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Research paper

LoRaWAN-Based Asset Tracking System Development and Performance Analysis within STEM-PBL Framework: A Mixed-Method Study

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ABSTRACT

This study examines the integration of project-based learning (PBL) within the integrative STEM framework to advance practical problem-solving skills and investigate students' perceptions of the STEM-PBL approach through developing an IoT-enabled asset tracking system using Long-Range Wide Area Network (LoRaWAN) technology to tackle real-world logistical challenges. Adopting a mixed-methods approach, the study combines an experimental approach utilizing quantitative system performance analysis with qualitative insights gathered through participant interviews with ten graduate students. Results reveal that the LoRaWAN system demonstrated high reliability with only 0.437% downtime, validating the technical feasibility of the educational project. Furthermore, participants perceived the STEM-PBL approach positively, with 78% of responses showing satisfaction with hands-on, inquiry-based learning strategies. Thematic analysis identified eight main themes, including enhanced learning strategies, practical skills development, 21st-century skills, and authentic assessment. Despite its successes, the project identified challenges such as resource constraints and initial technical hurdles. This study highlights the effectiveness of integrating IoT technologies with STEM-PBL methodologies in developing students' technical competencies while fostering innovation and teamwork skills essential for 21st-century careers.

Keywords: STEM education, project-based learning, LoRaWAN technology, student perceptions, IoT integration, mixed-methods approach

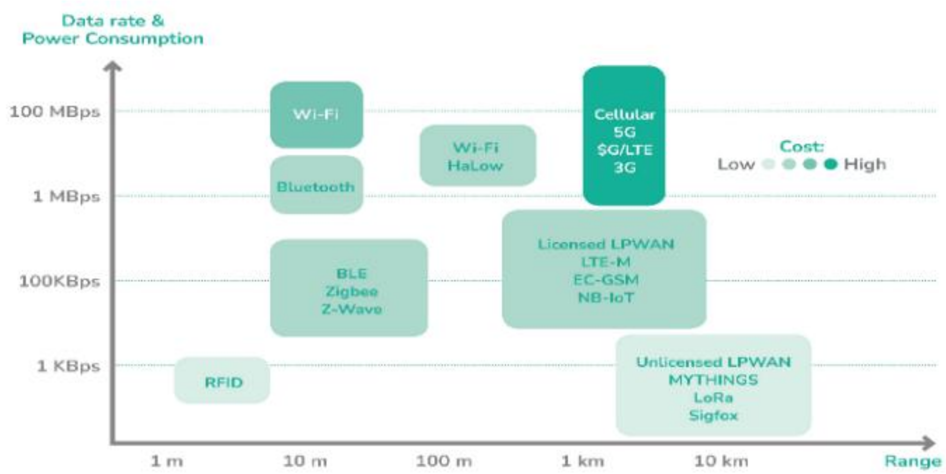
The integration of sustainable technology (T) and engineering (E) into education can empower students' enthusiasm for studying science (S) and mathematics (M) while enhancing their academic performance and environmental awareness. Effective integration of technologies allows educators to simulate real-life situations that promote environmental sustainability, nurturing and engaging students' mindsets toward science, technology, engineering, and mathematics (STEM) within a sustainability framework (Clark & Button, 2011; Rogers et al., 2015; Ruamcharoen et al., 2021; Smith & Watson, 2019; Turner et al., 2022; Grewe, 2025). However, while STEM education has made strides in many areas, there remains a gap in empirical studies that explore how emerging sustainable technologies - such as Internet of Things (IoT)- can be used within a project-based learning (PBL) framework to solve real-world problems while minimizing environmental impact (Ruamcharoen et al., 2021).

In this study, the technology employed includes Long-Range Radio (LoRa) combined with Arduino, sensors, and an IoT tracking application within a PBL STEM integrative approach to enhance problem-solving and foster creativity and innovation. When these methodologies are implemented in engineering courses, they provide a robust foundation for practical, hands-on learning, which in turn embraces an environment that promote meaningful learning (Alfarraj et al., 2025; Clark & Button, 2011; Rogers et al., 2015; Ruamcharoen et al., 2021; Sagala et al., 2022; Smith & Watson, 2019; Turner et al., 2022).

IoT has gained significant attention in various fields, including education, agriculture, healthcare, asset tracking, and smart cities. Originally employed in the shipping industry to locate vessels in the absence of internet signals, vessel tracking systems have evolved with technological progress and are now capable of being integrated with sensors and communication systems. Nevertheless, the constraints on communication range, as depicted in Figure 1, highlight the trade-offs between range, power consumption, and data rate for various IoT communication technologies. Wi-Fi and Bluetooth, for example, offer higher data rates but are limited in range, making them unsuitable for large-scale or remote tracking applications. Similarly, RFID requires proximity to readers, while BLE provides an extended range but at the cost of higher power consumption. Consequently, the Global System for Mobile Communication (GSM) is often employed to ensure broad coverage in areas with reliable connectivity. However, even GSM-based systems face challenges in tracking vessels in specific lake areas or remote locations due to signal loss (Sagala et al., 2022). These constraints highlight the importance of developing reliable, cost-effective tracking solutions such as LoRaWAN.

Figure 1

Comparison of IoT Wireless Communication Technologies



With the substantial volume of ton-kilometers being transported globally, there is a growing demand for asset tracking, particularly in the logistics and shipping industries. This demand is driven by the necessity of monitoring small-scale assets such as packages, equipment, and vehicles across international borders (Semtech Corporation, 2025). LoRaWAN, as a Low Power Wide Area Network (LPWAN) standard, offers significant advantages for IoT applications. It combines low power consumption, long-range communication, and adaptability, making it suitable for environments requiring cost-effective and wide-ranging coverage. LoRaWAN can cover distances of up to 5 km in urban areas, making it an excellent choice for smart cities and industrial applications. Compared to alternatives like 5G and Sigfox, LoRaWAN's low operational costs and bidirectional communication capabilities make it ideal for large-scale IoT deployments (Povalac et al., 2023).

Sustainability in IoT and Green Technology Education

The concept of sustainable development has become increasingly important in educational practices, particularly in STEM fields where technological solutions must balance functionality with environmental responsibility. Green IoT technologies, characterized by energy-efficient communication protocols and minimal environmental footprint, represent a paradigm shift toward sustainable technological solutions. LoRaWAN technology exemplifies this approach through its ultra-low power consumption (Mhatre & Lee, 2022), extended battery life, and reduced electronic waste generation compared to traditional cellular-based tracking systems.

Sustainability in STEM education encompasses three key dimensions: environmental sustainability through the use of eco-friendly technologies (Buriro et al., 2023), economic sustainability (Walker & Zhu, 2013) through cost-effective solutions, and social sustainability through inclusive educational practices (Clark & Button, 2011; Bicer et al., 2020) that prepare students for environmentally conscious careers. The integration of sustainable technologies in educational settings not only teaches students about environmental stewardship but also demonstrates practical applications of green engineering principles.

Conceptual Framework for STEM

STEM education, enriched with PBL, encourages students to explore, analyze, ideate, and work collaborative skills essential for addressing today's complex technological challenges. Through open-ended problem-solving strategies, students strengthen their understanding of STEM concepts while developing critical skills in communication, project management, and resourcefulness. These competencies are crucial for driving the knowledge economy and fostering national development (Walker & Zhu, 2013). In this study, these principles are applied through the development of an IoT-based tracking system.

