



Implementation of an IoT-based system for cold chain monitoring in the land transportation of perishable agri-food products

Implementación de un sistema IOT para el monitoreo de la cadena de frío en el transporte terrestre de productos agroalimentarios perecederos

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Abstract

The land transport of perishable agri-food products is a critical link in preserving food quality and safety in Colombia. However, monitoring is predominantly manual and discontinuous, which hinders traceability and increases the risk of losses during transit. This study designed and implemented a low-cost IoT system prototype for the real-time capture and transmission of temperature, relative humidity, and geographic position during refrigerated land transport. Development was organized using the Scrum agile framework, structured into three four-week sprints. The prototype integrated an ESP32 microcontroller, a DHT22 sensor, a U-blox NEO-M8N GPS module, and the ThingSpeak platform as a cloud visualization channel. Five experimental trips were conducted between Villavicencio, Granada, Puerto López, and Restrepo, recording samples locally every 2 s and retransmitting data to the cloud every 60 s. The results showed a mean temperature of 24.20 °C (standard deviation: 9.54 °C; range: 39.70 °C) and mean relative humidity of 64.66% (standard deviation: 15.25%; range: 100%). These values were consistent with a warm, humid environment and confirmed the device's ability to record actual operating conditions. The system provides an operational technological foundation on which future research can evaluate adoption in commercial fleets and integration with active refrigeration systems.

Keywords: agriculture, efficiency, food safety, innovation, Internet of Things.

Resumen

El transporte terrestre de productos agroalimentarios perecederos constituye un eslabón crítico para preservar la calidad e inocuidad de los alimentos en Colombia; sin embargo, predomina el monitoreo manual y discontinuo, lo que dificulta la trazabilidad y aumenta el riesgo de pérdidas durante el trayecto. En este estudio se diseñó e implementó un prototipo de sistema IoT de bajo costo para la captura y transmisión en tiempo real de temperatura, humedad relativa y posición geográfica durante el transporte terrestre refrigerado. El desarrollo se organizó mediante el marco ágil Scrum estructurado en tres sprints de cuatro semanas cada uno. El prototipo integró un microcontrolador ESP32, un sensor DHT22, un módulo GPS Ublox NEO-M8N y la plataforma ThingSpeak como canal de visualización en la nube. Se realizaron cinco recorridos experimentales entre Villavicencio, Granada, Puerto López y Restrepo, registrando muestras cada 2s en almacenamiento local y retransmitiendo datos a la nube cada 60s. Los resultados mostraron una temperatura media de 24,20 °C (desviación estándar 9,54 °C; rango 39,70 °C) y una humedad relativa media de 64,66% (desviación estándar 15,25%; rango 100%), valores consistentes con un ambiente cálido y húmedo y confirmatorios de la capacidad del dispositivo para registrar condiciones reales de operación. El sistema constituye una base tecnológica operativa sobre la cual futuras investigaciones podrán evaluar su adopción en flotas comerciales y su integración con sistemas activos de refrigeración.

Palabras clave: agricultura, eficiencia, inocuidad alimentaria, innovación, Internet de las Cosas.



Introduction

Food safety and quality management throughout the supply chain are fundamental pillars of food industries worldwide. Within this context, the land transportation of refrigerated food is a critical link in the cold chain because temperature variations may arise during this stage and compromise product safety and quality. Inadequate monitoring of critical parameters such as temperature and humidity can lead to breaks in the cold chain, jeopardizing food safety, increasing the risk of foodborne illness, and causing significant economic losses for companies in the sector (Manosalva and Cangrejo, 2018).

In Colombia, technological limitations and the limited adoption of continuous monitoring systems remain persistent challenges for traceability in food transportation. Ineffective monitoring and noncompliance with regulatory standards can lead to sanctions, loss of consumer confidence, and deterioration of product quality. In response, Internet of Things (IoT) technology offers a viable and transformative alternative for strengthening traceability by enabling real-time monitoring of variables such as temperature, humidity, and the geographic position of products during transportation (Yue, 2011; Witjaksono, 2018).

The use of IoT in the cold chain provides valuable tools for collecting and analyzing data in real time, enabling proactive intervention when temperature deviations or refrigeration failures occur (Protopappas et al., 2025; Müller et al., 2026). According to Witjaksono (2018), proper implementation of these technologies not only improves forward traceability but also supports regulatory compliance and the protection of public health. Integrating IoT can therefore optimize logistics processes, reduce food waste, and strengthen consumer confidence in refrigerated products.

