 2020–2025 period, identifying sensors, platforms, communication networks, benefits, and challenges.	A systematic review was conducted following the methodologies of Petersen et al. and Kitchenham and Charters. Scopus, IEEE Xplore, ScienceDirect, and SAGE Journals were searched. Inclusion and exclusion criteria based on PICOC were applied. Of the 1,045 initial records, 30 studies were selected for analysis.	Temperature and humidity were identified as the most commonly monitored variables. Applications involving pH and EC sensors were also found. Notable technologies include WSNs, LoRaWAN, Wi-Fi, and platforms such as ThingSpeak, Raspberry Pi, Ubidots, and ThingsBoard. The main advantages identified were continuous monitoring, cost reduction, and remote access.	The analysis focuses on agricultural environmental factors and not specifically on the composition of fertilizers or biofertilizers. Challenges related to costs, connectivity, interoperability, security, and data processing are identified. No prototype is built or validated.

Characterization of Biofertilizers Used in the Guasave Agricultural Valley, Sinaloa, Mexico.	To determine the physicochemical and microbiological characteristics of various organic fertilizers used in agriculture, with the aim of identifying quality indicators.	An experiment was conducted using a randomized block design, with four replicates and seven treatments corresponding to different organic fertilizers. pH and EC were measured using a YSI multiparameter probe. Organic matter was determined using the Walkley-Black method, and nutrients were analyzed using spectrophotometric techniques. Microbiological evaluations and statistical analyses were also performed.	pH values ranging from 3.3 to 8.28 were found, as well as differences in electrical conductivity among the products evaluated. The vermicompost, banana humus, and commercial fertilizers had high levels of nitrogen and phosphates. A positive correlation was identified between electrical conductivity and nutrients. Microbiological differences and the presence of heavy metals were also detected in some products.	Conventional analyses and spot measurements were used, without developing an automated monitoring system. No IoT sensors or predictive models were integrated. Furthermore, the characteristics of the fertilizers varied depending on their composition and origin, so universal ranges cannot be established based on a single study.

The reviewed literature confirms that agricultural monitoring using sensors and the IoT is technically feasible: measurement models with an R^2 of 0.9689 for urea, pH errors of less than 0.07, and N, P, and K measurements of up to 290, 17.78, and 111.7 mg/L in biofertilizers have been achieved. However, most studies measure isolated parameters, use laboratory equipment, and do not validate their results under real field conditions. Therefore, the development of a unified, calibrated, and validated API for measuring physiological ratios in crops represents a necessary and relevant contribution toward advancing sustainable precision agriculture.

THEORETICAL FRAMEWORK

This study is based on a conceptual model that integrates precision agriculture, the Internet of Things (IoT), and smart architectures as guiding principles for the monitoring and characterization of fertilizers and biofertilizers. This framework provides insight into how the integration of sensors and digital platforms transforms the measurement of physicochemical variables into useful information for agricultural decision-making.

Precision Agriculture and Continuous Monitoring

Precision agriculture is a technological approach aimed at the efficient use of resources through the collection and analysis of information from the production system. In this context, agricultural monitoring is evolving from traditional methods toward the integration of in-situ sensors, the Internet of Things (IoT), and artificial intelligence, which allows for more frequent data collection and its use in analyzing agricultural management (Sobhy & Anandhi, 2025). The incorporation of digital technologies aims to overcome the limitations of conventional laboratory methods, which, while accurate, make it difficult to obtain continuous data over extended periods.

Fertilizers, Biofertilizers, and Their Physicochemical Characterization

Biofertilizers and fertilizers are inputs whose composition and behavior vary significantly depending on their source materials and manufacturing conditions. Previous studies have shown that variables such as pH, electrical conductivity, and nutrient concentration differ significantly among different products, confirming the need to characterize each sample before establishing application recommendations (González-Márquez et al., 2021). In this regard, the potential of hydrogen (pH) stands out as a variable of central interest, as it directly influences the availability and uptake of nutrients. Measuring this variable, along with temperature and humidity, provides a basis for the experimental monitoring of the samples.