The integration of IoT-LoRaWAN technology into the STEM-PBL framework provides students with a unique opportunity to explore technical concepts while solving real-world problems. LoRaWAN's capacity for long-range communication, low power consumption, and cost-effectiveness makes it ideal for demonstrating practical applications of STEM concepts. This mirrors the iterative and collaborative strategies required to resolve real-world issues (Tsai et al., 2023; Dalle et al., 2021).

Project-based learning (PBL) acts as a catalyst for enhancing students' comprehension of STEM concepts. Unlike traditional lecture-based methods, PBL encourages active participation, where students tackle open-ended, real-world problems (Capraro & Slough, 2013). For instance, in developing the LoRaWAN tracking system, students engaged in research, tested solutions, and collaborated to refine their ideas. This iterative cycle fosters a deeper understanding of STEM principles while cultivating essential skills such as critical thinking, innovation, and adaptability (Kelley & Knowles, 2016).

In this study, we adopted a graphical conceptual framework for integrated STEM education (Kelley & Knowles, 2016). This framework employs a block-and-tackle system with four pulleys as a metaphorical representation, interlinking elements such as STEM-situated learning, engineering design, scientific inquiry, technological literacy, and mathematical thinking. These components represent various aspects of STEM education and are connected by the concept of a community of practice. Situated learning, a key component, refers to fostering learning within real-life contexts, emphasizing problem-solving and practical applications.

Engineering Design: A Foundation for Meaningful Learning

The Engineering Design Process (EDP) is a vital component of STEM education, bridging the gap between theoretical knowledge and real-world application, which enables scientists and mathematicians to transfer theories into tangible products. EDP follows a cyclical (DiFrancesca et al., 2014), iterative approach that involves defining problems, exploring solutions, designing, testing, and refining. Within the context of STEM-PBL, EDP provides students with an opportunity to deeply engage in practical problem-solving while honing critical thinking, teamwork, and innovation skills (DiFrancesca et al., 2014; Memić et al., 2022; Wicke & Nelson, 2021; Halpern et al., 2025).

In this study, EDP was applied to develop a real-time asset-tracking system using IoT LoRaWAN technology. This project exemplifies how EDP enables students to grasp technical concepts, such as long-range communication protocols, while cultivating the critical thinking required to address complex challenges. The iterative nature of EDP—where students refine and test their designs—parallels the problem-solving processes used in industrial and professional settings (Buriro et al., 2023).

LITERATURE REVIEW: SUSTAINABILITY IN IoT AND STEM EDUCATION

Green IoT Technologies and Environmental Benefits

The rapid proliferation of IoT devices has raised significant environmental concerns, leading to the development of green IoT technologies that prioritize sustainability (Memić et al., 2022). Green IoT encompasses energy-efficient communication protocols, sustainable manufacturing practices, and end-of-life device management strategies. Research by Kumar et al. (2021) demonstrates that LoRaWAN-based systems consume 90% less energy compared to cellular IoT solutions, significantly reducing their carbon footprint.

Studies have shown that implementing green IoT technologies in educational settings can reduce energy consumption by up to 60% while maintaining comparable performance levels (Ortiz et al., 2021). This energy efficiency directly translates to reduced greenhouse gas emissions and lower operational costs, making sustainable IoT solutions both environmentally and economically viable.

Sustainability Integration in STEM Education

The integration of sustainability principles into STEM education has gained momentum as educators recognize the importance of preparing students for environmentally conscious careers (Pham & Ehsan, 2020). Research indicates that students who engage with sustainability-focused STEM projects demonstrate increased environmental awareness and are more likely to pursue careers in green technology sectors (Jensen et al., 2021).

Project-based learning approaches that incorporate sustainability themes have been shown to enhance student motivation and engagement while developing critical thinking skills related to environmental problem-solving (Nguyen et al., 2020). Furthermore, interdisciplinary projects that combine technical skills with environmental consciousness prepare students for the complex challenges of sustainable development.

Environmental Impact Assessment of IoT Systems

Life cycle assessment (LCA) studies of IoT systems reveal that communication technology choice significantly impacts environmental sustainability (Bonvoisin et al., 2016). LoRaWAN systems demonstrate superior environmental performance across multiple metrics:

- Manufacturing Impact: Reduced component complexity and longer device lifespans
- Operational Impact: Ultra-low power consumption extending battery life to 10+ years
- End-of-Life Impact: Simplified device architecture facilitating recycling and material recovery

Research by Zhang et al. (2022) found that LoRaWAN deployments generate 75% less electronic waste compared to equivalent cellular IoT networks over a 10-year operational period (Memić et al., 2022).

RATIONALE AND QUESTIONS

The research problem centers on the scarcity of studies focused on designing and developing tracking systems using IoT LoRaWAN technology within the Project-Based Learning PBL-STEM framework (Adelantado et al., 2017; Hayati et al., 2024). Despite the growing recognition of the importance of integrating technology into education, comprehensive research is lacking on how IoT solutions can enhance the PBL experience by providing real-time tracking and feedback. Additionally, understanding participants' perceptions of how STEM integration facilitates solving real-world problems is crucial (Al Yahya et al., 2021).

This study aims to address these gaps by investigating the design and implementation of a LoRaWAN-based tracking system while capturing graduate students' perceptions regarding the effectiveness of STEM-PBL in addressing authentic challenges. By doing so, this research seeks to contribute valuable insights into the role of IoT in enhancing STEM education and promoting problem-solving skills in real-world contexts.

Research Questions

The study is guided by the main question and a set of sub-questions that explore the research objectives:

Main Question

- What are graduate students' perceptions of the STEM-PBL approach following their work on an IoT LoRaWAN-based tracking system project?

Sub-Questions

Quantitative Questions

- How do participants implement and develop a real-time tracking system using LoRaWAN and IoT technologies?
- How much downtime does the IoT LoRaWAN-based system experience during real-world use, measured as a percentage of total operational time?

Qualitative Questions

- How do participants perceive the process of developing a tracking system based on the STEM framework in a project-based learning (PBL) setting?

Significance of study

This study holds significant value in advancing both sustainable educational practices and green industrial applications by integrating the STEM-PBL framework with sustainable IoT LoRaWAN technology. It addresses a notable gap in the literature by exploring how emerging green technologies can be utilized within project-based learning (PBL) to solve real-world problems while promoting environmental sustainability. By doing so, it contributes to enhancing pedagogical approaches in STEM education, particularly in fostering 21st century skills, environmental consciousness, and sustainable problem-solving among students.

Through hands-on projects that simulate real-world sustainability challenges, the research demonstrates the effectiveness of STEM-PBL in cultivating essential 21st-century skills alongside environmental stewardship. These competencies, including collaboration, adaptability, technical proficiency, and sustainable thinking, are crucial for preparing environmentally conscious graduates who can address the dual challenges of technological advancement and environmental protection.

The study's practical focus on developing a sustainable IoT-based asset-tracking system underscores its direct relevance to green industrial needs and circular economy principles. The LoRaWAN system's ultra-low power consumption (enabling 10+ year battery life), minimal electronic waste generation, and reduced carbon footprint demonstrate significant environmental benefits compared to traditional tracking solutions. These findings reveal that sustainable technology integration not only enhances technical competencies but also develops students' capacity to design environmentally responsible solutions.

The broader implications extend to supporting the United Nations Sustainable Development Goals (SDGs), particularly SDG 4 (Quality Education), SDG 9 (Industry, Innovation and Infrastructure), and SDG 11 (Sustainable Cities and Communities). By demonstrating that green IoT technologies can achieve superior performance while minimizing environmental impact, this study provides a replicable model for sustainable STEM education and environmentally conscious industrial applications.

