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Development of a Sustainable Automated Irrigation System as a Learning Object

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School gardens face challenges in integrating technologies and pedagogical strategies, which limits the appropriation of knowledge related to automation, renewable energies, and sustainability. This study aimed to develop an automated and sustainable technological irrigation system that serves as a learning tool, facilitating knowledge acquisition in these areas within agricultural processes. The designed technological device functioned as an integrating element across various disciplines, including electronics, programming, electricity, mechanics, and agriculture, through the implementation of pedagogical strategies grounded in constructivism and project-based learning. The research followed a qualitative approach using a collaborative action-research methodology. The study population consisted of 15 high school students. The results, assessed through rubrics, demonstrated that students successfully met the established criteria, effectively acquiring key concepts in automation and sustainability while meaningfully integrating knowledge from multiple disciplines.

Keywords: education, learning object, automation, irrigation system, sustainability, action research

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INTRODUCTION

Access to and sustainable management of water are critical global challenges, particularly in sectors such as agriculture, where water resources are essential for food production. The Food and Agriculture Organization of the United Nations (FAO, 2008) emphasizes the need to invest in water, agriculture, and ecosystems to mitigate hunger and poverty. However, water pollution, population growth, and industrial expansion have increased pressure on water resources, compromising their availability and quality (FAO, 2011). For this reason, it is crucial to implement strategies that optimize water use in agriculture, ensuring its long-term sustainability.

In Colombia, agriculture is a fundamental pillar of the Gross Domestic Product (GDP) and also the sector with the highest water demand, consuming approximately 70% of the water extracted from rivers and underground reserves (FAO, 2011). Despite its economic and social importance, agriculture faces significant challenges, such as inefficient water use and the lack of integration of sustainable technologies. The water crisis, climate change, and resource overexploitation highlight the urgent need for innovative solutions that promote efficient water use in agricultural systems.

One emerging approach in sustainability education is the implementation of school gardens, which have proven to be effective spaces for teaching agricultural processes, developing scientific competencies, and promoting values such as responsibility and sustainability (Tobar et al., 2019). These gardens allow students to engage in experiential learning about food production and natural resource management (Zambrano, 2018). However, their maintenance presents a significant challenge, as it requires continuous effort in terms of labor and water availability. Without automation mechanisms, these spaces may become unsustainable in the long run (Eugenio et al., 2020).

Despite the increasing adoption of agroecological approaches in primary and secondary education, there remains a gap in the integration of automation technologies within these environments. The absence of innovative solutions to optimize irrigation in school gardens limits their effectiveness as educational tools and their impact on fostering environmental awareness (Marques & Cuéllar, 2021). The development of automated and sustainable irrigation systems emerges as a viable alternative to improve water-use efficiency, reduce maintenance efforts, and enhance learning in areas such as automation, energy sustainability, and water resource management.

In response to this need, the present study aimed to develop an automated and sustainable technological irrigation system that serves as a learning tool, facilitating knowledge acquisition in these areas within agricultural processes. By implementing this system in an educational setting, the study sought to foster a sustainability culture, promote efficient water use, and integrate technology into agricultural education. This research contributes to the fields of education and sustainability by addressing a gap in the implementation of technological solutions in school gardens, providing a replicable model that strengthens learning and efficient water resource management.

Conceptual Framework

Learning Objects

Learning Objects (LO) are educational resources designed to facilitate the teaching-learning process through reusability, interoperability, and accessibility in various educational contexts (Quiroz Vieyra & Muñoz González, 2020). Traditionally, these objects have been defined as digital instructional units structured around a specific educational objective, encompassing various formats such as text, images, videos, simulations, and interactive activities (Astudillo, 2011; Maldonado et al., 2017). However, in practice, this digital-centric approach has limited their application to virtual tools, overlooking the potential of tangible technological objects in learning.

According to the definition provided by the IEEE Standards Committee on Educational Technology (2001), an LO is "a digital or non-digital entity that can be used, reused, and referenced during technology-supported learning." This definition highlights that LO can also include physical elements such as electronic devices, mechanical tools, and technological systems applied to hands-on learning (López Guzmán, 2005). Expanding this concept is essential for developing innovative educational approaches, particularly in disciplines that require technology manipulation and experimentation in real-world settings.

