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RESEARCH ARTICLE

Transforming Electronics Engineering Classrooms: Fostering Students' Motivation to Design Technological Solutions Through Inquiry-Based Learning

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ABSTRACT This research analyzed the outcomes of an inquiry-based learning (IBL) activity presented to electronics engineering students to help them develop their abilities, propose new experiments, and construct their own knowledge. The IBL activity was led by a carbon nanotubes-based sensor prototype presentation where 39 engineering students were introduced to the operation of the prototype, followed by a discussion where the presenters highlighted possible applications of this type of prototype and a ten-minute questions session. At the end of the presentation, all participants answered a survey analyzing the impact of the IBL activity on their understanding of electronics engineering concepts and their motivation to design new experiments to explore and test their knowledge. The qualitative and quantitative data analysis showed that most of the participants were interested in the IBL activity, reporting that they would like to have more of this type of presentation in their engineering courses. Participants' interest in the prototype presentation was reflected in their understanding of electronics engineering-related topics and their motivation to design new prototypes. They reported that they learned something new or developed a better understanding of topics they previously learned in their courses from the examples shown during the IBL activity. This research suggests that more IBL activities and partnerships with the industry should be included in electronics engineering courses aimed at developing students' abilities to design and build technological applications.

INDEX TERMS Learning research, inquiry-based learning, engineering students, electronics engineering, carbon nanotubes, educational innovation, higher education, experiential learning.

I. INTRODUCTION

Science, Technology, Engineering, and Mathematics (STEM) professionals are fundamental to a country's development. They design technological solutions to solve the most relevant problems around the globe, which ultimately helps society live better [1]. Hence, the current interest in attracting more students to STEM careers and designing better teaching strategies to develop critical thinkers and professionals with the skills to solve problems using scientific and technological applications [2], [3].

Many teaching strategies could help STEM educators develop their students' understanding of STEM-related topics and their applications. These teaching strategies are used to

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engage students and promote their interest in science and technology topics [4], [5]. Inquiry-based learning (IBL) is a teaching strategy that could help students propose new hypotheses and develop experiments that could help them construct their knowledge based on observations [6]. Current literature analyzing the effectiveness of IBL as an instructional approach suggests that strategies such as direct instruction and unassisted discovery could result in better student learning experiences [7]. In most cases, learning outcomes are better for students guided by the IBL than those taught using traditional instruction methods [8], [9]. Students guided by IBL activities are more likely to develop skills such as identifying problems, formulating hypotheses, designing experiments, collecting and analyzing data, and drawing conclusions [10]. Table 1 shows the main differences between IBL and traditional laboratory classes and describes the similitudes between these learning methods. Additionally, the implementation of IBL activities in class has become easier than before thanks to the new technologies in laboratories and classrooms [11]; as well as by teaching in exciting locations such as hospitals, industry, government offices, museums, etc. Some examples of these IBL activities could be seen in the implementation of learning outside the classroom [12] or adding learning dynamics to the efforts of various institutions, such as global classrooms of instructors from different latitudes, to reach standardized content on academic programs [13], [14].

Learning STEM topics through IBL activities has helped students to develop essential skills such as using laboratory equipment and technical language, and exploring new ways to apply their knowledge to solve problems (see Table 1); these skills usually promote students' interest in investigating on their own and integrate all their knowledge to solve real-life problems which ultimately helps them to develop their critical thinking abilities [15]. IBL activities could also motivate students to try to understand complex scientific topics through their own thinking and reasoning, beneficiating them in different ways that are not commonly obtained following other learning strategies [16], [17]. The role of professors could be very important during the IBL activities in STEM education since they can guide experiments that generate questions from their students (see Table 1). These questions could motivate students to search for more information about science topics, aiming to find the answer, helping them to develop their own knowledge [18].

Professors could use IBL to promote their students' active participation in class activities and to emphasize their responsibility in the knowledge development process [19]. During this process, students should self-direct their learning by conducting experiments and building prototypes aiming to explore relations between different variables and hypothesized outcomes [20]. Experimentation is a key element in knowledge development, and IBL activities could help students build their confidence to propose new projects by observing how experts and scientists design and conduct their experiments in their daily work. In the end, this connection between experts and students' experimentation practices could facilitate students' understanding of new concepts and complex science applications [21] or, to go further, even educate society to develop citizen science by developing complex thinking on problems of global interest such as sustainable development goals [22].