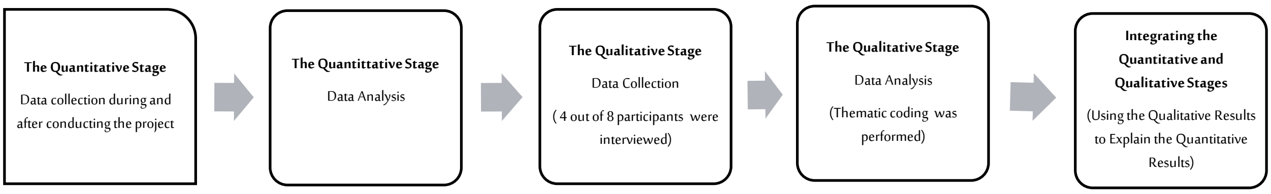
In conclusion, this study contributes to the advancement of sustainable educational methodologies while supporting the transition toward a green economy. The alignment of technical innovation with environmental responsibility demonstrates that sustainability and technological advancement are not only compatible but mutually reinforcing, preparing students to become leaders in the emerging green technology sector.

METHODOLOGY

We adopted a mixed-methods approach that incorporates both quantitative and qualitative data collection and analysis. This approach, increasingly acknowledged in recent studies, aims to provide a comprehensive understanding of the research problem Creswell & Creswell, 2017). By integrating quantitative and qualitative data, the mixed-methods approach enables researchers to explore diverse perspectives and uncover connections among the complex facets of research questions (Fàbregues et al., 2023) and provides a deeper meaning of the phenomenon (McKim, 2017). This process is illustrated in **Figure 2.**

Figure 2

Research Methodology



Quantitative Stage

In the first stage, students conducted real-life experiments using LoRaWAN technology to develop an IoT-based tracking system. The system was built using LoRaWAN gateways and nodes, with tracking devices that included GPS modules for asset location tracking. A Raspberry Pi 3B+ and ESP8266 served as control units, processing data collected from the devices.

The Things Network (TTN) was utilized for seamless communication between the LoRa nodes and the cloud. Data storage and visualization were managed using Google Cloud IoT, enabling real-time monitoring of assets. Python scripts and libraries, such as Pandas and NumPy, were employed to analyze the system's performance, focusing on metrics like downtime and data reliability. Microcontroller programming was conducted using Arduino IDE and Visual Studio Code to integrate sensors and LoRa communication protocols effectively. To ensure energy efficiency and long-term operation in real-world environments, the system was powered by lithium-polymer batteries.

RSSI Prediction Using Machine Learning

The prediction of missing RSSI values was conducted using a machine learning framework. LightGBM was chosen due to its efficiency and ability to capture non-linear patterns in the data (Nguyen et al., 2020). The model was trained using the dataset's features, including GPS coordinates, altitude, and timestamp, with hyperparameter tuning applied to maximize prediction accuracy. The introduction of predicted RSSI values addressed the dataset's incompleteness and strengthened the overall analysis.

Qualitative Stage

The second stage aimed to gather qualitative data to understand participants' perceptions of integrating STEM with LoRaWAN technology (Creswell, 2013; Nguyen et al., 2020). Data collection methods included:

- Interviews: Conducted with sample 10 out of twenty-eight participants to gain in-depth insights into their experiences and challenges during the project.
- Document Analysis: Evaluated project artifacts and reports to identify patterns in the application of STEM principles.
- Observations: Focused on sample of participants' interactions, problem-solving processes, and engagement during project activities.

Thematic coding was performed to analyze qualitative data, identifying key themes such as teamwork, innovation, and problem-solving. These themes provided a deeper understanding of how STEM-PBL methodologies influenced students' learning experiences.

Integration of Quantitative and Qualitative Stages

In the final stage, the results from the quantitative and qualitative phases were synthesized to provide a holistic understanding of the research questions. The qualitative results were used to explain and contextualize the quantitative findings, enabling a richer interpretation of the study outcomes (McKim, 2017). For instance, qualitative insights into students' problem-solving strategies were mapped against the technical performance of the IoT tracking system, highlighting the interplay between technical competencies and teamwork.

Study instruments

Quantitative instruments

The quantitative data was collected through the performance metrics of the LoRaWAN-based tracking system during the testing phase. The primary data points included the system's operational time, speed, downtime, and reliability. These metrics were captured automatically through hardware and software tools, enabling precise analysis of the system's performance in real-world scenarios.

The system testing process was conducted in two phases:

- Phase 1 (Pre-IRB Testing): Conducted by the main authors during August 2023 as part of the technical development and evaluation of the IoT LoRaWAN-based tracking system. This phase focused on ensuring the system's reliability and functionality prior to participant involvement.
- Phase 2 (Post-IRB Testing): Conducted by a larger participant sample after Institutional Review Board (IRB) approval on 01/10/2023. This phase involved 10 participants out of 28 testing the system and providing feedback, contributing to both the quantitative and qualitative components of the study. Participants sample evaluated the system's usability within the STEM-PBL framework.

LoRaWAN Devices

The study employed LoRa-enabled GPS modules and Arduino microcontrollers to collect data on the system's real-time location and speed. The GPS modules were configured to transmit location data, which was processed through a LoRaWAN gateway to enable long-range communication. The devices were powered by lithium-polymer batteries, ensuring energy-efficient operation in real-world conditions.

Qualitative instruments

To gather qualitative data, we conducted narrative interviews, observations, and document analysis. These methods were designed to explore participants sample' perceptions of implementing the STEM framework while deploying the IoT LoRaWAN-based tracking system. Narrative interviews were selected as the primary method because they emphasize participants sample' experiences and make them the central focus of the study (Bonvoisin et al., 2016).

Interviews

The interviews were conducted by the project supervisor and involved 10 participants. Open-ended questions were used to elicit detailed responses on topics such as (Creswell & Creswell, 2017):

- Learning strategies utilized during the project.
- Roles and contributions to the project.
- Skills developed through the project.
- Challenges encountered and strategies used to overcome them.

Observations

During the testing and implementation phases, observations focused on 10 participants' problem-solving processes, collaboration, and engagement in the STEM-PBL framework.

Document Analysis

Artifacts such as project plans, logs, and reports were analyzed to identify patterns in how 10 participants applied STEM principles and interacted with the LoRaWAN-based system.

Ethical Considerations

The ethical component of this study adhered to rigorous standards to protect participants' rights and ensure compliance with institutional guidelines. The quantitative phase, which involved system testing conducted by the main authors, was completed prior to participant recruitment in August 2023 and did not involve any participants.

For the qualitative phase, ethical approval was obtained from the Institutional Review Board (IRB) of King Saud University on 1 October 2023. Recruitment and data collection occurred between 01/10/2023 and 18/06/2024. Verbally informed consent was obtained from all participants before participation. The consent process included:

- Explaining the study's objectives.
- Clarifying the 10 participants' rights, such as the right to withdraw at any time.
- Highlighting the voluntary nature of participation.

Verbal consent was documented via audio recordings and witnessed by the second researcher. The consent procedure, including the documentation method, was reviewed and approved by the IRB, as outlined in the attached ethics approval letter. Furthermore, no identifiable or sensitive data was collected to ensure participant confidentiality and privacy.

