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Nanotechnology and Electronic Sensor Education Through a Research Project on Graphene-based Tactile Sensors

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Abstract:

Advances in nanomaterials and nanotechnology continue to transform the semiconductor and sensor industries, driving demand for engineers who can connect nanoscale material properties to functional electronic devices and systems. However, undergraduate engineering curricula often provide limited opportunities for students to engage directly in nanotechnology research, particularly in ways that integrate material fabrication, device characterization, and system-level application. This work aims to address such gaps by introducing a semester-long small-scale research project with nanotechnology research component into an undergraduate engineering program. Students participated in a mentored research project focused on developing flexible tactile sensors based on laser-induced graphene (LIG). The practical work centered on creating and characterizing LIG electrodes patterned onto flexible polyimide substrates using a commercial laser engraving machine. LIG is a conductive nanostructured carbon material which exhibits high electrical conductivity and mechanical flexibility, making it suitable for conformable sensor applications. Students designed electrode geometries using CAD tools, fabricated the LIG electrodes, and examined both structural and electrical properties of graphene films using Optical Microscopy, Raman Spectroscopy, Four-point Probe Resistivity measurements, and Scanning Electron Microscopy. The fabricated graphene electrodes were then coupled to a front-end readout circuit and a microcontroller to sense human touch. The project culminated in a functional human-computer interaction demonstration by using the fabricated tactile sensors as an input device to play a computer game, and a public research symposium presentation.

This paper presents a Scholarship of Teaching and Learning (SoTL) study examining the educational impact of embedding such mentored, research-based project on graphene-based tactile sensors into an undergraduate engineering course. The educational impact of the project was investigated using qualitative thematic analysis of end-of-semester student reflection essays. An inductive coding process identified recurring themes related to conceptual understanding of nanomaterials, systems-level reasoning in sensor design, research-oriented problem-solving practices, professional skill development, teamwork dynamics, and emerging research identity. Cross-case analysis revealed consistent evidence that engagement in an end-to-end nanotechnology research workflow supported deeper conceptual integration across materials, electronics, and systems, while also fostering research self-efficacy and professional competencies, such as teamwork, communication, documentation, and time management. The study demonstrates that accessible nanomaterial platforms such as laser-induced graphene can provide rigorous and authentic learning experiences that meaningfully bridge theory and practice in undergraduate engineering education.

INTRODUCTION:

Nanotechnology has emerged as a foundational driver of innovation across modern engineering, impacting fields ranging from semiconductors and flexible electronics to biomedical devices, human-computer interfacing (HCI), and cyber-physical systems. As demand for flexible conformal wearable electronics emerges, scientists and engineers are trying to explore and exploit unique properties of novel low-dimensional electronic materials to fabricate modern devices. Two-dimensional (2D) materials, such as graphene offers exceptional electrical conductivity, mechanical flexibility, and thermal conductivity, thus unlocking possibilities for entirely new classes of flexible electronic devices and applications.

Despite the rapid adoption of nanotechnology in industry and research, undergraduate engineering curricula have often lagged behind. In many programs, nanotechnology is introduced primarily through lecture-based formats that emphasize theoretical models and fundamental materials science concepts. While these approaches establish the necessary conceptual foundations, they limit hands-on opportunities to engage directly with nanomaterials, particularly fabrication and applications in integrated devices and systems. Consequently, students may develop a fragmented understanding of how nanomaterials and nanotechnology can be utilized to achieve functional engineering solutions. This gap between theory and practice is especially apparent in electronic sensor education. Sensor performance depends on a complex interplay of material properties, device design, fabrication methods, readout electronics, data processing algorithms, and environmental conditions. When these components are taught in isolation, students may struggle to develop systems-level understanding or research-oriented problem-solving skills. For instance, students may learn sensing transduction mechanisms in one course and materials science concepts in another, without clearly seeing how these areas converge in real-world functioning devices. Such compartmentalization can hinder students' ability to approach problems holistically and to integrate knowledge across disciplinary boundaries. Thus, nanotechnology education can benefit from such end-to-end experiential project-based approaches to bridge this gap and to better prepare students for emerging technical domains [1, 2].