Internet of Things (IoT) and Sensors

The IoT is defined as the infrastructure that enables physical devices to connect to processing and storage systems. In agricultural applications, this technology provides the ability to continuously collect data using sensors (Olivera-Ruiz & Vega-Ventocilla, 2026). For the development of the API, the ESP32 microcontroller acts as a central data acquisition and processing unit that receives signals from the sensors and transmits them via wireless connectivity. It is important to note that selecting sensors for complex agricultural systems requires consideration of technical challenges such as calibration, accuracy, stability, and potential interference (Pal et al., 2024). Therefore, the direct measurement of nutrients such as NPK is considered a later stage, with priority initially given to more controllable variables such as pH, temperature, and humidity (Silva et al., 2024).

Smart Architectures and the Role of the API

The integration of Artificial Intelligence with the IoT (AIoT) enables a shift from systems focused solely on data collection to architectures capable of analyzing information and identifying patterns (Khan et al., 2024). In this model, the API (Application Programming Interface) serves as the integrating and abstracting element between data acquisition devices (sensors and ESP32) and end-user applications. The API enables the structuring, storage, and provision of data from the sensors for querying and processing, facilitating connection to web or mobile interfaces (El Alaoui et al., 2024). This architecture does not seek to replace laboratory analyses but rather to generate systematic historical records that allow for the identification of trends and experimental relationships in the behavior of biofertilizers.

METHODOLOGY

This study follows a mixed-methods research design, integrating qualitative and quantitative approaches. The qualitative phase consists of a systematic literature review conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, with the aim of identifying the main physicochemical variables, sensor technologies, Internet of Things (IoT) architectures, and smart agriculture applications related to the monitoring of biofertilizers.

The quantitative phase focuses on the development, implementation, and experimental validation of an IoT-based monitoring system for biofertilizers. The research adopts an applied and technology-development approach, aimed at designing and evaluating a prototype capable of monitoring critical biofertilizer parameters in real time. Given this, the target population consists of scientific studies, sensor technologies, and biofertilizer monitoring systems, as well as samples of these, used for experimental validation.

The research was divided into four phases: literature review and variable selection, system architecture design, development of the electronic prototype and platform, and experimentation and data collection.