The IBL process could be divided into smaller, logically connected units that facilitate knowledge development [21]. These units are called in different ways depending on the inquiry approach that educators choose and how these units are connected during such approach. For example, the 5E learning cycle model lists five inquiry phases: Engagement, Exploration, Explanation, Elaboration, and Evaluation [23]. It is essential to highlight that the inquiry cycle is not a prescribed, uniform linear process, and the connections between these phases may vary depending on the context of each learning activity. Additionally, a single inquiry phase could be directly connected to more than one phase (or all the other phases) depending on the nature of the IBL activity proposed by the educator [24], [25].

This paper analyses the benefits and challenges of presenting an IBL activity to electronics engineering students to motivate them to design new technological devices. The methods of this research describe the IBL activity design and how it was presented to a group of electronics engineering students who reported their experience during the IBL presentation. The data collected was analyzed using mainly a qualitative approach, and the discussion of the results offers insight into how electronics engineering students respond to IBL activities and what needs to be improved in similar activities to help students get involved in the design of new technological solutions for the most relevant problems of their community.

Specifically, the document is structured as follows: Section II - Methods describes the design and implementation of the IBL activity using a carbon nanotubes (CNTs)-based sensor prototype, including the experimental setup and data collection procedures. Section III - Results presents the findings from the survey conducted among electronics engineering students, including both qualitative and quantitative analyses of their responses. Section IV - Discussion interprets the results in the context of existing literature and explores the implications for STEM education, particularly in electronics engineering. Section V - Conclusion summarizes the key contributions of the study, highlights the potential for further research, and discusses the broader impact of incorporating IBL activities in engineering curricula.

II. PURPOSE

The primary aim of this research is to enhance the application of IBL strategies within electronics engineering education, specifically through the use of CNTs. Literature posits that traditional lecture methods may not fully teach the necessary skills for scientific inquiry due to a lack of direct

TABLE 1. Attributes, similarities and differences of inquiry-based learning activities and laboratory classes.

Aspect	Inquiry-Based Learning	Traditional Laboratory Classes	Similarities	Differences	References
Objectives	Develops research skills, critical thinking, and problem-solving abilities.	Teaches specific scientific principles and experimental techniques.	Both aim to develop scientific skills and knowledge.	IBL focuses on broader skills development, while traditional labs focus on specific scientific content and techniques.	[26], [27], [28], [29], [30], [31]
Student Role	Active, takes on a researcher role, exploring and questioning.	More guided, follows predefined instructions to conduct experiments.	Students are directly involved in practical activities.	IBL promotes autonomy in learning, whereas traditional labs follow a more structured approach.	[32], [33]
Instructor Role	Facilitator, guides the research process, provides support and resources.	Director, provides specific instructions and demonstrations.	Both roles are crucial for learning and lab safety.	IBL emphasizes guidance in the learning process, traditional labs emphasize instruction and demonstration.	[26], [27], [28], [29], [30], [31], [32], [33]
Session Structure	Flexible, based on the research process.	Structured, based on predefined lab guides.	It can include theoretical presentations, practical work, and discussions.	IBL allows for flexible exploration, and traditional labs have a fixed structure.	[26], [27], [28], [29], [30], [31], [32], [33]
Evaluation	Based on the research process and outcomes (e.g., research reports, presentations).	Based on the following procedures and the accuracy of experimental results.	Both can include formative and summative assessments.	IBL evaluations are more process-oriented, traditional lab evaluations focus on procedural accuracy and results.	[26], [27], [28], [29], [30], [31], [32], [33]
Content Focus	Broader topics, connected to real research.	Focuses on specific concepts and techniques needed to understand the discipline.	Science is the core of learning.	IBL integrates with ongoing research, and traditional labs concentrate on established scientific knowledge.	[26], [27], [28], [29], [30], [31], [32], [33]
Collaboration	Strongly encouraged, mimicking real research in teams.	Less emphasized, though pair or small group work is common.	Collaborative work is a component of both modalities.	IBL often involves larger-scale collaboration, similar to professional research teams.	[26], [27], [28], [29], [30], [31], [32], [33]
Learning Flexibility	Higher, students have some freedom to explore their own research questions.	Lower students follow established procedures to achieve specific learning objectives.	Both methods can be adapted to encourage exploration and discovery.	IBL provides students with the opportunity to pursue their own interests within the subject matter.	[26], [27]
Theory and Practice Integration	Natural and ongoing, as students apply theoretical concepts to investigate real world questions.	Sequential, with theory often presented before its application in the lab.	Integrating theory and practice is essential for effective learning in both approaches.	IBL fosters a continuous interplay between theory and practice, traditional labs often separate these aspects.	[26], [27], [28], [29], [30], [31], [32], [33]

engagement and practical application, leading to a significant disconnect between theoretical instruction and practical understanding [34], [35], [36]. Furthermore, students who experience this disconnection between experimentation and the knowledge acquired during lecture sessions may struggle to express their conceptual knowledge during practical work and application designs [37].This gap is particularly pronounced in the context of rapidly evolving fields like electronics technology, where hands-on experiences are crucial to understanding complex concepts and systems.