This paper presents a qualitative study of a research-based project centered on graphene-based tactile sensors fabricated using laser-induced graphene (LIG). The undergraduate research project integrates nanomaterial fabrication, characterization, electronics interfacing, programming, and demonstration of a functional tactile sensing system. The study examines how participation in an end-to-end nanotechnology research experience influenced undergraduate students' conceptual understanding, problem-solving approaches, professional skills, and research identity.

BACKGROUND AND RELEVANT WORK:

A. Challenges in Nanotechnology Education:

Nanotechnology education poses unique challenges due to the abstract nature of nanoscale phenomena and the interdisciplinary knowledge required to understand them. Unlike macroscale engineering systems, nanoscale structures cannot be directly observed without specialized instrumentation and characterization techniques, making it difficult for students to develop intuitive mental models. Research has shown that students often struggle to relate nanoscale structure to macroscopic behavior, particularly when instruction relies heavily on symbolic or mathematical representations without experiential grounding [3-5]. Additionally, nanotechnology spans multiple disciplinary domains, including materials science, physics, chemistry, and electrical engineering. Students may encounter these domains in separate courses, leading to fragmented understanding. Without opportunities to integrate knowledge across disciplines, students may fail to appreciate how nanoscale material properties influence device performance and system functionality.

B. Project-Based and Research-Integrated Learning:

Project-based learning (PBL) has been widely adopted as a means of addressing the above-mentioned challenges. PBL emphasizes active engagement, collaboration, and application of knowledge to open-ended problems. In engineering education, PBL has been associated with improved conceptual understanding, increased motivation, and enhanced professional skills [6-9]. Research-integrated projects extend PBL by engaging students in authentic and exploratory research activities rather than predefined laboratory exercises. Students are required to navigate uncertainty, make design decisions, and interpret results – experiences that support systems thinking and professional identity formation.

Undergraduate research experiences have been shown to play a critical role in shaping students' academic identity and career aspirations. Studies consistently report that participation in research enhances students' self-efficacy, sense of belonging in STEM fields, and interest in graduate study [10-12]. These effects are particularly pronounced when research experiences involve meaningful contributions and tangible outcomes. In emerging fields such as nanotechnology, undergraduate research can demystify complex concepts and expose students to realistic career pathways. By engaging in authentic research, students begin to see themselves as capable contributors to technological advancement.

C. Research-Based Projects in Other Engineering Fields:

Research-based and project-based learning (RBL and PBL) approaches have been widely proposed as mechanisms for addressing fragmentation in engineering education. By engaging students in authentic design and inquiry, such approaches expose learners to uncertainty, iteration, and interdisciplinary integration – key elements of professional engineering practice. Within the Scholarship of Teaching and Learning (SoTL), research-based instructional interventions are examined not merely for technical outcomes, but for how they shape learning processes, professional identity, and epistemological development.

Across multiple engineering disciplines, educators have reported positive impacts of research-integrated and project-based learning on student outcomes. Noguez and Neri (2019) implemented research-based learning modules in which undergraduate students engaged in research projects, developing competencies in information retrieval, hypothesis testing, handling big data, algorithm development, application of deep learning, data analysis, and communication of results. Their study demonstrated that such activities – ranging from algorithm design and evaluation to preparing monographs and presenting their findings, enabled students to acquire the research skills necessary for professional practice or graduate studies [13]. Savage, Chen, and Vanasupa (2008) reported on curriculum-wide project-based learning initiatives in which students were engaged in interdisciplinary engineering projects, enhancing their ability to apply theoretical knowledge to real-world contexts and strengthening collaborative problem-solving skills [14]. Similar implementation in biotechnology, where students working on laboratory-based projects developed analytical, communication, and teamwork skills while increased motivation and commitment [15]. In another study by Palencia and Ontiveros, computer engineering students improved their understanding of statistics and probability through applied, research-driven tasks [16]. Other studies highlight structured RBL approaches, such as the 'Requirement, Reviewing, Solution, Discussion, and Improvement (RRSDI)' model in telecommunications engineering, which integrates research into the learning process and fosters both technical knowledge and real-world problem-solving skills [17]. In civil engineering, blended RBL and PBL approaches demonstrated the importance of gradually increasing student autonomy [18]. Overall, RBL has been shown to enhance student engagement, practical competence, and readiness for further studies or professional careers [19]. Across all these science and engineering domains, research-integrated project work consistently leads to enhanced conceptual understanding, stronger professional identity, and greater motivation toward future research or careers. Importantly, these works support the pedagogical significance of research-based projects even outside of nanotechnology or materials science and reinforces the premise that *active participation in the practice of research, specifically through hands-on undergraduate research fundamentally reshape how students learn and perceive the field of engineering*.