However, adopting these technologies entails technical, economic, and operational challenges. These include integrating IoT systems with existing infrastructure, managing large volumes of data, and meeting high initial installation and maintenance costs (Badía-Melis et al., 2018; Ammar et al., 2021). Despite these limitations, IoT offers important benefits, including precise monitoring of critical conditions and improved logistics efficiency, and it is also central to compliance with food-safety regulations (Mercier et al., 2017).

At the national level, Resolution 2674 of 2013 issued by the Ministry of Health and Social Protection establishes the

sanitary requirements applicable to the production, storage, transportation, and distribution of food intended for human consumption. It requires adequate hygiene, temperature control, and training for personnel involved in these processes (Ministry of Health and Social Protection, 2013). In addition, Colombian Technical Standard NTC-ISO 22005:2009 defines basic principles for the design and implementation of food traceability systems intended to ensure the identification, documentation, and communication of information throughout the supply chain (Instituto Colombiano de Normas Técnicas y Certificación [ICONTEC], 2009).

Despite this regulatory framework, the problem retains a considerable economic dimension nationwide. According to the National Planning Department (DNP) and the Food and Agriculture Organization of the United Nations (FAO), Colombia loses or wastes approximately 9.76 million metric tons of food each year, equivalent to 34% of the country's total production. The greatest losses occur in fruit and vegetable chains (62%) and root and tuber chains (25%), groups that are particularly sensitive to temperature variations during refrigerated transportation (DNP, 2019; FAO, 2019). Colombia's agricultural sector produces more than 25 million metric tons of perishable products annually, and FAO studies have indicated that in developing countries up to 40% of fresh food is lost before reaching the final consumer. Breaks in the cold chain during land transportation are one of the determining factors in these losses (FAO, 2019). The scale of the problem underscores the urgency of accessible monitoring solutions suited to the national context.

Recent literature confirms the potential of IoT in agri-food traceability. Vesga et al. (2023) highlighted the effectiveness of technologies such as RFID in cocoa traceability management, while Chaparro et al. (2021) demonstrated the use of remote terminal units (RTUs) to monitor agroindustrial processes through IoT networks. Manosalva and Cangrejo (2018) proposed an IoT technology architecture that improves logistics visibility by recording temperature, humidity, and location in real time. Pacheco da Costa et al. (2023) also emphasized how continuous monitoring technologies contribute to reducing food loss and waste, while Giraldo et al. (2021) demonstrated the impact of IoT on process optimization and cost reduction across industrial sectors.

Nevertheless, reported solutions have relevant limitations for adoption in Colombia. RFID systems such as the one proposed by Vesga et al. (2023) provide high traceability but involve substantial infrastructure costs that hinder scaling

among small and medium-sized carriers. The remote terminal units described by Chaparro et al. (2021) were designed for fixed agroindustrial processes and did not address the dynamic conditions of moving land transport. Although the architecture proposed by Manosalva and Cangrejo (2018) is conceptually similar to the present work, the study did not report field validation under actual transportation conditions or an economic-feasibility analysis supporting adoption. Likewise, commercially available solutions in Colombia based on data loggers or satellite telemetry systems commonly exceed the investment capacity of small and medium-sized carriers, which account for a considerable share of the country's perishable-food logistics operations.

Unlike the solutions described above, this work presents a low-cost IoT prototype experimentally validated under actual land-transportation conditions in the Department of Meta. It integrates temperature, humidity, and geolocation monitoring with an explicit analysis of technical and economic feasibility for adoption by perishable-food transport operators in Colombia. Accordingly, the study aimed to design and implement an IoT system for real-time cold-chain monitoring during land food transportation, thereby helping strengthen logistics management, operational efficiency, and food safety.

Materials and methods

The IoT system was developed using the Scrum agile framework, with the research structured into three four-week iterations, or sprints (figure 1). This approach enabled incremental delivery of results and continuous adjustment of the prototype in response to identified technical and regulatory requirements. Scrum facilitated ongoing collaboration and incremental delivery, allowing continuous monitoring and iterative adjustments during the design, development, implementation, and validation phases. The methodology was selected because of its effectiveness in managing deliverables in a controlled manner aligned with the project's specific objectives (Hernández-Salazar and Beltrán, 2020).