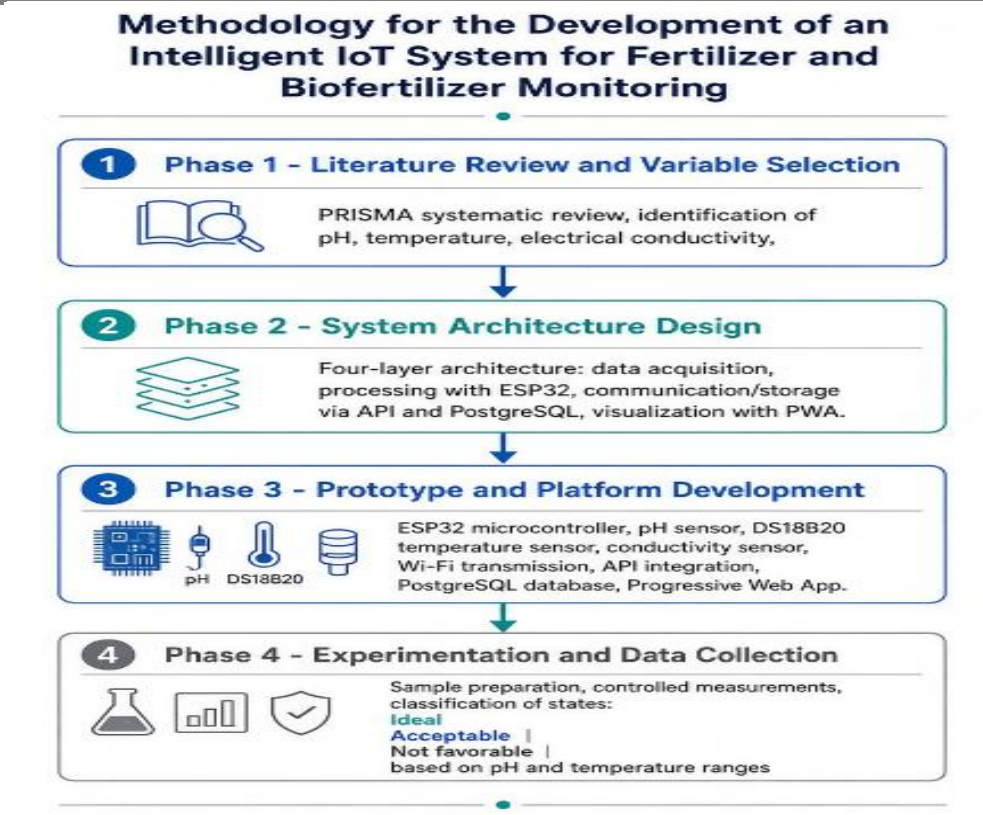


Figure 1. Methodology

The methodology is organized into four sequential phases. In the first phase, a systematic review of scientific literature published mainly between 2020 and 2026 was conducted to select the priority variables for the system. Based on the reviewed studies, pH, temperature, and electrical conductivity were identified as the most feasible and informative parameters for initial continuous monitoring, while nutrient measurements (N, P, K) were reserved for later stages due to sensor complexity and cost.

In the second phase, a four-layer technological architecture was defined. The data-acquisition layer incorporates physicochemical sensors; the processing layer uses an ESP32 microcontroller to collect and prepare the signals; the communication and storage layer transmits data via Wi-Fi to an API that stores records in a PostgreSQL database; and the visualization and analysis layer provides access through a Progressive Web App. The architecture was intentionally designed for low cost, ease of integration, and future expandability.

The third phase comprises the physical development of the electronic prototype and the supporting digital platform. The hardware integrates an ESP32 microcontroller, a pH sensor, a waterproof DS18B20 temperature sensor, an electrical conductivity sensor for liquid samples, and, when required, an ambient humidity sensor. After connection and calibration with standard solutions, the software components including the API, PostgreSQL database, and Progressive Web App were implemented to receive, store, and display each measurement together with its timestamp and sensor identifier.

In the fourth phase, experimental data collection is carried out under controlled conditions. Liquid fertilizer and biofertilizer samples are measured at defined intervals while selected factors such as temperature, concentration, or storage time are varied. The recorded values are automatically transmitted and stored. Classification thresholds for soil or sample condition (Ideal, Acceptable, and Not favorable) are applied based on established pH and temperature ranges, allowing the system to generate interpretable status information for agricultural decision-making.

This phased structure ensures that variable selection is grounded in evidence, the technical architecture remains modular and low-cost, the prototype is functionally integrated, and experimental validation provides concrete data on system performance and measurement reliability.

Phase 1. Literature Review and Selection of Variables

A systematic review of the scientific literature was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, with the aim of identifying the main physicochemical characteristics used to evaluate fertilizers and biofertilizers, as well as the technologies employed for their monitoring.

The search was conducted in databases and academic repositories such as Web of Science, ScienceDirect, SciELO, Redalyc, and Google Scholar. Combinations of keywords in Spanish and English were used, including: fertilizers, biofertilizers, physicochemical monitoring, sensors, Internet of Things, IoT-based monitoring, pH sensors, electrical conductivity, smart agriculture, and fertilizer quality monitoring.

The review primarily considered scientific articles published between 2020 and 2026, without excluding earlier research that provides relevant experimental information on the characterization of biofertilizers. Studies describing physicochemical variables, sensor systems, IoT architectures, validation methods, or intelligent data analysis were included. Documents that did not provide sufficient methodological information or that were not directly related to the research objective were excluded.

Based on the selected studies, the variables that make up the system were identified. Initially, pH, temperature, and electrical conductivity were considered. Relative humidity in the storage environment was also taken into account when relevant to the type of product.

Phase 2. System Architecture Design

A technological architecture consisting of four main components was established: data acquisition, processing, communication and storage, visualization, and analysis.