To address these educational challenges, our research study proposes an innovative IBL activity designed to integrate theoretical knowledge with practical experimentation using a CNT-based sensor prototype. This approach is intended to provide students with a tangible context to apply their theoretical knowledge, thereby enhancing their understanding and encouraging them to design and develop their own prototypes and technological solutions.

The study is guided by two fundamental research questions:

- R.Q. 1 What is the effect of IBL activities on electronics engineering students' understanding of electronics technology topics?
- R.Q. 2 What is the effect of IBL activities on electronics engineering students' motivation to design and conduct experiments and science applications?

To address these questions, an IBL activity using a CNT-based sensor prototype to elucidate the applications of nanomaterials in various technological fields such as medicine, agroindustry, robotics, and electronics, which was, in this case, introduced to electronics engineering students. The practical component of this activity was designed to expand students' understanding of nanomaterials, specifically their use in developing innovative sensing devices, thus providing a robust platform for applying theoretical concepts learned in classroom settings.

Previous studies have shown that guided inquiry can lead to superior learning outcomes compared to traditional teaching methods. Students engaged in IBL activities are more likely to develop crucial skills like problem identification, hypothesis formulation, experimental design, data collection, and analysis [7], [8], [9]. Therefore, our research is poised to build upon this foundation by demonstrating practical applications in electronics engineering education, fostering a more intuitive and deeper understanding of complex engineering concepts.

III. METHODS

A. NANOTUBES SENSOR PROTOTYPE DESIGN

The IBL activity was led by presenting a sensor prototype that used nanomaterials to detect substances at the nanoscale [38]. The sensor used in the prototype was developed by graduate students using polyvinyl alcohol, a polymer suitable for hydrogel manufacturing due to its chemical properties. The hydrogel conductivity and tenacity were enhanced by adding CNTs [39]. CNTs are rolled-up graphene sheets [40], and these materials have been used to take advantage of their unique properties in different technological applications such as advanced electronics, thermal, elastic, and chemistry, their exceptional electron mobility, chemical stability, and the ability to undergo functionalization [41].

The nanotube sensor prototype was integrated into a circuit powered by two 9V, 1A power sources in series. The core of this system was the voltage divider circuit (see schematic in Figure 1), which incorporated fixed resistances and the resistive film based on CNTs. This design allowed quantifying the sensor's deformation, providing a valuable measure of its response.

The signal generated by the nanotube sensor in the voltage divider was amplified using an operational amplifier (LM321, Texas Instruments), enhancing its precision and utility. Aiming to interpret the data obtained with the sensor effectively (example in Figure 2), a program using linear interpolation was implemented. This numerical technique allowed a precise estimation of the sensor's deformation, contributing to a detailed understanding of its behavior. The protocol to generate the nanotube sensor material is reported in supplemental materials.

B. IBL ACTIVITY PRESENTATION DESIGN

A presentation was developed by the two graduate students who designed the CNTs-based sensor prototype. This presentation was designed to enrich electronics engineering students' understanding of nanosensors applications and help them to think in more electronics-related applications for their future projects; as well as to promote a better understanding of basic knowledge of instrumentation and control systems topics. The presentation was designed to last 20 minutes describing the key characteristics of the CNTs-based sensor prototype, highlighting the high sensitivity, reduced size, rapid response time, low cost, and multifunctional capability of this type of material [42]. During the presentation, the two graduate students described the circuit design, emphasizing the interpretation of the results through the graphical interface.

This approach aims to provide students with a complete insight into the operation of nanosensors and how the collected information is translated into meaningful data in real-time. Additionally, students were allowed to interact with the developed sensor prototype during the presentation, aiming to provide an interactive environment (see Figure 3) where they could test the stretchability and consistency of the hydrogel nanosensors. The presentation was closed with an explanation of additional applications of the nanosensors in different fields such as medicine, environment, and agriculture, followed by a 15-minute question session where participants asked questions to solve their doubts and interchange ideas with the presenters (see Figure 4). This IBL activity was designed following the 5E learning cycle model due to the inductive (empirical/data-driven) approach that this cycle proposes in its initial phase [23], focusing on the engagement and exploration part of the inquiry that facilitates learning and motivates students' involvement in learning activities and experimentation.