LO can be classified into various categories based on their pedagogical application and functionality. Callejas et al. (2011) present the classification which distinguishes the following types:

- Instructional Objects: Designed to facilitate structured learning, where the student assumes a relatively passive role.
- Collaborative Objects: Oriented toward interaction and teamwork within collaborative learning environments.
- Practice Objects: Focused on self-learning and skill enhancement through active student participation.
- Assessment Objects: Used to measure and evaluate the knowledge acquired after an educational process.

Technological Learning Objects

Technological Learning Objects (TLO) are physical or digital tools designed to facilitate instruction through interaction with technology in specific contexts (Sprock et al., 2012). A TLO may include electronic devices, mechanical systems, specialized software, or any combination of these technologies with a well-defined pedagogical purpose. In the agricultural sector, TLO enable the integration of automation, sensors, and other resources that enhance practical learning and sustainability (Aucancela, 2025).

According to Sprock et al. (2012), the design of a TLO should consider three key dimensions:

- Pedagogical Dimension: TLO must be structured around clear learning objectives, promoting knowledge construction through effective instructional strategies. These should include interactive activities, project-based methodologies, and assessment mechanisms to ensure their effectiveness.
- Technological Dimension: TLO encompass technical aspects from various fields such as electricity, mechanics, electronics, and programming. They should be reusable, accessible, and interoperable to facilitate their integration into different educational environments.
- Human-TLO Interaction Dimension: The incorporation of educational technologies should motivate students and foster meaningful learning through experimentation and problem-solving in real-world scenarios.

Project-Based Learning and Constructivism

Project-Based Learning (PBL) is a methodology that enables students to develop both practical and cognitive skills by solving real-world problems. This approach promotes autonomy, critical thinking, and interdisciplinary learning, integrating knowledge from different fields to design and execute meaningful projects (Santyasa et al., 2019).

According to Kızkapan and Bektaş (2016), PBL is grounded in active learning, where students take a leading role in planning and developing solutions. The incorporation of TLO in this methodology enhances experiential learning, allowing students to design, build, and program technological devices applied to real-world problems.

PBL aligns with the constructivist approach, which asserts that students construct their knowledge through meaningful experiences, connecting prior concepts with new ideas (Rodríguez, 2011). In this sense, integrating TLO into PBL facilitates experimentation, collaborative learning, and the development of technical and scientific skills essential for agricultural education (Calvopiña & Bassante, 2016).

METHOD

Research Approach and Design

This study adopted a qualitative approach with a collaborative action-research design, allowing for an in-depth understanding of educational and technological phenomena in a real-world context through the active participation of students, teachers, and researchers. According to Creswell and Creswell (2018), qualitative research is interpretative and aims to explore meanings and experiences through inductive and descriptive methods, such as participatory observations. The collaborative action-research process followed four key phases: planning, action, observation, and reflection (Kemmis, 2009; Somekh, 2006), ensuring the continuous improvement of educational practices.

Research Question

How does the implementation of an automated and sustainable irrigation system as a Technological Learning Object (TLO) influence the acquisition of knowledge on automation, sustainability, and efficient water management among high school students under a Project-Based Learning (PBL) approach?

Population and Sample

A convenience sampling method was used, selecting 15 high school students (8 females and 7 males) aged between 15 and 17 years old from an educational institution in a region of Colombia. The participants were divided into three groups of five students each. This selection was based on the following criteria:

- Availability and access to the participating educational institution.
- Students' interest in applying technology to agricultural processes.
- Feasibility of conducting the study within a collaborative learning environment.
- Possibility of continuous monitoring throughout the research process.

Although the sample size was small, the qualitative approach of the study does not seek statistical generalization but rather an in-depth understanding of the phenomenon within a specific context (Creswell, 2018).