The first layer incorporates sensors to obtain measurements of the physicochemical characteristics of the fertilizer or biofertilizer. In the second layer, an ESP32 microcontroller receives signals from the sensors and performs initial processing of the measurements. Subsequently, via Wi-Fi connectivity, the data is transmitted to a storage platform. Finally, the information can be accessed through a digital interface, where the measurements, their history, and the analysis results are displayed.

The architecture was designed with the following factors in mind: low component cost, ease of integration, availability of information, and the ability to expand the number of sensors. The goal is for the system to allow for the incorporation of new variables in the future without requiring a complete overhaul of its structure.

Phase 3. Development of the electronic prototype and the IoT platform

- For the experimental implementation, a prototype based on an ESP32 microcontroller was developed, as it integrates Wi-Fi connectivity and allows for the connection of various measurement devices.
- The hardware consists of the following components:
- ESP32 microcontroller for data acquisition and transmission.
- pH sensor to determine the acidity or alkalinity of liquid samples.
- Waterproof DS18B20 sensor to measure the product’s temperature.
- Electrical conductivity sensor compatible with liquid solutions.

- Ambient humidity sensor, when storage conditions need to be monitored.
- Breadboard, cables, power supply, and supplementary electronic components.

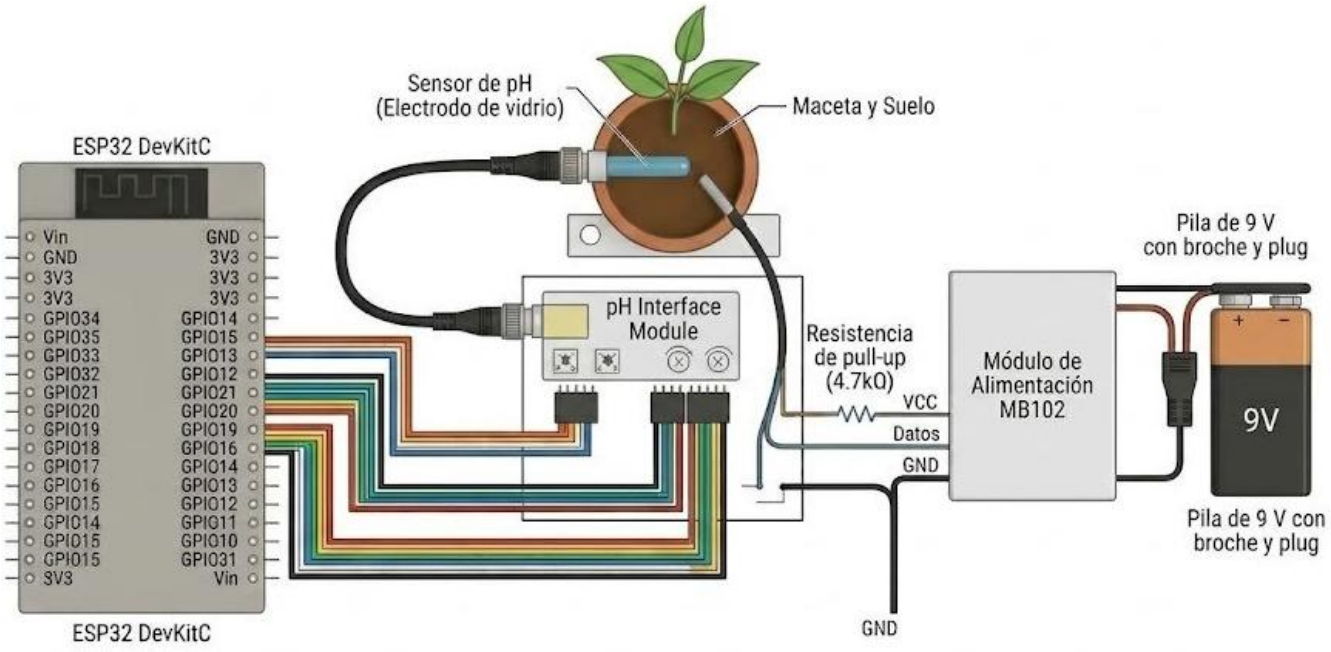


Figure 2. Prototipe

The sensors were installed and connected to the microcontroller in accordance with their technical specifications. Before performing the experimental measurements, their operation was verified, and the corresponding calibration was carried out using standard solutions or reference instruments.