D. Research-Based Nanotechnology Projects in Engineering Education:

In the field of nanotechnology education, some prior works reported that integrated hands-on project-based training can provide authentic learning experiences. For example, Strachan et al. described a research-enhanced undergraduate laboratory practical in which students synthesized and characterized silver nanoparticles and analyzed their catalytic activity, demonstrating that engagement in research-like laboratory projects supports understanding of nanoscale materials and characterization techniques [20]. In another study, Vahedi and Farnoud reported novel experimental modules designed to introduce students to nanoparticle characterization, where learners performed hands-on experiments, interpreted data, and were assessed on their analytical decision-making, illustrating the pedagogical value of project-based learning in nanotechnology education [21]. Studies have also highlighted that participation in research-oriented nano projects helps students build confidence with nanomaterials processing and characterization techniques and strengthens their identities as scientists [22]. Plass et al. described an undergraduate nanomaterials research program where students participated in faculty-led projects on nanorod synthesis and characterization, contributing to ongoing research while developing skills in experimental design, data analysis, and scientific communication [23]. Similarly, Kittredge et al. implemented a series of vertically integrated nanotechnology projects across multiple courses, allowing students to engage in progressively complex, research-like investigations that built both technical expertise and research competencies [24]. These prior works support the pedagogical significance of engaging students in authentic inquiry and strengthens the rationale for extending research-based project designs into graphene and tactile sensor contexts. This paper presents a qualitative SoTL study of a semester-long, research-based project centered on graphene-based tactile sensors. The study examines how participation in an end-to-end nanotechnology research experience influenced undergraduate students' conceptual understanding, problem-solving approaches, professional skills, and research identity.

E. Laser-Induced Graphene (LIG) Sensors as a Nanotechnology Educational Tool

Laser-induced graphene has emerged as a versatile platform for flexible electronics and sensing applications. The process involves converting polymer substrates into porous multi-layer graphene structures through localized laser irradiation [25-27]. LIG fabrication is rapid, visually engaging, and compatible with commercially available low-cost laser engraving systems, thus making it particularly suitable for undergraduate educational settings. From a pedagogical perspective, LIG as the nanotechnology platform offers several advantages at the introductory stage: it eliminates the need for chemical processing, reduces safety concerns, and allows students to directly observe the relationship between fabrication parameters and material properties. LIG's electrical conductivity and mechanical flexibility make it suitable for the fabrication of tactile sensors and a variety of other types of electronic sensors, wearable electronics, and HCI applications, rendering it particularly attractive for undergraduate education, and therefore is an effective vehicle for teaching structure–property–function relationships in nanotechnology.

COURSE CONTEXT AND LEARNING OBJECTIVES:

The study was conducted within an undergraduate Electrical Engineering degree program. The project was embedded in an upper-level elective course focused broadly on electronic materials and devices with strong emphasis on laboratory-based hands-on experiential learning. All participating students had completed foundational coursework in semiconductors, circuit analysis, and physics prior to enrollment. The course was based on hands-on lab activities, where instructions and direct training to students were provided in the laboratory.

Learning Objectives: The specific project has the following learning objectives:

1. Demonstrate basic knowledge of nanomaterials, such as graphene.
2. Apply laser-based fabrication techniques to produce graphene.
3. Perform sensor electrode design and fabricate graphene sensors.
4. Characterize the fabricated graphene samples.
5. Integrate tactile sensors with front-end electronics and a microcontroller.
6. Perform programming and demonstrate a functional tactile sensor application.
7. Develop technical presentation and communication skills.