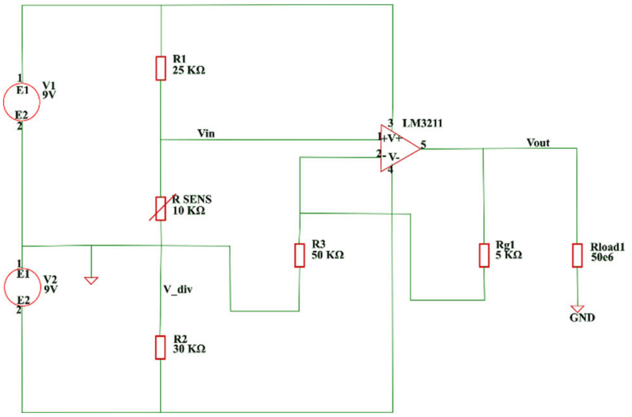

FIGURE 1. Schematic of the electrical circuit used to capture the nanotube sensor prototype´s response.

At the end of the presentation, the participants were notified that the IBL activity was not part of their course grade and would not be evaluated. However, the presenters asked the participants to complete an exit survey to analyze their experience during the IBL activity, help their professors improve this kind of activity, and promote the inclusion of more IBL activities in their electronics engineering courses.

C. DATA COLLECTION AND PARTICIPANTS

The presentation was followed by applying a survey with 12 questions developed by the authors of this paper, with six yes or no questions and six open-ended questions (see Tables 2 to 8). The survey was designed using the 5E learning cycle model [23] as a framework, aiming to develop questions that would enable a thorough qualitative analysis of the participants' experience during the IBL activity presentation. The 12-question goal was to develop a better understanding of how electronics engineering students react to IBL activities in the classroom, focusing on the engagement and exploration part of the inquiry that could facilitate students' understanding of electronics concepts and their motivation to get involved in more experiments and new prototype designs. The qualitative nature of this research made the six open-ended questions the main focus of the data analysis, and these six questions were specially designed to create a stress-free environment where participants could freely express their experience and facilitate the interpretation of the IBL activity's impact on their learning. A face

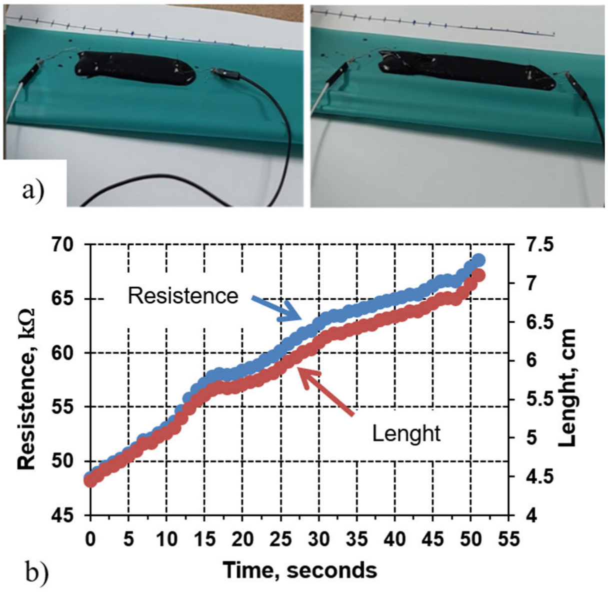

FIGURE 2. Changes in the graphical interface when deforming the sensor. Top view (images of the prototype view of the resistance sensor made with CNT. Bottom view (resistance and length vs distance and time).

validation process [43] was conducted using a focus group with the two graduate students who designed the IBL activity and two electronics professors. This focus group analyzed the questions' clarity and context, aiming to facilitate participants' understanding of each question. The feedback of this analysis helped to establish the survey's trustworthiness as a tool to collect reliable qualitative data for this research analysis (Creswell).

Data was collected from the 39 participants at the IBL presentation, with 35 male and three female participants (one participant chose not to answer the gender question). These participants were electronics engineering students enrolled in one of these two courses: machine learning (20 participants) or instrumentation (18 participants, with one participant choosing not to answer this question), aged 20 to 26 years old. Participants from the machine learning course were in the 9th semester, while the participants from the instrumentation course were in the 6th semester. Students taking these two courses were selected for the IBL presentation due to their understanding of basic electronics concepts and experience solving problems using engineering applications. Students from upper-level semesters, such as the 6th semester and beyond, have completed the basic electronics engineering courses where they have learned the theory of the most relevant electronics topics, and they understand the basic applications of these topics. The machine learning and instrumentation courses were designed to help students use their theoretical knowledge to develop new technological solutions using electronic devices such as sensors, nanomaterials, control systems, and advanced circuits. Therefore, students from these two courses were prepared to fully understand and take advantage of the information presented during the IBL activity.