As for the software, a query interface was developed that allows users to view the recorded values and access the measurement history. PostgreSQL was used for data storage, as it is an open-source database management system. Communication between the ESP32 and the platform occurs via an application programming interface (API), which is responsible for receiving, processing, and storing the records.

Each record contains, at a minimum, the sample ID, date, time, sensor ID, and the measured values. This structure allows the data to be organized and facilitates its retrieval and subsequent analysis.

Phase 4. Experimentation and Data Collection

The purpose of the experimental phase was to evaluate the prototype's performance and analyze the behavior of the samples' physicochemical characteristics under different conditions.

Samples of liquid fertilizers or biofertilizers were used, selected based on their availability, declared composition, and physical characteristics. Each sample was identified by a code to ensure the traceability of the measurements.

An experimental protocol was established that includes controlled variations in factors such as temperature, concentration, and storage time. Efforts were made to keep conditions not part of the experiment constant, in order to reduce the influence of external factors.

The samples were placed in appropriate containers, and measurements of pH, temperature, and electrical conductivity were taken at the intervals specified in the protocol. Where applicable, ambient humidity will be recorded. The measurements are automatically stored in the database via the ESP32's connection to the IoT platform.

To conduct the analysis, soil pH and temperature values were established to classify each measurement; these are presented below:

Table 2 values

State	pH	Temperature
Ideal	6.0 -7.0	18 - 25 °C
Acceptable	5.5 - 5.99 / 7.01 - 7.5	15 - 17.99 / 25.01 - 30 °C
Not favorable	< 5.5 o > 7.5	< 15 °C o > 30 °C

Data Availability

The data used in this project falls into two categories: data collected directly by IoT sensors and external data obtained from reliable agricultural sources.

Data collected by the system. The proposed system monitors soil pH and temperature using sensors connected to microcontrollers. Each measurement may include the date, time, and sensor ID to facilitate the organization, visualization, and analysis of the information via a progressive web app (PWA). This data will enable the monitoring of soil conditions and the generation of recommendations based on the measurements obtained.

Data used for soil monitoring:

Table 3 variables

Variable	Data source	Unit	Purpose
soil pH	pH Scale	pH Scale	Determine the soil's acidity or alkalinity.
Soil Temperature	Temperature sensor	°C	Monitor soil temperature conditions.
Date and time	Registration System	Date and time	Identify when each measurement was taken.
Sensor ID	Microcontroller or system	Alphanumeric code	Identify the device that generates the data.
Nitrogen, phosphorus, and potassium	Laboratory tests or external sources	According to the analysis	To supplement the assessment of soil conditions.

External sources of information. Agricultural information will be obtained from reliable institutions, such as the National Institute for Forestry, Agricultural, and Livestock Research (INIFAP), the Food and Agriculture Organization of the United Nations (FAO), and the Natural Resources Conservation Service of the U.S. Department of Agriculture (USDA-NRCS). These institutions provide information on soil properties, nutrient management, and soil health indicators. The information will serve as a reference for interpreting sensor measurements and establishing appropriate values based on agricultural conditions.

Table 4 vInstitutions

Institution	Information provided by	Application in the project
INIFAP	Physicochemical properties of soil.	Interpret soil characteristics.

FAO	Nutrient Management and Fertilization	Provide a basis for agricultural recommendations.
USDA-NRCS	Soil health indicators.	Supplement the evaluation of the measurements.

Data Accessibility. The system is designed to display soil measurements through the progressive web app (PWA), allowing authorized users to view the available information. Data visualization, measurement history, and export options will depend on the features implemented in the app. Additionally, external agricultural information can be accessed on the official websites of the institutions mentioned.

It is important to note that nitrogen, phosphorus, and potassium concentrations will not be considered direct measurements by the system unless specific sensors are used or laboratory analyses are conducted. Similarly, recommendations should take into account the type of crop, soil characteristics, and agricultural conditions in the area.