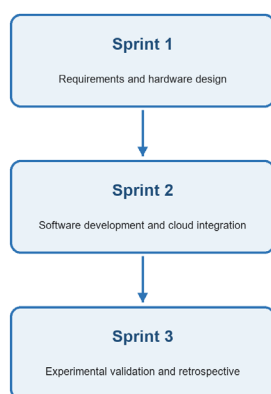


Figure 1. Visual diagram of the Scrum methodology used.

Sprint 1: requirements and hardware design

Objective: define the system architecture and select components compatible with transportation environments.

Deliverables: wiring diagram and functional prototype on a universal printed circuit board.

Acceptance criteria: the components (ESP32, DHT22, and NEO-M8N GPS) had to operate as an integrated unit powered by a 3.7 V source (18650 battery), ensuring efficient energy consumption and adequate system autonomy.

Retrospective: initial integration tests revealed that placing the DHT22 sensor on the breadboard close to other electronic components caused temperature-reading interference unrelated to actual environmental variations. As a corrective action, the sensor was moved farther from the other components and its wiring was adjusted, producing stable readings consistent with the subsequent calibration process.

Sprint 2: software development and cloud integration

Objective: program the logic for data capture, processing, and transmission.

Deliverables: Python source code and a configured thingspeak visualization channel.

Acceptance criteria: the system had to capture data every 60 seconds, store it locally in .csv format as a backup, and transmit it successfully to the cloud through HTTP GET requests. Exception-handling routines were included to reconnect automatically if the Wi-Fi signal was lost.

Retrospective: the first integration tests experienced intermittent Wi-Fi disconnections that interrupted data transmission to ThingSpeak. Corrective action consisted of implementing exception-handling routines (try-except) with automatic reconnection. When connectivity failed, the system retained a local backup in Datos.csv without losing records. This correction was validated through forced-disconnection tests before field deployment.

Sprint 3: experimental validation and retrospective

Objective: evaluate system performance under actual land-transportation conditions.

Deliverables: report on five experimental trips and a telemetry database.

Control mechanisms: after each trip, retrospective sessions were conducted to analyze connection stability and measurement variability. These reviews identified temperature fluctuations associated with exposing the sensor to external air currents. As a corrective action, the device was moved to the central area of the container to improve measurement representativeness. The sensitivity of the DHT22 to placement, initially identified during bench testing

in Sprint 1, prompted particular attention to this factor during field deployment and facilitated rapid identification and correction of exposure to air currents during Sprint 3.

Technical and regulatory requirements

The IoT system for cold-chain monitoring during the land transportation of refrigerated food was designed in accordance with the technical and regulatory requirements established in Resolution 2674 of 2013 and Colombian Technical Standard NTC-ISO 22005:2009, which are intended to protect product safety and traceability during transportation.

Within this context, the following fundamental requirements were established:

1. Continuous monitoring

The system was intended to safeguard refrigerated food throughout the trip by continuously monitoring environmental conditions. This requirement addressed Resolution 2674 of 2013, which requires ongoing temperature and humidity control during food transportation.

2. Accuracy and reliability

Recorded data had to be accurate and reliable in order to support informed decisions and compliance with quality and safety standards. This aspect falls within the good manufacturing practices defined by Resolution 2674 of 2013.

3. Wireless communication

The system had to transmit data in real time from vehicles to the IoT platform, enabling remote supervision and timely decision-making. This requirement is consistent with NTC-ISO 22005:2009, which emphasizes efficient communication throughout the supply chain for exchanging critical information.

4. Data storage and visualization

The collected information had to be stored securely and presented clearly and intuitively, thereby enabling analysis, anomaly detection, and traceability for each food lot. This requirement responded to the obligation in NTC-ISO 22005:2009 to maintain documentary records of product movement and handling.

5. System scalability

The system had to be adaptable to different types of vehicles and fleets so that it could be implemented at scale in the food-transport sector. This principle is also addressed in NTC-ISO

22005:2009, which defines requirements for designing and implementing traceability systems throughout the food chain.

Selection of materials and components

Materials and electronic components were selected through a technical analysis based on local availability, cost, performance, reliability, and compatibility with system requirements (table 1).