FIGURE 3. Experimental setup in class on the deformation of the sensor made with CNT.

D. QUALITATIVE ANALYSIS

Participants' answers to the open-ended questions were analyzed using an open coding philosophy to let the codes emerge from the data. This qualitative analysis helped to keep the findings as close as possible to participants' own words [44]. The final codes coming from the analysis of each participant were compared side by side, with the aim of finding similarities that could be coded together into meaning units. This coding philosophy was similar to the methodology proposed by the constructivist grounded theory [45], helping to draw conclusions that appropriately reflected participants' experiences during the IBL activity.

E. QUANTITATIVE ANALYSIS

The IBL framework proposed by Pedaste et al. [21] was used as a lens to analyze and compare these meaning units, aiming to determine how participants' knowledge was affected by this learning activity. In the end, findings were presented using descriptive statistics and graphics [46], and some of the most relevant participants' comments were included to support such findings. Additionally, the data collected with the six yes or no questions was analyzed using descriptive statistics; and the responses of students from the 6th and 9th semesters were compared using the Chi-square and Fisher's exact tests when values were under five subjects aiming to determine possible differences between students across different academic stages.

IV. RESULTS

Participants' responses to the open-ended questions are presented in the following tables.

Participants' responses to the yes and no questions are presented in the following table.

V. DISCUSSION

The participants asked questions that reflected a deep interest in the IBL activity and a good understanding of the electronics

FIGURE 4. Presenters answering participants' questions.

TABLE 2. Descriptive statistics of the responses to the yes and no survey questions.

questions.

Question	Yes	No	NR
Q1. Did you learn something new with this experiment presentation?	37 (94%)	1 (3%)	1 (3%)
Q3. Have you ever learned electronics topics using experiments as a teaching tool?	23 (59%)	15 (38%)	1 (3%)
Q5. Did you improve your knowledge about any electronics-related topic that you previously knew after the experiment?	25 (65%)	14 (35%)	0
Q7. Would you like more electronics-related courses to use this type of experiment as a teaching tool to explain laws and concepts?	37 (94%)	1 (3%)	1 (3%)
Q9. After the experiment presentation, do you think that you could design and develop a new experiment applying the same topics used in this experiment in a different way?	26 (67%)	12 (30%)	1 (3%)
Q11. After the experiment presentation, can you think of an industrial or day life problem that could be solved by applying electronics-related topics?	25 (65%)	13 (32%)	1 (3%)

NR = No Response

TABLE 3. Q2. Can you explain what you learned or the reasons why you did not learn anything new?.

Response	Participants
Eco-friendly materials and devices	5 (13%)
Novel and updated nanosensors	34 (87%)
Measurements and data transmission methods	10 (26%)
Materials' resistivity, deformation, and resistance	9 (23%)

TABLE 4. Q4. What did you like or what did you not like about the experiment?.

Response	Participants
Positive Responses	
Applied electronics-related topics with real-time results	11 (28%)
Novel applications for solving daily problems	14 (36%)
Interactive and practical experiment	10 (26%)
A detailed explanation of the whole process	8 (20%)
Negative Responses	
Experiment technical failures	7 (18%)
Hydrogel technical disadvantages	8 (20%)

TABLE 5. Q6. Can you explain what electronics topic you understand better after the experiment, or was missing during the experiment to help you improve your previous knowledge about electronics topics?.

Response	Participants
Positive Responses	
Sensor's design and applications	13 (33%)
Data measuring and programming	12 (31%)
Topics that I have not seen before in class	3 (8%)
Advantages and disadvantages of novel material for manufacturing sensors	6 (15%)
Electronics basic topics	4 (10%)
Negative Responses	
More examples of applications in different areas were missing	8 (20%)
There was no new information that we had not seen before in class	5 (13%)

TABLE 6. Q8. Can you explain what advantages or disadvantages you see in the usage of this type of experiment to explain electronics-related topics?.