Research Design

This study employs a mixed-methods research design that combines a systematic literature review with an applied approach to technology development. The qualitative component follows the PRISMA guidelines to identify relevant physicochemical variables, sensor technologies, and Internet of Things (IoT) architectures applied to agricultural monitoring. The quantitative component focuses on the design and implementation of an IoT-based monitoring system consisting of an ESP32 microcontroller, physicochemical sensors, an application programming interface (API), a PostgreSQL database, and a progressive web app (PWA).

This design is appropriate because the research aims to identify monitoring technologies and establish an integrated technological architecture for acquiring, transmitting, storing, and visualizing agricultural data. The main variables considered are soil pH and temperature, while electrical conductivity is included as an additional parameter when applicable. The proposed system aims to facilitate continuous monitoring and the interpretation of measurements in accordance with crop needs and soil characteristics.

Instruments and Data Analysis

The technological system incorporates an ESP32 microcontroller, a pH sensor, a waterproof DS18B20 temperature sensor, an electrical conductivity sensor compatible with liquid solutions, and an ambient humidity sensor when necessary. The electronic components are connected in accordance with their technical specifications. Additionally, the system includes provisions for verifying sensor operation and calibrating them using standard solutions or reference instruments, as appropriate.

The software architecture integrates an application programming interface (API), a PostgreSQL database, and a progressive web app (PWA). Each record is designed to include the sample ID, date, time, sensor ID, and the measured values obtained.

RESULTS AND DISCUSSION

A Progressive Web App (PWA) was developed to monitor soil pH and temperature in agricultural crops, using an architecture that integrates sensors, an ESP32 microcontroller, and an API for data transmission.

The application uses Next.js and TypeScript for the user interface, PostgreSQL with Neon for data storage, Prisma for data management, and Recharts for graphical visualization. It also incorporates authentication with NextAuth and password protection using bcrypt.

The system consists of six stages: data acquisition, transmission via IoT, reception by the API, validation, storage, and visualization on a dashboard. Its purpose is to facilitate the monitoring of soil conditions and support agricultural decision-making.

To evaluate its performance, four indicators were established: Sensor Integration, data transmission, log storage, general operation. The corresponding percentages must be obtained through experimental testing.

Table 5 Indicators for Evaluating System Performance

Indicator	Descripción	Forma de evaluación
Sensor Integration	Check the communication between the sensors and the ESP32.	Verification of readings from each sensor.
Data Transmission	Evaluation of data transmission from the ESP32 to the API.	Records sent and received successfully.
Record Storage	Verification that the measurement records have been saved in the database.	Comparison of generated and stored records.
Validity of Measurements	Evaluation of the agreement between the values obtained and those from reference instruments.	Comparison and Calculation of Measurement Error.
General Operation	Assessment of the performance of the various stages of the architecture.	Joint evaluation of acquisition, transmission, storage, and retrieval.

CONCLUSION

The development of an intelligent monitoring system based on IoT sensors, an ESP32 microcontroller, an application programming interface (API), and a Progressive Web App demonstrates a technically feasible and low-cost approach for the continuous characterization of fertilizers and biofertilizers. The systematic literature review confirmed that variables such as pH, temperature, and electrical conductivity are widely recognized as informative indicators of product quality and stability, yet most existing studies rely on laboratory equipment and discrete measurements. By integrating these variables into a connected architecture, the proposed system addresses a clear gap between conventional characterization methods and the need for real-time, field-accessible data.

The four-phase methodology enabled a coherent progression from evidence-based variable selection to architectural design, prototype construction, and experimental planning. The resulting architecture data acquisition with calibrated sensors, local processing and wireless transmission via ESP32, structured storage in PostgreSQL through an API, and visualization in a Progressive Web App provides a modular and expandable foundation. This design prioritizes accessibility and future scalability, allowing the later incorporation of additional sensors (for example, nutrient-specific probes) without requiring a complete system redesign.

Although the prototype remains in the development and presentation stage, the implemented components already verify the functional integration of hardware and software layers. The capacity to acquire, transmit, store, and display measurements of pH and temperature establishes a practical basis for generating historical records that can reveal trends in product behavior under different storage or dilution conditions. Classification thresholds defined for Ideal, Acceptable, and Not favorable states further translate raw sensor readings into interpretable information that can support agricultural decision-making.