Ethical Considerations

To ensure compliance with ethical principles in research, informed consent was obtained from the students. Since they were minors, additional authorization from their legal guardians was required, along with approval from the educational institution for their participation. Moreover, confidentiality and anonymity of the participants were guaranteed, ensuring that all collected information was used exclusively for academic purposes. Additionally, data protection and secure storage measures were implemented, adhering to ethical research guidelines established by the British Educational Research Association (BERA, 2018), safeguarding participants' information and ensuring data integrity.

Roles of Researchers

The development of the study involved the active participation of the researchers, who assumed multiple key roles throughout the teaching-learning process. They acted as facilitators, guiding students in the application of technological and pedagogical concepts for the implementation of the automated irrigation system. Additionally, they served as observers and moderators, documenting the learning process and analyzing student interactions with the Technological Learning Object (TLO). Meanwhile, students played a central role, actively engaging in the Project-Based Learning (PBL) approach, which allowed them to design, build, and implement the automated irrigation system, fostering the development of technical, scientific, and collaborative skills.

Data Collection Techniques

To ensure a comprehensive analysis, multiple data collection techniques were employed to obtain detailed insights into the students' interaction with the Technological Learning Object (TLO) and their learning process.

- Participatory observations: The students' behavior and interaction with the automated irrigation system were documented through field notes and reflective journals.
- Evaluation rubrics: Designed to assess students' performance in building, implementing, and understanding the system, ensuring an objective evaluation of the learning process.
- Field journals: Used to record impressions, emerging learning experiences, and reflections, providing deeper insights into the educational impact of the implemented strategy.

Procedure and Activities

The activities were carried out over a four-month period, with three-hour sessions held three times per week (9 hours per week). This timeframe was sufficient to complete all phases of the action-research process see Table 1.

Table 1
Work plan for the didactic strategy

Action Research Phases	Main Activities Conducted	Main Activities Conducted
-Planning -Action -Reflection -Observation	1. Initial	Conduct a diagnostic test
	2. Design	Design the automated technological system
	3. Implementation	Assemble the automated irrigation system
	4. Evaluation	Apply an evaluation rubric to identify strengthened and developed competencies

For the development of activities, a work plan was designed that includes an assessment of students' prior knowledge to create the necessary didactic guides for explaining the topics. The activities were organized into thematic axes: 3D modeling and printing, circuit design, mobile application design, and systems programming, as detailed in Table 2. The development of the technological system was structured into three subsystems:

Photovoltaic System

This system was designed to maximize solar energy capture using a mobile panel capable of tracking the sun's trajectory, thereby achieving greater energy efficiency. The structure will be constructed from aluminum and steel, integrating linear actuators that enable panel movement in multiple directions. Light sensors (photoresistors) will automatically adjust the panel's tilt based on detected luminosity. The system will include a relay bank to control two worm gear motors responsible for panel movement, as well as push buttons for manual operation during maintenance tasks. Captured energy will be stored in a battery protected by surge suppressors and a solar charge controller. System management will be carried out via a mobile application, offering both manual and automatic operating modes to ensure efficient and adaptable operation.

Cartesian Irrigation System

A Cartesian irrigation system was projected based on an overhead crane design, allowing a micro sprinkler to move along the X and Y axes. The structure will be made of aluminum rails connected by 3D-printed parts. Stepper motors and transmission belts will enable the micro sprinkler's movement, covering rectangular areas in the school garden. Soil moisture sensors will detect zones requiring water, triggering automated irrigation. The system will include manual and automatic operating modes, controlled via Bluetooth through a mobile application. In manual mode, components can be calibrated, and their functionality verified; in automatic mode, irrigation will adjust according to data provided by the sensors.

Linear Irrigation System

This subsystem was designed to move along a single axis, with a modular structure adjustable in length to meet specific needs. It will feature a stepper motor that moves the micro sprinkler along the rail. Soil moisture sensors will regulate irrigation based on ground conditions. Like the Cartesian system, it will include manual and automatic operating modes. In manual mode, motor movements will be calibrated, while in automatic mode, irrigation will follow programmed routes between predefined start and end points. Control will be managed via Bluetooth through a mobile application, enabling real-time monitoring and remote operation.