Response	Participants
Positive Responses	
Motivation for designing technological solutions using electronics applications	10 (26%)
Better understanding of concepts that could be confusing if they are taught only with theory	21 (54%)
Learning how to use new technologies and novel materials	6 (15%)
More attractive and less monotonous classes	4 (10%)
Negative Responses	
Designing experiments to apply electronics-related topics could be expensive	3 (8%)
The designed experiment could fail, creating confusion	2 (5%)
The experiment could create a hazardous situation if the design is not reliable	3 (8%)

topics used in the sensor prototype presentation. The interaction between graduate students and the participants during the question session was friendly, and all the questions were responded to and discussed until the participants felt that all aspects of the sensor prototype were apparent. This interaction between participants and presenters suggests that the IBL activity was interesting, and it fulfilled the goal of helping participants learn new topics and understand how to apply electronic concepts to develop technological solutions [6]. The success of the IBL activity was confirmed with the analysis of the survey responses, where 94 % of the participants reported that they had learned something new during the presentation (see Q1 in Table 2). The prototype presentation helped participants learn about different topics [17]. Still, most of them (87 %, see Table 3) reported learning about novel and updated nanosensors with comments such as "[I learned about] the applications that electronics could have, and the instrumentation for data collection. The importance of multidisciplinary work to develop projects involving chemistry, programming, and electronics".

TABLE 7. Q10. How this new experiment would be, or what could be the reason you cannot think of a new experiment using these electronics-related topics in a different way?.

Response	Participants
Positive Responses	
Use the same experiment concepts in different applications	17 (44%)
Improve the current electronics applications	3 (8%)
Measurements and data comparison using sensors build with different materials and sizes	5 (13%)
Negative Responses	
Lack of theory understanding to design different experiments	8 (20%)
I am interested in different topics	4 (10%)
Lack of time and resources to design and develop new experiments	6 (15%)

TABLE 8. Q12. How would you solve such problem, or what kind of knowledge would you miss to think of a problem's solution using electronics-related topics?.

Response	Participants
Positive Responses	
Improve the characteristics of the experiment sensor materials	4 (10%)
Analyze the wear and movement of industry materials	8 (20%)
Sensors' applications in different industries	11 (28%)
Negative Responses	
Lack of knowledge of the current industry problems	10 (26%)
There is a need to reinforce and refresh the theoretical knowledge	6 (15%)

TABLE 9. Analysis of dichotomous questions with the Chi-square test and Fisher's exact test in the sixth and ninth semesters.

Question	Answer	sixth semester* n(%)	ninth semester* n(%)	p -value
Q1. Did you learn something new with this experiment presentation?	No	1 (2.7)	0	1.000 ^{b}
	Yes	18 (48.65)	18 (48.65)	
Q3. Have you ever learned electronics topics using experiments as a teaching tool?	No	10 (27.03)	5 (13.51)	0.07 ^{a}
	Yes	8 (21.62)	14 (37.84)	
Q5. Did you improve your knowledge about any electronics-related topic that you previously knew after the experiment?	No	5 (13.16)	9 (23.68)	0.179 ^{a}
	Yes	14 (36.84)	10 (26.32)	
Q7. Would you like more electronics-related courses to use this type of experiment as a teaching tool to explain laws and concepts?	No	1 (2.63)	0	1.000 ^{b}
	Yes	18 (47.37)	19 (50)	
Q9. After the experiment presentation, do you think that you could design and develop a new experiment applying the same topics used in this experiment in a different way?	No	7 (18.42)	5 (13.16)	0.728 ^{a}
	Yes	12 (31.58)	14 (36.84)	
Q11. After the experiment presentation, can you think of an industrial or day life problem that could be solved by applying electronics-related topics?	No	9 (23.68)	4 (10.53)	0.87 ^{a}
	Yes	10 (26.32)	15 (39.47)	

* number of valid cases; n: sample per semester; a: Chi-square test; b: Fisher´s exact test when values were under five subjects

Although 59% of participants reported having a previous experience learning electronics topics using experiments or prototype demonstrations as a teaching tool (see Q3 in Table 2), this CNTs-based sensor prototype presentation was especially interesting for participants due to the novel approach presented for electronics topics applications and the interactive way that presenters showed the prototype with real-time results [5]. Most of the positive comments about the IBL learning activity were about how this presentation showed novel applications for solving daily problems (36 %, see Table 4), with comments like: "I liked how they [the presenters] are applying different subjects as electronics, instrumentation, and programming in a practical way with the goal of solving a real-life problem"; and how the prototype presented applied electronics-related topics with real-time results (28 %, see Table 4), with comments such as: "I liked that the presentation wasn't only about the theory. They showed how it works, with graphical examples of the resistance measurements of the sensor deformation, and I was really surprised to see these values return to their original value when the sensor recovered its original form". Only a few participants reported negative comments about the prototype presentation technical failures (18%, see Table 4) or the hydrogel technical disadvantages (20 %, see Table 4) shown during the IBL activity with comments like: "I didn't like the colors selection for the presentation display because it was difficult to understand the measurement". These findings suggest that this type of IBL activity could be used to help engineering students learn new topics and expand their knowledge about topics that they have previously learned in class [16]. As presented in Q5 in Table 1, 65% of participants reported improving their knowledge about electronics-related topics that they have previously learned in class, showing that IBL activities could be helpful in reinforcing students' understanding of topics taught in regular lectures [47]. Participants reported that they developed a better understanding of topics such as sensor design and applications (33 % see Table 5) and data measuring and programming (31 % see Table 5) with positive comments such as: "I understood how the sensor works very well, and how it sends data about the resistance measures and the size changes. I understood its functionality and applications perfectly". On the other hand, 20 % of participants (see Table 5) expressed that more examples of applications in different areas were missing during the presentation to help them develop their previous knowledge about electronics topics and applications, with comments like: "A deeper explanation of applications of this type of sensors in different fields was missing, as well as its [the sensor] disadvantages".