Participants

The study was conducted with a total cohort of 28 students, representing diverse academic backgrounds, who participated in the larger STEM-PBL project. From this cohort, ten participants were purposively selected for this study. This approach ensured that the 10 participants reflected a range of experiences, academic disciplines, and levels of engagement throughout the project, thus capturing a comprehensive set of insights relevant to the implementation of STEM-PBL and IoT technologies (Creswell, 2013). The purposive sampling method allowed us to focus on participants who had significant contributions to various aspects of the project. While this sample size represents 35.7% of the total cohort, it was sufficient for in-depth qualitative analysis, which aligns with the objectives of this mixed-methods research. The 10 participants came from different engineering majors and management sciences, showcasing the multidisciplinary nature of the project. Table 1 provides detailed information about the selected 10 participants:

Table 1

Participants Details

Student	Major	Gender	Level	Contribution
A	Electronics and Communications Engineering	Male	Fourth	Hardware Design and Assembly
B	Electronics and Communications Engineering	Male	Fourth	System Testing
C	Management Sciences	Male	Third	Coding
D	Mechatronics Engineering	Male	Second	3D Printing
E	Computer Engineering	Female	Fourth	Microcontroller Programming
F	Computer Engineering	Male	Fourth	Software Integration
G	Electronics and Communications Engineering	Female	Third	Data Analysis
H	Mechatronics Engineering	Female	Third	Prototyping
I	Management Sciences	Male	Second	Documentation and Reporting
J	Electronics and Communications Engineering	Female	Fourth	Testing and Optimization

By selecting participants from different academic disciplines, this study was able to explore how the integration of STEM-PBL with IoT technologies fosters collaborative learning and problem-solving in an interdisciplinary environment. Engineering students contributed to technical tasks such as hardware design, microcontroller programming, and system testing, while management sciences students focused on documentation and project coordination. This carefully chosen sample highlights the importance of multidisciplinary collaboration in tackling real-world problems, reflecting the broader goals of the STEM-PBL framework.

The ten interviewees were purposively selected to represent diverse academic majors and functional roles within the project, including hardware design, coding, testing, and data analysis.

DATA ANALYSIS

The data analysis process involved distinct methods for the quantitative and qualitative components of the study. This mixed-methods approach allowed us to evaluate both the technical performance of the IoT LoRaWAN-based tracking system and the 10 participants' experiences with the STEM-PBL framework. The integration of these analyses provided a comprehensive understanding of the research questions.

Quantitative Analysis

The quantitative data collected from the LoRaWAN-based system were analyzed to evaluate its performance in real-world scenarios. Key performance metrics included:

- Operational Time: The total time the system was functional and transmitting data.
- Downtime: The time periods when the system was not operational, caused by delays in GPS fixes or LoRa module latency.
- System Reliability: Measured as the percentage of operational time relative to total time.
- Missing RSSI Data: During the data analysis, it was observed that some instances in the dataset lacked RSSI (Received Signal Strength Indicator) values as shown in **Figure 3.** RSSI is a critical metric in evaluating the performance of LoRaWAN-based systems, as it provides insights into signal quality, reliability, and coverage. The absence of these values in parts of the dataset presented a challenge in assessing the system's behavior across varying environmental conditions.

Figure 3

Sample of the data collected features

Date	Latitude	Longitude	Speed	Satellites	Altitude	GPS Time	GPS Date	RSSI	Trip
8/27/2023	29.957344	30.956099	2.35	9	219.9	13104400	270823		4
8/27/2023	29.957507	30.956154	0.78	9	218.6	13105200	270823		4
10/16/2023	29.980759	31.233474	0.61	0	23	16303500	161023	-157	5
10/16/2023	29.980733	31.233406	3.43	4	23.3	16303600	161023	-157	5
10/16/2023	29.980727	31.233385	4.33	4	23.3	16303700	161023	-157	5
10/16/2023	29.980665	31.233397	8.52	4	23.6	16303800	161023	-157	5
10/16/2023	29.980668	31.233395	6.17	4	23.8	16303900	161023	-157	5
10/16/2023	29.980692	31.233392	5.52	4	28	16304100	161023	-157	5
10/16/2023	29.98069	31.233394	5.89	4	28.6	16304200	161023	-157	5
10/16/2023	29.980685	31.233396	4.7	4	28.9	16304300	161023	-157	5
10/16/2023	29.980694	31.233387	3.63	4	30	16304400	161023	-157	5
10/16/2023	29.980698	31.233384	3.83	4	30.5	16304500	161023	-157	5
10/16/2023	29.980692	31.233326	10.43	4	34.4	16304700	161023	-157	5
10/16/2023	29.980696	31.233305	7.46	4	35.9	16304800	161023	-157	5
10/16/2023	29.980705	31.233294	5.22	4	37	16304900	161023	-157	5
10/16/2023	29.980737	31.233487	2.33	4	29.6	16301900	161023	-157	5

Data Collection and Processing

The system automatically recorded raw data, including timestamps, GPS coordinates, speed, and signal strength, into Google Sheets for analysis. A custom Python script was used to:

Calculate Operational Time: Derived from the difference between the first and last timestamps.

Identify Downtime: Based on delays caused by the Neo-6M GPS module acquiring a fix and LoRaWAN transmission latency.

Compute Downtime Percentage: Using equation (1)

$$\text{Downtime Percentage} = \frac{\text{Total Downtime}}{\text{Total Operational Time}} * 100\ \% \qquad (1)$$

For example, in one trial conducted on 27th August 2023:

- Total operational time: 458 seconds.
- Total downtime: Approximately 2 seconds (including GPS fix and LoRa latency).
- Downtime percentage: 0.437%.

This high level of operational reliability demonstrates the effectiveness of the system in real-world applications.

Addressing Missing RSSI Data with Machine Learning

To address the missing RSSI values, a machine learning-based prediction model was developed using LightGBM, a gradient boosting framework known for its efficiency and ability to capture non-linear relationships. Features such as GPS coordinates, altitude, and timestamps were utilized to predict RSSI with accurate prediction. Hyperparameter tuning was employed to optimize model performance, ensuring reliable predictions.

The model's predictions filled the gaps in the dataset, enabling a more comprehensive analysis of the LoRaWAN system's performance. For example, the predicted RSSI values allowed the evaluation of signal quality across different locations, providing deeper insights into the system's reliability and coverage.

To address this issue, we developed a machine learning-based predictive model. The LightGBM model, known for its efficiency and capability to handle non-linear relationships, was employed to predict missing RSSI values. Key features used for training the model included GPS coordinates, altitude, and timestamps.

Model Training and Validation:

Hyperparameter tuning was applied to optimize the LightGBM model, ensuring robust performance.

The model was evaluated using three performance metrics: Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), and R-squared (R^2).

Qualitative Analysis

The qualitative data, gathered through narrative interviews, observations, and document analysis, were analyzed to understand participants' perceptions of the STEM-PBL framework and its integration with LoRaWAN technology.

Thematic Analysis

Using an inductive approach (Creswell & Creswell, 2017, we systematically coded the data to derive theoretical concepts and themes. The process involved:

- Open Coding: Breaking the data into smaller units to identify patterns.
- Axial Coding: Categorizing related codes into themes and subthemes.
- Selective Coding: Refining themes and integrating them into a cohesive narrative.

Emerging Themes

The analysis yielded eight main themes and 36 subthemes, as will be discussed in the upcoming section.

Interrater Reliability

To ensure the robustness of the qualitative analysis, interrater reliability (Gisev et al., 2013) was calculated at 91%, indicating high agreement among the research team.