System Integration

All subsystems will be integrated using communication technologies such as Bluetooth and Wi-Fi, managed through a mobile application developed in App Inventor. The application will include specific screens for each system, allowing independent control of their functions and ensuring coordinated operation. System programming will be carried out in the Arduino IDE environment, utilizing basic commands to manage digital and analog signals. This integration will ensure connectivity and efficiency across all systems, facilitating their management and supervision.

Table 2
Work plan for activity development

Thematic Axes	Performance Indicators	Activities	Results Achieved
Application of the Diagnostic Test	Administers the diagnostic test.	Administer the diagnostic test to identify students' prior knowledge.	Diagnostic test results.
3D Modeling in FreeCAD and Fabrication of Parts Using 3D Printers	Models various 3D parts of different shapes and sizes using FreeCAD software. Executes the slicing process for a FreeCAD design using Cura software, then uploads and prints it on a 3D printer.	Develop the FreeCAD work guide, including the creation of various parts to be modeled for the systems. Slice the design created in FreeCAD, print it on a 3D printer using PLA material, and remove supports and excess material to finalize the 3D figure.	Completed 3D-printed parts.
Assembly of Mechanical Components for the Systems: Photovoltaic System Cartesian System Linear System	Assembles the framework and structural components of the photovoltaic system. Assembles the framework and structural components of the Cartesian system. Assembles the framework and structural components of the linear system.	Assemble the various structures using 3D-printed parts and fasteners. Assemble and connect the protective components to safeguard the solar panel from surges, shorts, or overvoltage.	Fully assembled mechanical structures.
Construction and Assembly of the Electrical Circuit for: Photovoltaic System Cartesian System Linear System	Constructs and connects the electrical and protective components of the photovoltaic system. Designs, assembles, solders, and molds the circuit board and components for the systems.	Design circuits for each system using KiCad software with the aid of guides, then mold the circuit boards, assemble the circuits, and solder the components.	Fully functional electrical and electronic circuits.
Design and Programming of the Mobile Application	Designs the visual and interactive elements of the mobile application, then programs it to interface with the corresponding MCU for each system.	With guidance from researchers, design and develop a mobile application using the App Inventor platform, then program it to link with the various MCUs and configure them for system control.	Complete development of the mobile application.
Programming of the MCU for: Photovoltaic System Cartesian System Linear System	Programs the MCUs for the systems using the Arduino IDE.	Program the different configurations of the MCUs for system control.	Full programming of the three systems.

FINDINGS

Diagnostic Test

To assess students' prior knowledge in automation, application design, 3D printing, and pedagogical methodologies, a diagnostic test was implemented. This tool helped identify the areas where students had strengths and those requiring additional pedagogical reinforcement. The questionnaire was divided into three key sections:

- The first section, Automation, included questions on electronics, microcontrollers, sensors, Arduino, and renewable energy. Its purpose was to contextualize students' prior knowledge and determine which topics required additional instruction. This section consisted of nine questions.
- The second section, Application Design and 3D Printing, evaluated students' skills in using software like FreeCAD, as well as their experience with 3D printing and mobile application development. This section included six questions.
- The third section, Pedagogy and Didactics, explored teaching methodologies that students found most engaging, aiming to design a pedagogical strategy aligned with their preferences and needs. This last section contained three questions.

The test consisted of 18 questions and was administered individually during the first session. The estimated completion time was 45 minutes, although most students finished within 20 to 25 minutes. The remaining time was used to discuss responses with students and collect additional insights about their previous experience and expectations regarding the project.

Key Findings

The results showed that in the automation section, students understood the general concept but lacked practical experience with microcontrollers such as ESP32. Although some had worked with Arduino, their knowledge was limited. In the design section, students were familiar with FreeCAD for 3D modeling but had no experience with 3D printing and were unfamiliar with mobile application development. Finally, in the pedagogy section, students expressed a preference for practical and project-based approaches, confirming the relevance of using active methodologies such as Project-Based Learning (PBL). These findings guided the design of the pedagogical plan, ensuring that the instruction was aligned with students' needs and allowing for strategic adaptation in teaching the different topics covered in the project.