Table 1. Components evaluated for the cold-chain IoT system used in land food transportation.

Component	Alternatives evaluated	Evaluation criteria	Final selection	Rationale
Microcontroller	ESP32; Raspberry Pi Pico W; Arduino Yún	Performance, connectivity, energy use, and cost	ESP32 (ESP-WROOM-32)	Integrated Wi-Fi and Bluetooth, low energy use, and an appropriate cost-performance ratio for IoT applications
Temperature and humidity sensor	DHT22/ AM2302; SHT31-D; BME280; DS18B20	Accuracy, cost, and ease of integration	DHT22/ AM2302	Adequate accuracy for environmental monitoring at low cost and easy integration with the ESP32
GPS module	U-blox NEO-M8N; GY-NEO6MV2; Adafruit Ultimate GPS	Accuracy, compatibility, and energy use	U-blox NEO-M8N	Greater accuracy and support for multiple satellite positioning systems
Display	0.96-in OLED; 16×2 LCD; 1.8-in TFT	Energy use, visibility, and size	0.96-in OLED	Low energy use, high contrast, and easy integration through an I ² C interface
Power source	18650 battery; alkaline battery; NiMH battery	Autonomy, service life, and cost	18650 Li-ion battery	Higher energy density and better autonomy

IoT platform

ThingSpeak was selected as the data-management platform because of its ease of use, intuitive interface, and integrated visualization and analysis tools. The free version provides sufficient capacity for testing and prototyping. Although it offers less scalability than platforms such as AWS IoT or

Azure IoT Hub, its rapid implementation and low cost make it suitable for academic projects and technology pilots.

System design and prototype development

The system was assembled on a breadboard (universal PCB), integrating all the components described. The ESP32 processed sensor data and managed wireless communication with ThingSpeak, as shown in figure 2. The circuit included the system components listed in table 2.

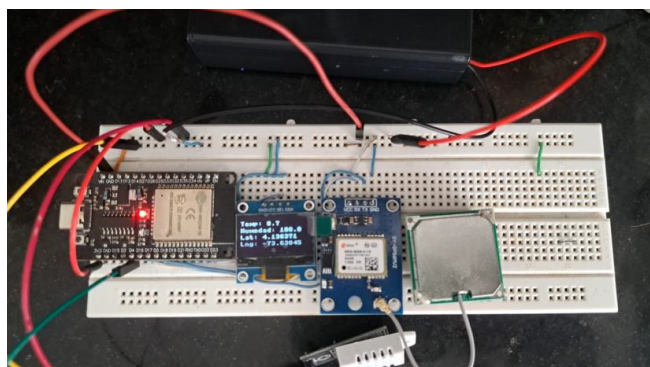


Figure 2. IoT breadboard assembly for the cold-chain system used in land food transportation.

Table 2. Components of the cold-chain IoT system used in land food transportation.

DHT22 sensor	U-blox NEO-M8N GPS module	0.96-in OLED display	Lithium battery
Measures temperature and humidity	Obtains geographic coordinates	Displays measurements in real time	Provides system autonomy

Software development

The software was developed in Python using the Thonny IDE. The code implemented sensor readings, data processing, and transmission to ThingSpeak over a Wi-Fi connection.

1. Initial configuration

The necessary libraries were imported, and the network credentials (SSID and password) and ThingSpeak API key were configured and stored in the secret.py file.

2. Data reading and visualization

The readGps() function continuously reads values from the DHT22 sensor (temperature and humidity) and GPS module (latitude and longitude). The data were displayed on the OLED screen to provide immediate feedback to the user.

3. Data Transmission

Every 60 seconds, the data were sent to ThingSpeak through an HTTP GET request. The device confirmed successful

transmission on the screen and stored a local copy in the Datos.csv file.

4. Error handling

The code included exception handling (try-except) for automatic reconnection if the Wi-Fi connection was lost or a sensor-reading error occurred.

Experimental validation and sensor calibration

Before the field tests, the DHT22 sensor was verified against a calibrated commercial digital thermohygrometer. Measurements were taken continuously for one hour, with data recorded every two seconds. The observed differences remained within the manufacturer's stated accuracy ranges ($\pm 0.5^{\circ}\text{C}$ for temperature and $\pm 2\%$ for relative humidity); the sensor was therefore considered suitable for experimental testing.