Even when some participants commented on some negative aspects of the IBL activity that could be improved in future presentations, almost all participants (94 %, see Q7 in Table 2) reported that they would like more electronics-related courses to use this type of prototype presentations as a teaching tool to explain new concepts. Participants pinpointed that IBL activities could help them to understand concepts that could be confusing if they are taught only with theory [10], [20], with 54% of participants (see Table 6) expressing comments such as: "the practical examples are more interesting. I think that seeing the development of this type of experiment reinforces the theoretical knowledge as we understand how it [the sensor] works and the applications that it might have". Furthermore, 26 % of participants (see Table 6) reported that this prototype demonstration motivated them to think about the design of other technological solutions using electronic applications, with comments like: "It [the prototype presentation] motivates you to imagine new experiments since many of the things we do in class are very common and repetitive". These findings are essential because electronics engineering students' understanding of basic electronics concepts is fundamental to the development of new technological solutions and applications, and improving engineering students' motivation to think and develop technological designs is a paramount goal of STEM educators around the world [1]. Including more IBL activities in their courses could help electronics engineering educators get their students involved in more prototype designs and build a learning environment where students could develop their own knowledge through experimentation and self-conducted research [18].

After the IBL activity, 67 % of the participants (see Q9 in Table 2) reported that they would be able to design and develop a different prototype applying similar concepts to the ones used in the presentation. Approximately half of the participants (44 %, see Table 7) reported that their main idea to design their prototype would be using similar nanosensors and measuring concepts used during the presentation to design a new application in a different field, with comments such as: "it [the new prototype] could be about electronics applications in screens. In sports aiming to improve the shoes, measuring its deformation or efficiency". These findings suggest that having more IBL activities in electronics engineering courses could help students develop their interest in designing more technological solutions to solve global problems [17], since 65 % of participants (see Q11 in Table 2) stated that they feel confident that they can think of industrial problems that could be solved by designing new technologies that apply electronics-related topics. Most of the participants' ideas to solve industrial issues were based on the topics presented in the IBL activity, with 28 % of participants (see Table 8) reporting that they would use sensors' applications in different industries; and 20 % of participants (see Table 8) stating that they would analyze the wear and movement of industrial materials with comments like: "It could be an experiment with different sensors' sizes to use it in bigger things, as measurements of metallic structures to evaluate how these structures are affected by the heat".

On the other hand, most of the participants' negative responses suggested that the biggest challenge in developing technological solutions to industrial problems was that they lacked an understanding of the current problems that industries are facing [12]. This was a recurrent response, with 26 % of the participants (see Table 8) reporting comments such as: "At the beginning, what is missing is facing the industry problems and the understanding of the industry to seek ways to use the sensors [in technological solutions]". In addition to the lack of knowledge of the current industry needs, 20 % of the participants (see Table 7) reported that they feel that they are missing a better understanding of the theory to be able to design new technological solutions using electronics applications, with comments like: "I don't have enough knowledge about these devices [sensors] and the theory to imagine more applications"; and 15 % of participants (see Table 6) mentioned that the prototype and experimentation process could be costly and time-consuming as the main reason to avoid this type of activities in their classes and free time, with comments such as: "I could definitively develop a project where chemistry and electronics engineering work together, but I would face the challenge of lacking chemistry materials and lab resources". Electronics engineering professors and educators should try to facilitate their students' access to laboratories where they can practice their theoretical knowledge; this way, students can design and build prototypes that may develop into technological solutions for global problems. In addition, electronics engineering professors need to include more industrial visits [12] and interactions with industry workers and owners that may facilitate the connection with real-life industry examples in their courses' designs, aiming to help their students understand the current industrial needs. These industrial connections would motivate students to think of solutions using electronic applications, as well as new ideas to develop prototypes and technological solutions that may help their society's development.