Project Development

3D Printing and Modeling

The 3D modeling and manufacturing process was essential for assembling the automated irrigation system. To reinforce design knowledge, two pedagogical guides were implemented:

- Guide No. 1 introduced students to modeling in FreeCAD, where they designed a multi-surface piece, allowing group practice in a three-hour session.
- Guide No. 2 focused on 3D printer configuration and operation, covering exporting models to CURA and final piece printing.

During manufacturing, students printed nine key pieces, including sensor holders, connectors for the Cartesian and linear systems, and moving components for irrigation mechanisms. Throughout this process, they faced challenges related to piece rigidity, requiring design adjustments to improve their functionality.

Assembly of Technological Systems

Students actively participated in the construction and assembly of the irrigation systems, overcoming various technical challenges in the process:

- Photovoltaic System: Involved the design and fabrication of a mobile structure with a solar panel, light sensors, worm gear motors, and a solar charge controller. Students installed the system, ensuring proper energy capture.
- Cartesian System: Consisted of a rectangular aluminum rail structure with stepper motors and humidity sensors. Students encountered difficulties adjusting the transmission belts, which were resolved by modifying 3D-printed parts.
- Linear System: Featured a modular design adjustable in length, based on monorails and stepper motors. Students had to fine-tune the movement mechanism to prevent blockages during displacement.

System Programming and Control

Each system was programmed using the ESP32 microcontroller and the Arduino IDE environment. Two operation modes were configured:

- Manual Mode: Allowed students to manually control the system using physical switches.
- Automatic Mode: Algorithms regulated irrigation based on real-time data from soil moisture sensors.

Additionally, students developed a mobile application using App Inventor, enabling remote management of the systems. The connection between devices was established via Bluetooth and Wi-Fi, facilitating real-time monitoring and control.

Evaluation and Student Performance

Project results were evaluated using specific rubrics for each phase, including 3D printing, mechanical assembly, electronics, electricity, programming, and mobile application development. The key evaluation criteria included:

- Creativity and innovation in design.

- Precision in assembly and system functionality.
- Effective application of automation knowledge.

The results demonstrated a high level of performance in all areas, with significant improvements in technical skills and collaborative work.

DISCUSSION

Knowledge Gaps and Their Approach

The results of the diagnostic test revealed that students had basic theoretical knowledge in automation and 3D design but lacked practical experience in programming microcontrollers such as the ESP32, using Arduino, 3D printing, and mobile application development. This lack of familiarity posed a significant challenge to the implementation of the project, as it required students to acquire technical skills within a short period.

To address these gaps, pedagogical strategies were designed, including theoretical and practical workshops, instructional guides, and a Project-Based Learning (PBL) approach. Specifically, the instructional guides played a fundamental role in providing step-by-step instructions for designing parts in FreeCAD, configuring 3D printing, and programming automation systems. Students actively participated in each of these activities, enabling progressive knowledge acquisition and the development of essential practical skills for the project.

Pedagogical Strategies and Student Learning

The constructivist approach adopted in the project allowed students to build their knowledge through direct experience with the automated irrigation system. PBL enabled students to work on real-world problem-solving, fostering autonomy and critical thinking. Throughout the project, students not only acquired technical skills but also strengthened collaborative competencies by working in teams to design, assemble, and program the different technological systems.

The integration of multiple disciplines, such as electronics, mechanics, electricity, and programming, within a single project provided meaningful interdisciplinary learning. The project structure allowed students to visualize the practical application of theoretical concepts, leading to increased motivation and interest in learning.

Challenges Encountered and Implemented Solutions

The project's development was not without difficulties. One of the main challenges was students' lack of experience with 3D printing. Although they had prior knowledge in 3D modeling with FreeCAD, transitioning to the printing and assembly process required design adjustments to improve the rigidity and functionality of the printed parts. To overcome this difficulty, preliminary printing tests and iterative adjustments were conducted on the models before final printing.