Integration of Quantitative and Qualitative Data

The final stage of data analysis synthesized findings from both the quantitative and qualitative components to provide a holistic understanding of the research questions (Creswell & Creswell, 2017; Gisev et al., 2013; Almalki, 2016). For instance:

- Quantitative metrics such as downtime were contextualized with qualitative insights from 10 participants regarding the challenges of system implementation.
- The 10 participants' feedback on their hands-on experience with STEM-PBL was analyzed alongside system performance data to highlight the educational and technical outcomes of the project.

RESEARCH FINDINGS

This section presents the outcomes of the study, focusing on the quantitative performance of the IoT LoRaWAN-based tracking system and the qualitative insights into participants' experiences with the STEM-PBL framework. The findings are supported by relevant figures and references.

The Quantitative Results

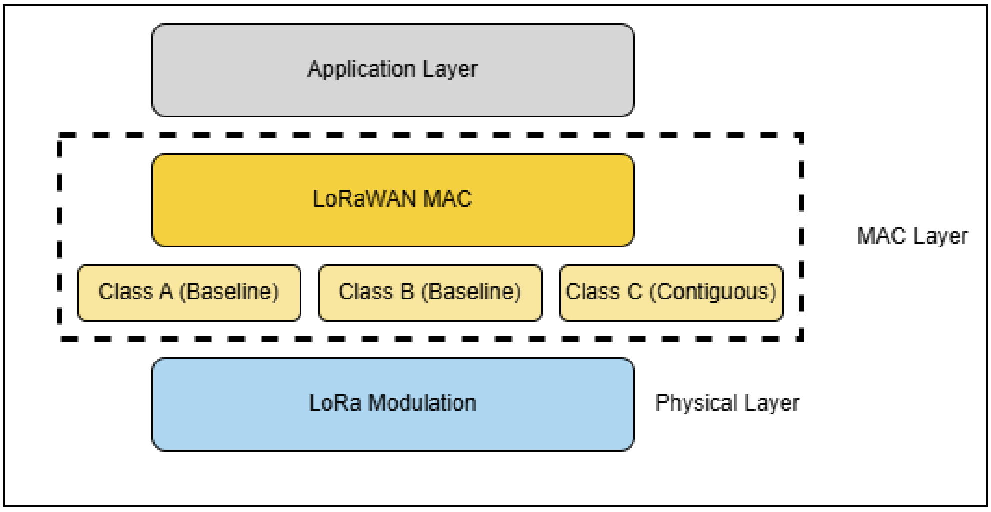
System Development and Performance

The first research question aimed to explore: How do participants implement and develop a real-time tracking system using LoRaWAN and IoT technologies?

System Design:

The LoRaWAN architecture includes the Application Layer, the MAC Layer (which handles communication classes such as Class A, B, and C), and the Physical Layer (responsible for LoRa modulation). This layered structure ensures scalability and energy efficiency, as depicted in Figure 4.

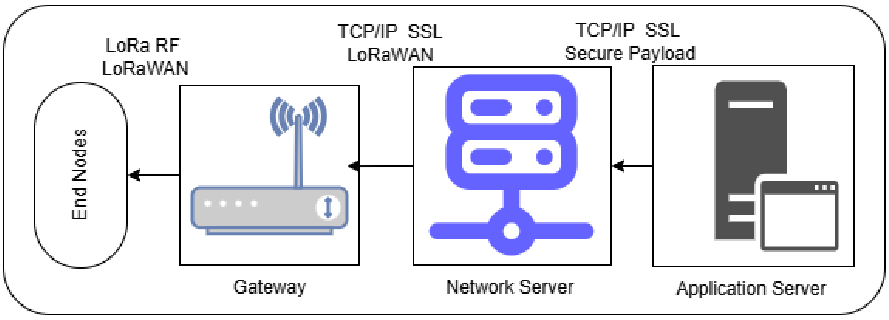
Figure 4
LoRaWAN Network Architecture



LoRaWAN Network Architecture:

The LoRaWAN architecture consists of four main components: end devices, gateways, network servers, and application servers. These components work together to enable efficient, long-range communication with low power consumption, as illustrated in Figure 5.

Figure 5
A Typical LoRaWAN Network Architecture



End devices communicate with nearby gateways via RF signals. The gateways relay data to a network server using TCP/IP protocols. Finally, the data is transmitted to an application server, where it is processed and visualized for the end-user.

By leveraging this architecture, the system achieved seamless communication between IoT devices and cloud-based applications, enabling real-time asset tracking. The system utilized LoRa end devices (equipped with GPS modules), gateways, and a cloud-based data visualization platform. The schematic diagrams of the end nodes and gateways are shown in Figures 6 and 7, respectively.

Operational Concept:

LoRaWAN operates in unlicensed RF bands, facilitating long-range communication with minimal power consumption (Hayati et al., 2024; Al Yahya et al., 2021).

The GPS modules transmitted location data to the gateways, which were processed and stored in Google Sheets. A sample of the tracking data is presented in Figure 8.