The quantitative analysis comparing the data collected from electronics engineering students in the sixth and ninth semesters provides insightful feedback on the impact of the IBL activity implemented through a hands-on experiment involving CNTs. The data analysis showed high engagement and perceived educational value among the students in both semesters, with no statistically significant differences in the responses between the two groups. This uniformity suggests that IBL activities, particularly when involving cutting-edge technologies like CNTs, are equally effective across different academic stages fostering a deeper understanding of electronics concepts and enhancing student motivation.

Learning New Concepts: Both sixth (94.7%) and ninth (100%) semester students reported learning something new through the experiment presentation (see Table 9), indicating the effectiveness of IBL activities in introducing novel scientific concepts and applications. This outcome aligns with existing literature advocating for IBL's role in enhancing conceptual understanding and engagement in STEM education [2].

Prior Experience With Experimental Learning: There was a noticeable difference, though not statistically significant ($p = 0.07$, see Table 9), in prior exposure to experimental learning tools between the two groups. A higher proportion of ninth-semester students (37.84%) reported previous experience compared to sixth-semester students (21.62%). This variation may reflect curriculum differences or an accumulation of experiences as students progress in their studies.

Enhancement of Knowledge: Both groups reported an improvement in their understanding of electronics-related topics, with 36.84% of sixth-semester and 26.32% of ninth-semester students acknowledging this benefit (see Table 9). The lack of a statistically significant difference ($p = 0.179$) underscores the role of IBL activities in reinforcingexistingknowledge irrespective of the student's academic level.

Preference for IBL Methods: The strong preference for more electronics-related courses using experiments as a teaching tool (97.4% in the sixth semester and 100% in the ninth semester, see Table 9) emphasizes the value students place on practical, hands-on learning approaches. This universal appeal highlights the potential for broader adoption of IBL strategies in the curriculum.

Application of Learned Concepts: When asked about their ability to design and develop new experiments applying the learned concepts in a different way, about one-third of students from each group felt capable (see Table 9), demonstrating the IBL's effectiveness in fostering creativity and applied thinking in engineering contexts.

Solving Real-world Problems: Finally, more ninth-semester students (39.47%) than sixth-semester students (26.32%) felt confident in applying electronics-related topics to solve real-world problems (see Table 9), though this difference was not statistically significant ($p = 0.87$). This suggests that as students advance, they might perceive a greater ability to apply their knowledge practically, potentially due to the cumulative effect of their education.

The inferential analysis carried out with the dichotomous questions showed similar conclusions to the ones observed during the qualitative analysis. These findings suggest that the IBL activity was an effective educational strategy in electronics engineering across different academic stages. Both sixth and ninth-semester students benefited from the enhanced understanding of complex topics, improved engagement, and increased motivation to apply knowledge to real-world problems. These outcomes support the continued use and expansion of IBL methodologies in STEM education [2], [11], [12], advocating for its integration at various levels of the curriculum to better prepare students for professional challenges in the field of electronics engineering. This research study contributes to the growing body of evidence that hands-on and inquiry-based educational practices can significantly enhance the learning experience in engineering education, promoting deeper learning and greater student involvement.

VI. CONCLUSION

The IBL activity helped electronics engineering students to understand new topics and expand their understanding of the electronics-related topics that they had previously learned in their classes. These findings suggest that more IBL activities should be included in electronics engineering courses. This way, electronics engineering students could observe the functioning of prototypes and interact with experiments and laboratory equipment, aiming to develop their abilities to design and build technological applications. Additionally, having more IBL activities in class could motivate students to get involved in more self-directed prototype designs and experiments, which ultimately would have a positive impact on their relationship with the industry and its growing need for more technological solutions to the orb's most relevant problems.

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ETHICS STATEMENT

This study was carried out with human participants whose protocol was reviewed and approved by the Research and Ethics Committees, respectively, by the Vicerectory of Education at Tecnologico de Durango, Durango, Mexico. The students who agreed to participate in the study signed an informed consent letter.

AUTHOR CONTRIBUTIONS

The authors' contribution is presented in the title page.

DECLARATION OF COMPETING INTEREST

The authors declare there is no conflict of interest.

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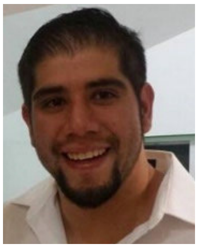

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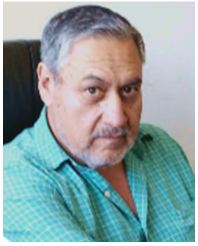

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