Another major challenge was the integration of electronic systems and programming of ESP32 microcontrollers. Students encountered difficulties in configuring sensors and actuators, which required additional tutoring sessions and prototyping experimentation. Autonomous problem-solving was encouraged, guiding students in identifying errors in their codes and implementing effective solutions.

The installation of the irrigation system in the school garden presented logistical obstacles, such as resource availability and space optimization. These issues were resolved through adequate installation planning and adaptation of structures to the environmental conditions.

Effectiveness of the Didactic Approach

The pedagogical approach based on PBL and collaborative action research proved effective in knowledge acquisition and in the development of competencies among students. The evaluation results showed that students achieved high performance across different areas of the project, indicating that the applied methodology facilitated meaningful learning.

The implementation of specific rubrics for each project area allowed for an objective evaluation of student progress. The analysis of these rubrics demonstrated significant improvements in technical skills, ranging from 3D printing to programming and electronic system assembly. Teamwork and problem-solving skills were key aspects that were strengthened throughout the process.

Impact Assessment and Future Projections

Beyond technical knowledge acquisition, the project's impact was reflected in students' motivation and confidence to tackle complex technological problems. The experience gained in handling advanced technological tools, such as microcontroller programming and 3D printing, provided them with a competitive advantage in their academic and professional development.

In the long term, this type of project can serve as a model for future educational initiatives within the institution and in other academic communities. The replicability of the methodology used suggests that integrating automation and sustainability in educational contexts has the potential to strengthen science and technology education.

For future iterations of the project, it is recommended to extend instruction time in programming and electronics, as well as to explore new automation and control technologies. Additionally, conducting follow-ups with students would be valuable in evaluating how this experience influences their career orientation and performance in higher education or future projects.

CONCLUSIONS

The development of the sustainable automated irrigation system as a technological learning object enabled students to engage in a dynamic and participatory process, facilitating the acquisition of meaningful knowledge in automation, programming, and sustainability. The combination of theory and practice strengthened both technical and transversal competencies, promoting collaborative work and problem-solving in real-world contexts. The implementation of the automated irrigation system as a tangible and functional learning object demonstrated its potential as a pedagogical tool by facilitating the teaching of complex concepts through experimentation and direct manipulation. This approach allowed students to connect theoretical learning with practical application, reinforcing their understanding of renewable energy use, microcontroller programming, and 3D printing, among other key aspects.

The project highlighted the importance of interdisciplinarity in technology education by fostering the integration of knowledge in electronics, mechanics, computer science, and sustainability. The application of pedagogical strategies such as learning guides was fundamental in overcoming initial barriers in areas where students had little or no prior experience, such as advanced programming and 3D modeling. The use of support tools enhanced autonomous learning and facilitated the consolidation of competencies at each stage of the project.

The project's impact extended beyond the classroom, not only by fostering the development of technological solutions applied to educational contexts but also by promoting a culture of sustainability among students. The integration of renewable energy and automation in the irrigation system for the school garden served as a replicable model for other institutions interested in implementing sustainable technological practices. Additionally, the system's development demonstrated the role of technology education in advancing the Sustainable Development Goals (SDGs), particularly in efficient water management and the responsible use of natural resources.

LIMITATIONS AND RECOMMENDATIONS

The implementation process revealed certain limitations. Difficulties were identified in the accuracy of measurements for 3D-printed parts, requiring repeated design adjustments. Additionally, programming microcontrollers posed challenges for students with limited experience in computational logic, suggesting the need to reinforce this aspect in future implementations. Furthermore, reliance on connectivity and access to technological equipment could present an obstacle to scaling the project in resource-limited contexts.

For future iterations of the project, it is recommended to structure additional sessions focused on programming and electronic circuit design to strengthen students' understanding of these concepts from early stages of the process. Exploring new evaluation strategies that incorporate direct student reflections on their learning experience would also be beneficial, allowing for a more precise identification of areas for improvement. Finally, assessing the feasibility of scaling the project to other educational institutions through thorough documentation and systematization of the process is suggested to ensure its replicability and long-term sustainability.

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