Figure 6

End Node Schematic Diagram

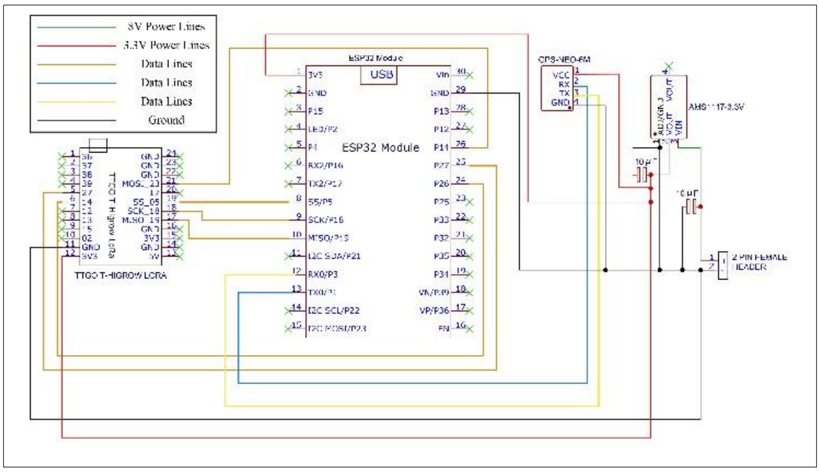


Figure 7

Gateway Schematic Diagram

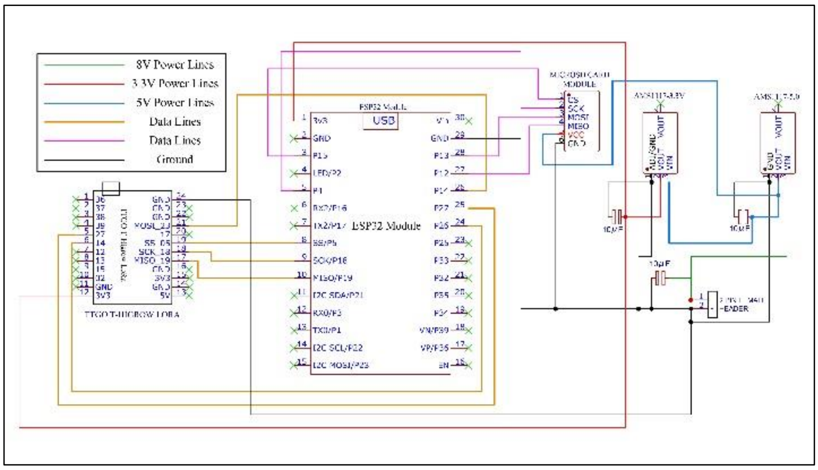


Figure 8

Test Results Sample Saved in Google Sheets

Date	Latitude	Longitude	Speed	Satellites	Altitude	GPS Time	GPS Date
8/25/2023	29.957177	30.958777	9.24	0	227.1	9515900	250823
8/25/2023	29.957177	30.958777	9.24	0	227.1	9520600	250823
8/25/2023	29.957177	30.958777	9.24	0	227.1	9521300	250823
8/25/2023	29.957177	30.958777	9.24	0	227.1	9521900	250823
8/25/2023	29.957177	30.958777	9.24	0	227.1	9522600	250823
8/27/2023	29.957083	30.958806	1.76	6	224.8	13033400	270823
8/27/2023	29.957069	30.958815	0.09	6	221.5	13034200	270823
8/27/2023	29.957078	30.958799	0.46	6	220.8	13034800	270823
8/27/2023	29.95708	30.958778	0.69	6	220.6	13035400	270823
8/27/2023	29.9571	30.958718	2.91	6	219.4	13040100	270823
8/27/2023	29.957097	30.958688	5.13	6	219.5	13040700	270823
8/27/2023	29.957103	30.958609	4.37	6	217.4	13041300	270823
8/27/2023	29.957121	30.958565	1.2	6	215.9	13042000	270823
8/27/2023	29.957132	30.958571	0.44	5	213.4	13042600	270823
8/27/2023	29.95714	30.958589	1.09	5	211.8	13043300	270823
8/27/2023	29.957099	30.958631	3.39	5	223	13044000	270823
8/27/2023	29.956986	30.958728	7.33	5	226.5	13044800	270823
8/27/2023	29.956881	30.958786	7.85	5	245.4	13045500	270823
8/27/2023	29.956842	30.958802	5.26	4	230.6	13050200	270823
8/27/2023	29.956913	30.958744	1.91	4	231.9	13050900	270823
8/27/2023	29.95697	30.958733	2.5	5	232.3	13051600	270823
8/27/2023	29.95703	30.958744	2.3	6	232	13052300	270823
8/27/2023	29.957062	30.958787	3.04	6	232	13052900	270823
8/27/2023	29.957122	30.958815	3.83	5	231.8	13053600	270823
8/27/2023	29.957202	30.958833	4.37	6	232	13054200	270823
8/27/2023	29.957287	30.958867	4.41	5	232.8	13054900	270823
8/27/2023	29.95736	30.958883	2.41	6	233.4	13055600	270823
8/27/2023	29.957388	30.958919	3.19	6	234.4	13060200	270823

Hardware Setup:

The system incorporated TTGO T-Higrow LoRa shields for data transmission, GPS NEO-6M modules for location tracking, and lithium-ion batteries for power supply, ensuring energy efficiency.

System Performance and Downtime Analysis

The system's performance was evaluated through quantitative metrics:

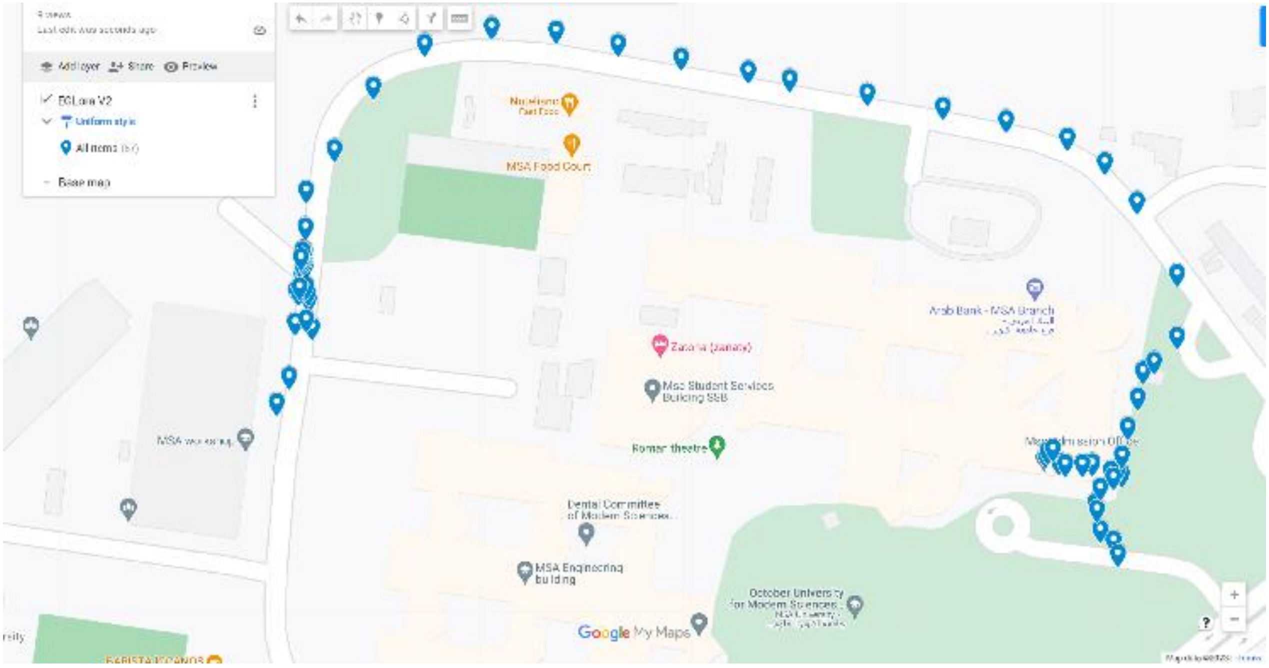
Total Operational Time: Based on logs, the system ran for 458 seconds during one trial conducted on 27th August 2023.

Downtime Percentage: The total downtime of approximately 2 seconds was caused by delays in the GPS module acquiring a fix and LoRaWAN latency. This resulted in a downtime percentage of 0.437%, indicating high reliability and suitability for real-world applications (Muylaert et al., 2014; Domínguez & Jaime, 2010).

The tracking data, including parameters such as latitude, longitude, speed, and altitude, are shown in Figure 8. This data was visualized in real-time using Google Maps, as depicted in Figure 9, demonstrating the system's accuracy in asset tracking.

Figure 9

Visualized Test Results



Predicted RSSI Values and Model Evaluation

To address gaps in the dataset, the missing RSSI values were predicted using a LightGBM model. The model demonstrated exploratory prediction of signal strength, allowing for a more comprehensive evaluation of system performance. Key findings include:

Model Performance: The LightGBM model achieved an MAE of 25.83 and RMSE of 30.08, indicating its robustness for handling non-linear data as the model is used as an exploratory tool rather than a strong predictive solution. The R^2 value, while slightly negative, reflects the challenges of accurately predicting RSSI in a dynamic environment.

Practical Implications: The predicted RSSI values enabled better understanding of the system's signal reliability under varying conditions.

Table 2 illustrates the model's performance and Figure 10 presents the comparison between actual RSSI values and predicted RSSI values.