PROJECT DESIGN AND IMPLEMENTATION

A. Laser-Induced Graphene (LIG) Sensor Fabrication:

Students worked in a small team of four, comprising of three undergraduates and a graduate student in electrical and computer engineering. Total four students were engaged in this project. Faculty mentorship emphasized guidance, feedback, and laboratory meetings on a weekly basis. Students fabricated LIG electrodes by patterning polyimide substrates using a commercial benchtop laser engraving machine equipped with a 450 nm laser. Two scanning galvo mirrors steer the laser beam to focus on the substrate and directly create complex graphene electrode patterns which can be observed in real-time through the front window of the machine. Photograph of the laser engraver used in this project is shown in Fig. 1(a). The laser 'power' and 'depth' parameters in the control software were tuned to obtain high quality graphene samples. For this purpose, students created a set of 25 graphene samples, each engraved using a specific value of laser power and engraving depth parameter within the instrument's allowable range. These samples were characterized and the quality of graphene samples were evaluated based on mechanical adhesion, Raman signature, and electrical conductivity. After analyzing all 25 samples, 10% 'depth' and 25% 'power' settings were concluded to be the best setting for this laser engraver machine and the given polyimide (PI) substrates used in this research, yielding the optimal quality graphene. These optimal parameters were used in the next steps to fabricate tactile sensor electrode patterns.

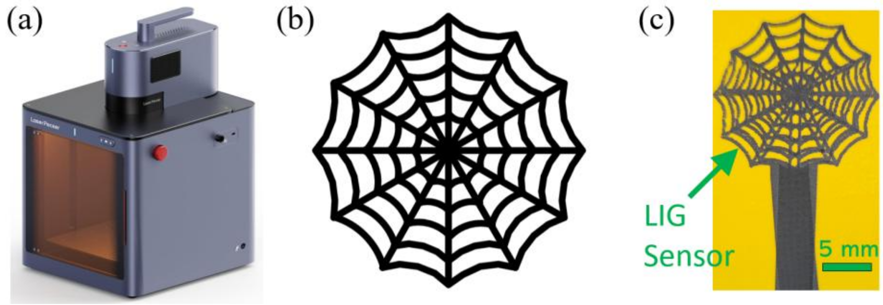

Fig. 1. (a) Laser Pecker LP5 laser engraving machine, (b) CAD design of electrode, (c) fabricated laser-induced graphene electrode sensor.

The sensor electrode design is depicted in Fig. 1(b). The design was created using a CAD tool and then the image file was loaded into the laser engraver software platform for laser writing.

B. Structural and Electrical Characterization:

Characterization activities included optical microscopy, Raman spectroscopy, four-point probe resistivity measurements, and Scanning Electron Microscopy (SEM). These activities reinforced theoretical discussions on carbon nanostructures and nanomaterial characterization techniques.

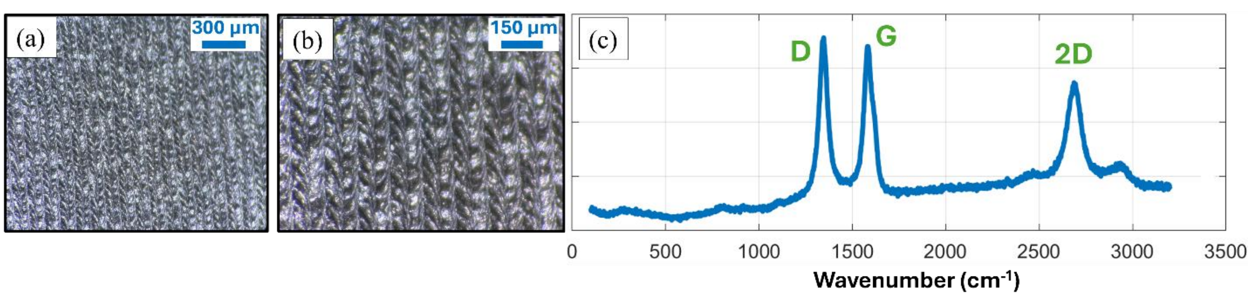

Fig. 2. (a–b) Optical micrographs of best LIG sample, and (c) Raman spectra of the sample.