The U-blox NEO-M8N GPS module was validated by comparing recorded coordinates with geographic points previously identified using commercial mapping applications. Observed errors were less than 5 m under open-sky conditions.

The experimental trips were conducted under passive-transport conditions, that is, without an active refrigeration system in the container, to evaluate the prototype's capacity to capture and transmit critical environmental variables during transit. Integrating the system with active refrigeration equipment was identified as future work. Five experimental trips were conducted among the municipalities of Villavicencio, Granada, Puerto López, and Restrepo (Meta, Colombia). The device was placed in the center of the transport container, avoiding direct exposure to external air currents and metal surfaces that could alter the measurements.

The experimental trips transported meat and fish products (chicken and fish), selected as highly perishable, temperature-sensitive categories relevant to evaluating the system's ability to detect out-of-range conditions. Because the trials involved passive transport without active refrigeration, the purpose was to validate the prototype's technical capacity to monitor and transmit environmental variables in real time, not to assess or certify the safety of the products transported. Trip duration ranged from one to three hours, depending on the route and traffic conditions among the municipalities evaluated.

During each trip, temperature, relative humidity, latitude, and longitude were recorded automatically at two-second intervals. Data were simultaneously stored in local CSV files and transmitted to ThingSpeak for remote visualization. Functional validation was based on three criteria: (i) continuous data acquisition throughout the trip, (ii) successful transmission of information to the cloud platform, and (iii) local backup storage without loss of records.

Results and discussion

The IoT system designed for cold-chain monitoring during land food transportation underwent experimental testing to evaluate its performance under actual conditions. The tests verified device stability, real-time data transmission, and sensor accuracy during simulated transportation trips, as shown in figure 3.



Figure 3. Transport container used for the cold-chain IoT system during land food transportation.

Experimental configuration

The assembled prototype was first verified under controlled environmental conditions and then placed in a food-transport container to monitor internal conditions during actual trips (figure 4). Five trips were conducted among Villavicencio, Granada, Puerto López, and Restrepo (Meta, Colombia) on May 11 and 13 and June 1, 2, and 21, simulating typical refrigerated land-transport conditions.

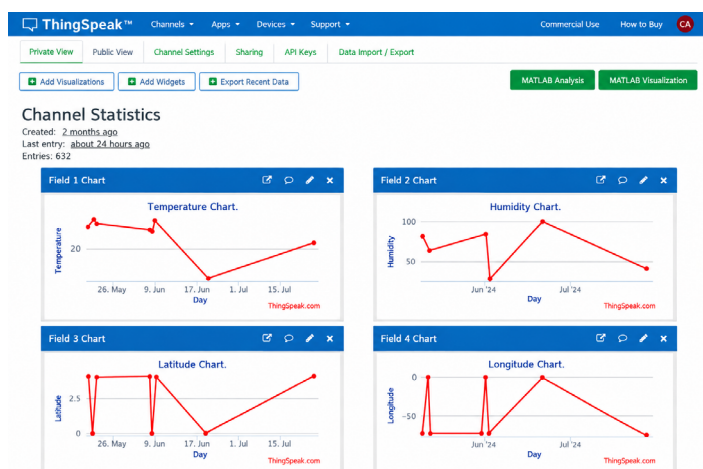


Figure 4. Publication of the cold-chain IoT system outputs on ThingSpeak.

During each trip, the system recorded temperature, humidity, and geographic-coordinate data, which were sent to ThingSpeak at one-minute intervals. Values were published in designated channels (Field 1: temperature; Field 2: humidity; Field 3: latitude; Field 4: longitude) and made publicly accessible through the platform.

Data collection and visualization

Real-time data transmission was validated using ThingSpeak visualization tools, which represent measurements through line graphs and geographic maps.

For detailed route analysis, the recorded coordinates were exported in .csv format and displayed in Google My Maps (figure 5), enabling the actual route to be compared with the temperature behavior observed during the trips.