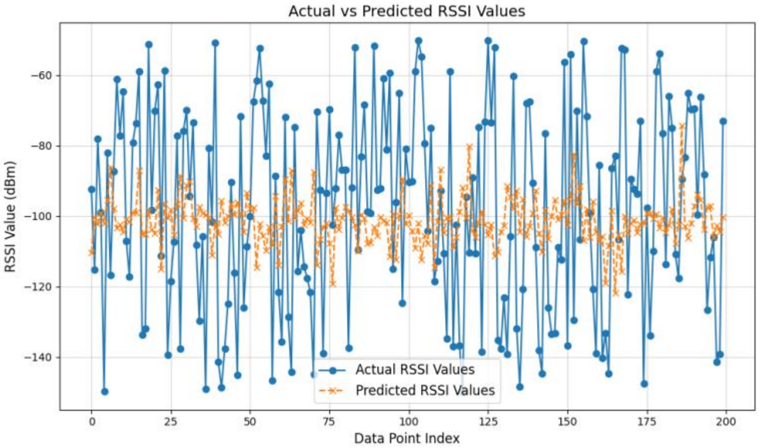
Table 2

LightGBM Performance Metrics

Metric	Value
Mean Absolute Error (MAE)	25.829151
Root Mean Squared Error (RMSE)	30.085118
R-squared (R2)	-0.094284

Figure 10

The comparison between actual RSSI values and predicted RSSI values



Qualitative Results

Participants' Perceptions of STEM-PBL

The qualitative analysis addressed the research question: How do participants perceive the process of developing a tracking system based on the STEM framework in a project-based learning (PBL) setting? This section was carried out with participants to explore their experiences in greater depth, given that engineering students typically emphasize experimental research. Through thematic analysis (Creswell & Creswell, 2017; McKim, 2017; Bonvoisin et al., 2016), eight main themes and 36 subthemes emerged, as detailed in **Table 3.**

The main focus of the qualitative analysis is the learning strategies implemented in the project. These strategies are centered on students and encompass approaches such as inquiry-based learning and PBL. According to Student (A), "the project prioritizes student-centered learning methods that involve gradually developing students' knowledge (scaffolding) and working together to support their learning (collaborative learning)." Similarly, additional feedback from the remaining nine participants highlighted the importance of combining independent exploration with structured team guidance to enhance problem-solving efficiency.

The central theme for our qualitative analysis is the second theme, Practices, with specific emphasis on the subtheme of Developing Prototypes. Interviews with the eight engineering students revealed that prototyping was a critical step in their learning process. This was corroborated by the responses of other participants, who echoed the importance of iterative testing and refinement. As Student (B) highlighted in our conversations, "The project places importance on involving students in the gradual development of prototypes, offering a hands-on learning experience that fosters problem-solving skills and innovation in a real-world context." Students across the sample recognized the value of prototyping, as it allowed them to test and refine their ideas, ensuring the effectiveness and functionality of the asset-tracking system they were working on.

Within the scope of our qualitative analysis, we turn our attention to the third theme, Thinking Skills, focusing specifically on the domain of creative thinking. Feedback from all 10 students indicated that the project encouraged them to think innovatively. For instance, when asked to provide examples of creative solutions, students shared ideas such as leveraging LoRaWAN's long-range capabilities to address signal interference challenges in urban environments. As Student (E) explained, "The asset tracking project has provided an avenue for thinking outside the box. We introduced inventive solutions using LoRaWAN technology, which not only enhanced the project's effectiveness but also expanded our creative thinking skills. Through these creative endeavors, we cultivated a culture of innovation.

The analysis also explored 21st Century Skills, such as Collaboration and Teamwork and Digital Citizenship. Management Sciences students engaged in the asset-tracking project highlighted the importance of these skills in their work. Interviews with the two participants revealed detailed collaborative experiences, while feedback from the other eight participants supported the emphasis on teamwork across disciplines. According to Student (H), "Collaboration and teamwork have been pivotal in achieving project milestones, demonstrating the value of shared knowledge and skills since the project required specialists from several domains." Similarly, digital citizenship emerged as a significant theme. Students reflected on the importance of responsible and ethical technology use, particularly in maintaining data privacy and security. As noted by one student, "Fostering a sense of digital citizenship is integral to the project's ethos. We worked actively to ensure data privacy, security, and ethical conduct throughout the project."

The themes of Engineering Habits of Mind, Integration, and Challenges were similarly enriched by the combination of interview data and additional feedback from the entire sample. Students emphasized system thinking, adaptability, and perseverance as critical traits that guided their project execution. They also noted the macro-level integration of the project with industry and community partnerships, which added real-world relevance to their work. Within the theme of Assessment, participants across the sample highlighted the use of portfolios, performance tasks, and simulations to evaluate their progress. Portfolios served as a comprehensive record of their work, enabling them to track milestones and showcase achievements effectively.

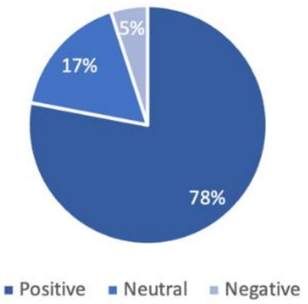
Table 3

Participants' Perceptions of STEM-PBL

Main Theme	Subtheme
Learning strategies (Students-center strategies)	1. Project-based learning 2. Inquiry-based learning 3. Collaborative learning 4. Self-learning strategy
Practices	5. Asking questions and defining specific problems 6. Developing prototypes 7. Analyzing and interpreting data 8. Enhancing mathematics thinking 9. Using computational thinking 10. Constructing solutions for specific defined problem 11. Engaging in evidence-based argumentation 12. Information acquisition, evaluation, and communication 13. Model development and experimentation
Thinking skills	14. Critical thinking 15. Creating thinking 16. Analytical thinking 17. Decision-making 18. Logical reasoning
21st century skills	19. Collaboration 20. Teamwork 21. Creativity and innovation
(Engineering) habits of mind	22. System thinking 23. Problem finding 24. Visualizing 25. Adapting 26. Improving 27. Curiosity 28. Persevereness
Integration	29. Micro-level Integration 30. Classroom integration 31. Macro-level Integration 32. Aligning curriculum with standards through society and business sectors.
Assessment (Authentic)	33. Portfolios 34. Performance tasks 35. Simulations
Challenges	36. Limited resources 37. Lack of sufficient budget 38. Professional collaboration and support 39. Technical issues

To better illustrate the emotional tone of the responses, a sentiment distribution pie chart is presented as a pie chart in **Figure 11.** It demonstrates that participants overwhelmingly perceived the STEM-PBL approach as beneficial and effective for learning. 78% of responses were positive, reflecting participants' satisfaction with the STEM-PBL framework and its focus on real-world problem-solving. 17% of responses were neutral, often involving technical descriptions or factual observations. 5% of responses were negative, primarily highlighting challenges like resource limitations and initial technical hurdles.

Figure 11
Sentiment Distribution of Participants' Perceptions of STEM-PBL



Regarding challenges, participants reported several issues during the project, including resource limitations and budget constraints, which were common across responses and encouraged creative problem-solving and efficient resource allocation. Signal interference in urban environments caused problems with signal strength and reliability, while limited hardware and budgets hindered the system's scalability. Additionally, data gaps, such as missing RSSI values in specific segments, posed challenges for comprehensive performance analysis and optimization.

To address these challenges, participants implemented a range of solutions. To mitigate signal interference, additional gateways were deployed to improve coverage and reduce latency, and network configurations were optimized to enhance data transmission reliability. Machine learning techniques, such as using the LightGBM model, were employed to predict missing RSSI values based on features like GPS coordinates, altitude, and timestamps. The model's accuracy, evaluated using metrics such as RMSE and MAE, demonstrated its effectiveness in addressing data gaps. Furthermore, participants prioritized hardware upgrades and budget reallocation to expand system scalability and ensure more robust data collection in future deployments.