Optical Microscopy and Raman spectroscopy were performed on the LIG samples which exhibited good mechanical adhesion. As shown in Fig. 2(c), Raman spectra confirmed the formation of graphene with strong D, G, and 2D peaks which originate from in-plane vibration of sp^2 carbon atoms and defect-activated breathing mode of sp^2 rings in graphene. Students analyzed the Raman peaks and the best LIG sample revealed a G/D ratio of 0.575 and a 2D/G ratio of 0.724, representing high-quality multi-layer graphene structure with relatively low defects.

Table 1. Four Point Probe Resistivity Results

	Spot # 1	Spot # 2	Spot # 3	Average
Current (mA)	1 mA	1 mA	1 mA	1 mA
Voltage (mV)	19.80 mV	21.62 mV	20.51 mV	20.64 mV
Sheet Resistance	89.74 Ω/Sq	97.99 Ω/Sq	92.97 Ω/Sq	93.6 Ω/Sq

Electrical sheet resistance measurements were performed on the fabricated LIG samples using four-point probe technique. Large area samples were fabricated for this purpose. On each sample, three measurements were performed at three slightly different spots near the center of the sample and then averaged to determine the sheet resistance. Table 1 summarizes the sheet resistance data obtained for a graphene sample that was produced using 25% laser 'power' and 10% 'depth' settings.

C. Sensor Integration and Human–Computer Interaction Demonstration

Students integrated the fabricated LIG electrodes into tactile sensing assemblies using copper tapes and alligator clamps and interfaced them with front-end readout circuits and an ESP32 microcontroller. Firmware development and deployment through Arduino IDE enabled real-time data acquisition and signal processing. The fabricated LIG sensors were interfaced with a capacitance sensor controller chip (MPR121), which applies an excitation signal to the LIG electrode and measures the capacitance. The MPR121 was interfaced with the ESP32 board and it and sends the measured capacitance values to the microcontroller using I²C protocol. Schematic of the touch sensing measurement setup is shown in Fig. 3(a).