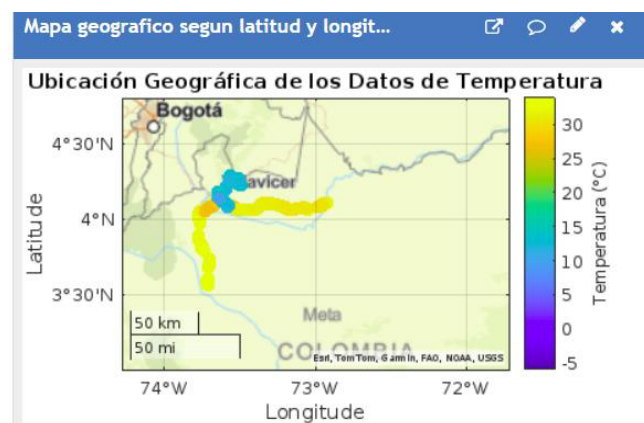


Figure 5. ThingSpeak geographic map of the cold-chain IoT system output during land food transportation.

Data stored on ThingSpeak were processed in Python to verify measurement consistency and stability. The results showed substantial variability in temperature, with a range of 39.70 °C, and in relative humidity, with a range of 100%. Mean temperature was 24.20 °C and mean humidity was 64.66%, reflecting the warm, humid environment typical of the Llanos foothills (figure 6). The standard deviations, 9.54 °C for temperature and 15.25% for humidity, indicated considerable fluctuations attributable to changes in sun exposure and ventilation during transit.

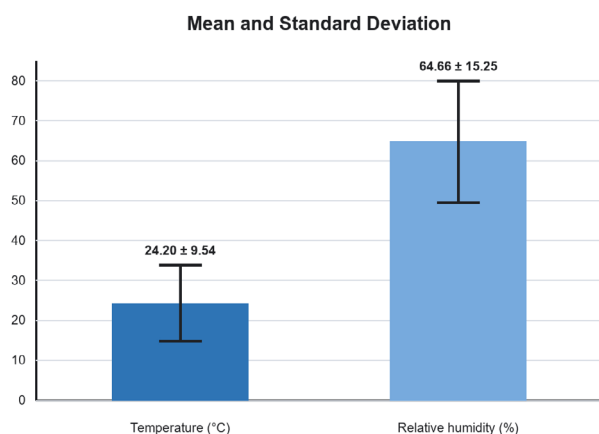


Figure 6. Mean and standard deviation of output data from the cold-chain IoT system used in land food transportation.

Correlation analysis showed a weak negative relationship (-0.12) between temperature and humidity, indicating that the two variables varied independently under the conditions evaluated. The linear regression model confirmed this relationship, explaining only 1.42% of temperature variability. This result suggested that, under land-transportation conditions, ambient humidity was not a determining predictor of thermal behavior inside the container. Taken together, the results validated the effectiveness of the IoT prototype for real-time monitoring of critical cold-chain variables, enabling remote supervision, geographic traceability, and identification of out-of-range conditions during food transportation.

Using meat and fish products under passive transport made it possible to observe actual high-risk temperature conditions, reinforcing the relevance of monitoring systems such as the proposed one. However, future studies should validate system performance when integrated with active refrigeration equipment, which is required for commercial transportation of these products under applicable regulations (Resolution 2674 of 2013). The sample of five trips represented an initial proof-of-concept validation; increasing the number of trips would improve the statistical robustness of the findings. Finally, the study did not empirically measure battery autonomy or systematically quantify the connectivity-loss rate during trips. Both aspects were identified as key metrics for future work assessing the system's operational scalability.

Regarding transmission reliability, intermittent connectivity losses occurred during some field trips, similar to those observed in Sprint 2 integration tests. In every case, the implemented automatic-reconnection mechanism restored transmission to ThingSpeak without loss of records because data were simultaneously backed up in a local CSV file.

Nevertheless, this study did not systematically quantify packet-loss rates or reconnection time. Future studies should explicitly incorporate this metric to evaluate system reliability under the variable-connectivity conditions characteristic of rural areas.

Comparison with recent international studies (table 3) contextualized the contributions and limitations of the prototype within current trends in IoT cold-chain monitoring. Consistent with Alshdadi et al. (2024), who examined warm, humid climatic conditions similar to those of the Llanos foothills, the low-cost microcontroller architecture with wireless connectivity and a cloud platform proved a viable, replicable alternative in resource-constrained settings. Unlike that study, whose validation used a mobile-phone simulation, the present work provides field evidence obtained under actual transportation conditions with real perishable products.

Table 3. Comparison with recent international studies of IoT cold-chain monitoring.