Several limitations must be acknowledged. The current system has not yet undergone extensive field validation or long-term stability testing. Sensor calibration, measurement error relative to reference instruments, and the reliability of data transmission under variable connectivity conditions remain to be quantified. In addition, direct measurement of nutrients such as nitrogen, phosphorus, and potassium was intentionally deferred because of sensor complexity and cost; therefore, the present prototype provides only a partial physicochemical profile. Recommendations generated by the system will ultimately need to be contextualized with crop type, soil characteristics, and local agricultural conditions to avoid over-generalization.

In conclusion, the proposed IoT-API-PWA architecture constitutes a relevant contribution toward accessible precision agriculture. It offers a practical pathway to move from isolated laboratory analyses to continuous, low-cost monitoring of fertilizers and biofertilizers, with the potential to reduce soil degradation risks associated with improper application. Future work should prioritize rigorous calibration and validation of the sensors, evaluation of transmission and storage stability under real operating conditions, expansion of the variable set, and assessment of the system's usability and decision-support value for end users. By advancing these steps, the prototype can evolve from a functional demonstration into a reliable tool for sustainable fertilizer management.

REFERENCES

1. Cano-Hernández, M., Bennet-Eaton, A., Silva-Guerrero, E., Robles-González, S., Sainos-Aguirre, U., Castorena-García, H., Cano-Hernández, M., Bennet-Eaton, A., Silva-Guerrero, E., Robles-González, S., Sainos-Aguirre, U., & Castorena-García, H. (s. f.). Caracterización de bioles de la fermentación anaeróbica de excretas bovinas y porcinas. https://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S1405-31952016000400471
2. Creswell, J. W., & Creswell, J. D. (2018). Research design: Qualitative, quantitative, and mixed methods approaches (5th ed.). SAGE Publications.
3. Davis, F. D. (1989). Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology. MIS Quarterly, 13(3), 319-340. https://doi.org/10.2307/249008
4. FAO. (2020). The State of Food and Agriculture 2020: Overcoming water challenges in agriculture. Food and Agriculture Organization of the United Nations.
5. González-Márquez, L. C., Félix-Gastélum, R., Sandoval-Romero, J. A., Escobedo-Urías, D. C., & Longoria-Espinoza, R. M. (2021). Caracterización de biofertilizantes utilizados en el valle agrícola de Guasave, Sinaloa, México. Terra Latinoamericana, 39. https://doi.org/10.28940/terra.v39i0.859
6. Hartono, R., Yoeseph, N. M., Purnomo, F. A., Safi'ie, M. A., & Bawono, S. A. T. (2024). Portable internet of things-based soil nutrients monitoring for precision and efficient smart farming. Bulletin Of Electrical Engineering And Informatics, 13(5), 3326-3333. https://doi.org/10.11591/eei.v13i5.7928
7. Internet of Things Approach for Monitoring Agricultural Environmental Factors: A Systematic Review. (s. f.). https://fundacionkoinonia.com.ve/ojs/index.php/ingeniumetpotentia/article/view/4909/8162
8. Lim, Z., Mun, H. K., Low, J., Kwan, B., & Tan, C. (2024). A two-port microwave sensor for real-time liquid fertilizer concentration measurement system with Internet of Things. Computers And Electronics In Agriculture, 226, 109460. https://doi.org/10.1016/j.compag.2024.109460
9. Silava et al. (2024) Precision Fertilization: A critical review analysis on sensing technologies for nitrogen, phosphorous and potassium quantification. https://www.sciencedirect.com/science/article/abs/pii/S0168169924006112
10. Talaviya, T., Shah, D., Patel, N., Yagnik, H., & Shah, M. (2020). Implementation of artificial intelligence in agriculture for optimisation of irrigation and application of pesticides and herbicides. Artificial Intelligence In Agriculture, 4, 58-73. https://doi.org/10.1016/j.aiia.2020.04.002