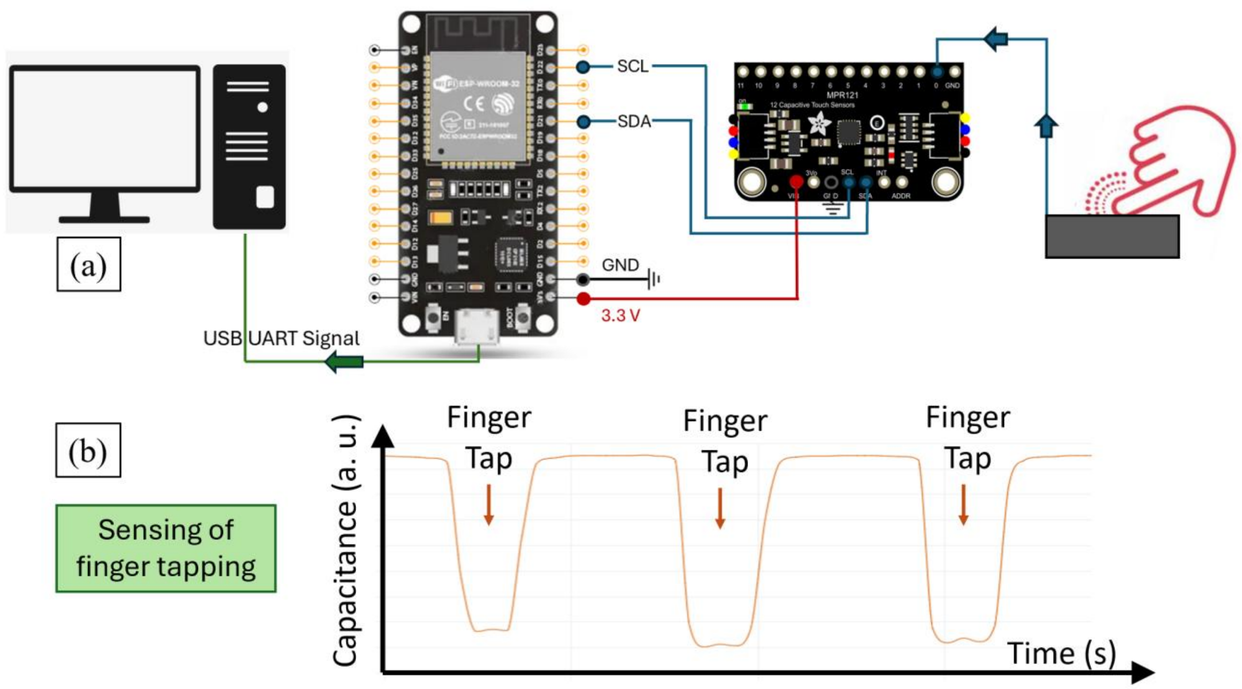

Fig. 3. (a) Touch sensor measurement setup, and (b) Time-series sensor data plot showing finger tapping events.

The optimal configurations and thresholds for the MPR121 chip to detect finger touch and release events were programmed through the microcontroller firmware. The microcontroller sends the capacitance values at every 10 ms interval to a computer over USB. The sensor data was plotted in real-time on a serial monitor window, as presented in Fig. 3(b). Finger taps on the tactile sensor produced valley as evidenced in Fig. 3(b). The capacitance value drops and stays at the lower value as long as the finger is in contact with the LIG electrodes, and jumps back to equilibrium when the finger is release. As a result, the tap and press actions could be clearly identified, which demonstrates a functional tactile sensor that can be used in human-computer interface (HCI) applications.

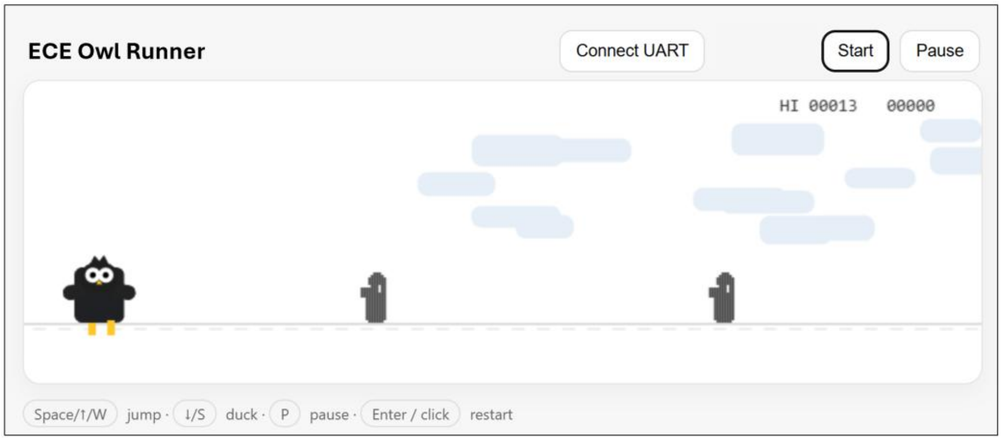

Fig. 4. Web browser-based computer game created in Javascript to demonstrate sensor's application in real-life human-computer interaction.

Finally, the project culminated in a system-level demonstration in which the tactile sensors were used as input devices to control a computer game. This application provided immediate, tangible feedback on sensor performance. Students developed a web browser-based computer game in JavaScript to demonstrate human-computer interaction application. In this endless runner type game, tapping the LIG sensor allowed the owl character to jump across barriers (Fig. 4).