Study	Technology/ components	Validation context	Energy autonomy	Difference from the present study
Present study	ESP32, DHT22, NEO-M8N GPS, ThingSpeak (Wi-Fi)	Five actual trips; passive land transport (Meta, Colombia)	Not measured empirically	—
Alshdadi et al. (2024)	NodeMCU; temperature/humidity sensor; Wi-Fi + 4G/5G mobile network; RFID; GPS	Smartphone-based simulated test in Jeddah, Saudi Arabia; warm-humid climate similar to this study	Not reported	Validation was simulated rather than deployed in a vehicle; includes a cost analysis
Garrido-López et al. (2024)	Portable cellular-IoT data logger; temperature, humidity, CO ₂ , light, and vibration sensors	Laboratory tests and battery-autonomy testing	Empirically validated: up to one month	More sensors and formal validation of energy autonomy—the exact metric identified as a limitation here
Mohammed et al. (2022)	IoT control system for cold-storage rooms (not transport); temperature, humidity, CO ₂ , and ethylene sensors	Validated in fixed storage for dates, comparing a modified chamber with a conventional one	Not applicable (fixed mains power)	Fixed storage rather than moving transport; uses active refrigeration control, unlike passive transport here
Abiguru et al. (2026)	ESP32, DHT11, GPS, GSM module, ThingSpeak; includes gas and door-status sensors	Tests in “real-world situations”; limited methodological detail in the source	Not reported	Very similar ESP32 + ThingSpeak architecture, but adds SMS threshold alerts and does not report land transport validated with real products

The ESP32 and ThingSpeak architecture reported by Abiguru et al. (2025) was also largely consistent with the present system, suggesting that this technological combination is an established, readily replicable solution for monitoring

environmental variables in the cold chain. Both systems nevertheless share opportunities for improvement, including automatic threshold alerts and additional sensors for gas, vibration, and door status.

A relevant finding from this comparison was the absence of empirical validation of system energy autonomy in the present study. Garrido-López et al. (2024) addressed this aspect rigorously, reporting up to one month of autonomy in their cellular data logger through energy-consumption optimization strategies. This comparison reinforces the limitation already identified and indicates a specific direction for future research: formal characterization of energy consumption under actual, prolonged operating conditions. Finally, comparison with the system developed by Mohammed et al. (2022), which was designed for fixed storage with active refrigeration, clarifies the scope of the present study. Their system operates under controlled conditions with a continuous power supply, whereas the present prototype was validated in the more demanding scenario of moving land transport, powered autonomously by a battery and without active refrigeration. This difference represents a contribution in terms of practical applicability for perishable-food carriers in Colombia.

An Internet of Things (IoT)-based monitoring-system prototype was developed and implemented to track critical environmental variables during the land transportation of perishable food in Colombia. The results confirm the technical feasibility of the proposal under actual operating conditions and its potential to help strengthen food traceability in the country.

The system, consisting of temperature, humidity, and geolocation sensors integrated with an ESP32 microcontroller and connected to ThingSpeak, performed stably during the five field trips. It transmitted and displayed data in real time, even when connectivity was intermittently lost, owing to the automatic-reconnection mechanism. The modular, low-cost architecture is compatible with the general provisions of Resolution 2674 of 2013 and NTC-ISO 22005:2009 concerning continuous monitoring, communication, and traceability. However, adopting it as a formal regulatory-compliance tool would require additional validation and certification processes beyond the scope of this work.

Experimental analysis showed that the system can continuously capture and transmit environmental conditions during transit, enabling relevant temperature and humidity variations to be identified for logistics decision-making. The tests were conducted under passive-transport conditions without active refrigeration and used meat and fish products. The results therefore demonstrate the prototype's monitoring capacity but do not, in themselves, constitute evidence guaranteeing food safety during the trials.

Conclusion

The developed prototype provides an accessible and technically viable technological basis for monitoring critical variables during the land transportation of perishable food in Colombia. Its adoption, together with future integration into active refrigeration systems, validation across more trips and seasonal conditions, and empirical quantification of energy autonomy and connectivity reliability, could help strengthen operational efficiency and traceability in Colombia's agri-food sector. Developing local, affordable solutions adapted to the national context represents a relevant step toward the technological modernization of perishable-food transportation in the country.

Conflict of interest

The authors declare that they had no conflicts of interest at any stage of this publication.

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CRediT author contribution statement

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