DISCUSSION

Developing innovative products, such as a LoRaWAN-based asset tracking system, requires a learning environment that encourages students to integrate diverse elements and think creatively. Within the context of the present study, the STEM-PBL approach supported this creative engagement by enabling participants to explore unconventional solutions while working on an authentic, institutionally situated project. Prior research highlights several advantages of incorporating PBL into STEM education, including enhanced scientific literacy, memorable learning experiences, increased engagement, improved conceptual understanding (Jensen et al., 2021; Saleh et al., 2020), and the development of creativity compared to traditional teaching methods (Hanif et al., 2019). Additionally, PBL has been shown to positively influence 21st-century skills, such as environmental problem-solving abilities (Zhang et al., 2022; González-Arechavala et al., 2025). By involving learners in real-life, problem-oriented activities, PBL facilitates the integration of science, technology, engineering, and mathematics, thereby supporting both academic and non-academic outcomes, including teamwork and collaborative attitudes (English & King, 2015; Mesutoglu & Baran, 2020; Purwaningsih et al., 2020).

Through the application of the engineering design process, the project's guiding question encouraged participants to reflect on their responsibilities, challenges, and decision-making strategies, yielding meaningful qualitative insights within this specific educational setting. Problems were identified, solutions were proposed and evaluated, and designs were iteratively refined through testing and improvement, reflecting core practices of STEM engineering design. These processes are known to foster critical thinking, creativity, and collaboration, which are essential competencies for addressing complex, real-world problems; however, in this study, such outcomes should be interpreted in relation to the project's institutional context and participant cohort (Walker & Zhu, 2013).

One of the most significant findings emerging from the qualitative analysis was participants' articulation of integration at two levels: micro-level integration within classroom practices and macro-level integration aligning curricula with broader societal and industry standards. These forms of integration underscore the importance of connecting classroom activities to external contexts, a principle supported by prior research advocating for the incorporation of engineering standards and diverse pedagogical approaches in STEM education (Moore et al., 2014). At the same time, existing literature emphasizes that achieving macro-level integration requires coordinated efforts among educational institutions, industry partners, governmental bodies, and communities (English & King, 2015; Moore et al., 2014; Milner-Bolotin & Martinovic, n.d.; Doğuş & Tabak, 2024; Sarkar, 2025; Halpern et al., 2025). Within the scope of this study, such integration was explored at a pilot level and should therefore be viewed as indicative rather than broadly generalizable.

The findings also highlight the role of engineering habits of mind in supporting integrated STEM learning. These habits including inquiry and problem-solving, cognitive flexibility, the application of prior knowledge, creativity, innovation, and autonomous thinking—were evident in participants' reflections and practices. Consistent with previous research, these dispositions contribute to the development of critical thinking and problem-solving skills that are essential for learning in future high-demand occupations, particularly those requiring authentic assessment methods such as performance tasks and simulations applied to real-world problems (Hashim et al., 2018).

Despite the observed benefits of integrating PBL within a STEM framework, several challenges remain. Factors such as teacher preparedness, limited training and support (Bilski, 2019), constraints related to infrastructure and resources (Rehman, 2023), alignment with real-world complexities, and the facilitation of interdisciplinary integration (Lavado-Anguera et al., 2024) may hinder the effective implementation of such approaches. These challenges suggest that successful adoption and potential scaling of STEM-PBL initiatives require careful consideration of contextual conditions, institutional capacity, and available support structures.

The integration of the qualitative themes with the quantitative outcomes highlights the association between participants' experiences and measurable outcomes. The qualitative findings enhance the contextual depth of the numerical patterns, clarifying the rationale behind specific outcomes. This study's quantitative component analyzes factors including system design, hardware configuration, operational duration, downtime, system dependability, missing RSSI data, and assessments of overall project functionality. The qualitative component examines participants' perceptions of the development process of a tracking system utilizing a STEM framework in a project-based learning (PBL) context. The combination of qualitative and quantitative elements demonstrate that a mixed-methods approach is the most appropriate strategy for addressing the research questions.

CONCLUSION

This study provided a comprehensive exploration of students' experiences with STEM-PBL methodology through developing an IoT LoRaWAN-based asset tracking system. Through interviews with ten graduate students from diverse academic backgrounds, meaningful insights were gained into their perceptions of the Engineering Design Process (EDP) and the STEM-PBL framework. From problem identification to developing innovative technical solutions using LoRaWAN technology, students demonstrated significant growth in critical thinking, collaboration, and technical competencies.

The mixed-methods approach revealed that 78% of student responses were positive regarding the STEM-PBL experience, with thematic analysis identifying eight main themes including enhanced learning strategies, practical skills development, and improved 21st-century skills. The project successfully demonstrated the feasibility of integrating IoT technology within educational settings, with the LoRaWAN system achieving 99.563% operational reliability and minimal downtime of 0.437%.

Students particularly valued the hands-on, inquiry-based learning approach, emphasizing the importance of prototyping, iterative problem-solving, and collaborative teamwork. The research questions regarding system development and student perceptions of STEM-PBL were thoroughly addressed through active participant engagement, with data saturation achieved during qualitative collection.

This study contributes to STEM education methodology by demonstrating how technology integration through project-based learning can effectively enhance students' technical and collaborative competencies. The findings provide educators with evidence-based insights for implementing IoT technologies within STEM curricula while addressing real-world engineering challenges. The successful integration of LoRaWAN technology serves as a replicable model for institutions seeking to enhance STEM education through practical, industry-relevant projects that prepare students for technological careers.

Future research should conduct a systematic benchmarking of LoRaWAN against other LPWAN technologies, such as NB-IoT and Sigfox, to further contextualize the findings of this study. Such comparative analyses could evaluate key performance metrics, including power consumption, communication range, network capacity, and cost-effectiveness across diverse deployment environments. These investigations would provide deeper insights into the suitability of each technology for educational and asset-tracking applications beyond the specific institutional context examined in this work.

Limitation

While every study has its limits, we worked hard to minimize them to make sure our results were accurate. The interview sample size (n=10), while constrained, provided significant and thorough insights aligned with the study's objectives. Moreover, despite the study being conducted within a specific institutional context, this focus enabled a comprehensive analysis of the framework's application in a real-world setting. Rigorous measures to reduce potential bias, including triangulation and transparent reporting, were implemented. Further research could enhance this study by examining additional contexts, larger samples, other variables to further expand upon our findings.

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Ethical Statement

This study was approved by Vice Rectorate for Graduate Studies and Scientific Research under approval number [KSU-HE-23-920]

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

YA participated in Conceptualization, Methodology, Resources, Writing – Original Draft, Supervision, Writing – Review & Editing, and Project Administration. GA participated in Conceptualization, Supervision, Methodology, Software, Resources, Writing – Original Draft, Writing – Review & Editing, and Project Administration. AA participated in Methodology, Software, and Writing – Original Draft. ME participated in Methodology, Resources, Writing – Original Draft, and Software. JA participated in Writing – Review & Editing.

Data availability

All data generated or analyzed during this study are included in this research article. The data are made available in a way that ensures their integrity. In accordance with applicable data protection and privacy rules, we followed the best practices in data handling in the presented prototype and took precautions to ensure the long-term preservation and accessibility of the study data, as we are currently working on transforming this MVP model into a high-end product.

AI disclosure

Artificial intelligence tools were used to support language editing and clarity of expression in this manuscript. All scientific content, analysis, interpretations, and conclusions were developed by the authors, who take full responsibility for the accuracy, originality, and integrity of the work.

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