ASSESSMENT AND RESULTS

This study employed a qualitative SoTL framework focused on examining evidence of student learning through authentic artifacts. The study analyzed student reflection essays submitted at the end of the semester. All students submitted individual reflection essays addressing their learning experiences, challenges, teamwork, and perceived relevance of the project. The reflection essays were a required activity. Thematic analysis revealed rich insights into both technical growth and professional development throughout the semester. Analysis followed Braun and Clarke's six-step thematic analysis framework, including data familiarization, initial coding, theme development, reviewing, defining, and reporting [28]. Four overarching themes emerged as listed below:

(i) Technical Skill Development
(ii) Systems Thinking and Problem-Solving
(iii) Collaboration and Professional Skills
(iv) Research Identity and Motivation

(i) Technical Skill Development:

All students reported substantial growth in hands-on technical skills, particularly in laser-induced graphene (LIG) fabrication, device characterization, and sensor integration. Students engaged directly in generating graphene patterns on flexible polyimide substrates and experimenting with laser machine parameters to optimize electrode quality. They also analyzed samples via Raman spectroscopy to interpret 2D, G, and D peaks and their ratios, linking defects and graphene quality to usability and device performance. A few representative quotes are given below: "Firsthand, I got to see the creation of laser-induced graphene using polyimide… the highest power/depth settings… caused slight peeling". "I did literature research... This allowed me to analyze Raman data, including the 2D, G, and D peaks and their ratios... I now understand what each peak means in terms of defects, layer structure, and crystallinity of the graphene".

Students designed and implemented functional **capacitive touch sensor systems**, integrating electrodes with MPR121 capacitive touch-sense chips, ESP32 microcontrollers, and interactive software interfaces. They developed schematic diagrams and block diagrams linking tactile input to graphical user applications. A few representative quotes are given below: "my colleague and I were able to create a block diagram of the entire capacitive touch-sense system from the finger touching the sample to the MPR121 to the ESP32 to the application of a key signal for a computer application".

Students also gained experience with **front-end electronics**, capacitance-to-digital converters, and evaluating sensor performance under real-world conditions, including repeated mechanical stress and environmental variability.

Table 2. Summary of Technical Skills Developed

Skill Area	Specific Activities	Students Reporting
LIG Fabrication	Laser patterning on polyimide, power/depth optimization	4/4
Characterization	Raman spectroscopy, optical microscopy, defect/layer analysis	3/4
Sensor Integration	MPR121, ESP32, interactive game/application	4/4
Embedded Electronics	electronics, firmware, touch-sensing circuits	3/4

(ii) Systems Thinking and Problem-Solving:

Students emphasized the importance of **viewing the research project as an interconnected system**, rather than isolated tasks. They learned to identify sources of error across multiple components, including noise, signal drift, environmental effects, and mechanical variations. Iterative testing and validation became critical, reinforcing a holistic understanding of sensor performance and embedded systems. Some representative quotes are given below: "One major learning for me this semester was to treat measurement problems as full system problems… If something is wrong, it can be due to noise, poor contact, wrong timing, temperature effects, or even small changes in how the setup is handled". "I learned to make simple test cases and verify each part separately before trusting the final output". "Working through technical challenges and adjusting to unexpected changes improved my problem-solving abilities and showed me that research is an iterative process requiring patience and persistence".

(iii)Collaboration and Professional Skills:

Students consistently highlighted collaboration, communication, and organizational skills as major areas of growth. Task delegation, documentation, and coordinated experimentation were essential for timely completion of the symposium poster and system demonstration. Maintaining lab notes, shared files, and clear communication enhanced both technical accuracy and team efficiency. Some representative quotes are given below: "Collaborating with lab mates strengthened my communication skills and reinforced the importance of teamwork in engineering research". "Organization has been extremely important because inside and outside of labs… ". "Whether it's an EXCEL experimental datasheet, a diagram, a presentation, or documentation, it is important that those files are easily accessible and easy to interpret". "…progress depends on good coordination, like sharing updates, discussing issues, and aligning on the next steps".

Table 3. Summary of Professional and Collaborative Skills Development

Skill Area	Observed Growth	Representative Quote
Communication	Explaining technical concepts, responding to questions	"I felt clear and confident explaining the scope of our project"
Teamwork	Coordinating experiments and poster preparation	"Collaborating with lab mates strengthened my communication skills"
Time Management	Balancing research, coursework, and symposium preparation	"Having to balance coursework, personal obligations, research responsibilities, and symposium preparation required careful planning"
Documentation	Maintaining lab notes, schematics, and datasheets	"Documentation is useful not only for final reporting, but also for debugging"

(iv) Research Identity and Motivation:

Participation in research enhanced students' confidence, curiosity, and motivation to pursue future research opportunities. Exposure to hands-on experimentation and integrated device design strengthened their sense of belonging in STEM research. Presenting at the Fall Symposium reinforced achievement and recognition of their work in a public forum. Some representative quotes are given below: "Working on the graphene-based touch sensor project has strengthened my technical knowledge and exposed me to emerging research areas". Overall, this experience increased my confidence and has motivated me to continue pursuing research where I can combine theory with experimentation and contribute to society as an engineer". "Despite the strife, the research I've participated in has given me great joy…".

Table 4. Summary of Thematic Findings Across Students

Theme	Subtheme	Students Reporting	Representative Quote
Technical Skills	LIG fabrication, Raman spectroscopy, sensor integration	4/4	"…observe the physical characteristics… highest power… caused slight peeling".
Systems Thinking	Iterative testing, system-level problem solving	4/4	"…treat measurement problems as full system problems".

Theme	Subtheme	Students Reporting	Representative Quote
Collaboration & Professionalism	Teamwork, communication, documentation	4/4	"…progress depends on good coordination… sharing updates, discussing issues, and aligning next steps".
Research Identity	Confidence, motivation, engagement	4/4	"I recognize clear growth in my confidence as a researcher". "…this experience increased my confidence… motivated me to continue pursuing research"

CONCLUSIONS:

The findings indicate that the LIG tactile sensor project effectively supported deep, integrative learning across cognitive and affective domains. The end-to-end structure enabled students to connect nanomaterials fabrication and nanotechnology with tangible system-level outcomes, addressing a key gap in nanotechnology education. The study demonstrates that embedding small comprehensive research projects, such as this laser-induced graphene tactile sensor-based research project within an undergraduate engineering course can significantly enhance student learning in nanotechnology and electronic sensors. Through authentic, end-to-end research experiences, students developed robust understanding, effective problem-solving skills, increased research self-efficacy, and gained experience in real-world engineering solution with nanotechnology application. The findings support the integration of LIG-based projects as a scalable and impactful model for nanotechnology education.

REFERENCES:

[1] J. V. Ernst, Nanotechnology Education: Contemporary Content and Approaches, The Journal of Technology Studies, vol. 35, pp. 3-8, 2009.

[2] S. Lavado-Anguera, P.-J. Velasco-Quintana, and M.-J. Terrón-López, "Project-Based Learning (PBL) as an Experiential Pedagogical Methodology in Engineering Education: A Review of the Literature," Education Sciences, vol. 14, no. 6: 617, 2024.

[3] M. G. Jones, R. Blonder, G. E. Gardner, V. Albe, M. Falvo, and J. Chevrier, "Nanotechnology and Nanoscale Science: Educational challenges", International Journal of Science Education, vol. 35, pp. 1490-1512, 2013.

[4] A. O. Joseph, and K. Teker, "The Impact of Hands-on Experience in Undergraduate Nanotechnology Education", MRS Online Proceedings Library, vol. 1320, article no. 404, 2011.

[5] Y. Zhu, J. B. Tracy, J. Dong, X. Jiang, M. G. Jones, and G. Childers, "Teaching a multidisciplinary nanotechnology laboratory course to undergraduate students", Journal of Nano Education, vol. 5, pp. 1–10, 2013.

[6] M. Prince, "Does active learning work? A review of the research," Journal of Engineering Education, vol. 93, no. 3, pp. 223–231, 2004.

[7] J. E. Mills and D. F. Treagust, “Engineering education – Is problem-based or project-based learning the answer?” Australasian Journal of Engineering Education, vol. 3, no. 2, pp. 2–16, 2003.

[8] A. Kolmos, F. K. Fink, and L. Krogh, The Aalborg PBL Model: Progress, Diversity and Challenges, Aalborg, Denmark: Aalborg Univ. Press, 2004.

[9] V. Sooklal, and S. Das, “Impact of an Interdisciplinary Engineering Design Project on First Year Students”, 2025 ASEE Southeast Conference, Mississippi. Doi: 10.18260/1-2--54174.

[10] D. Lopatto, “Undergraduate research experiences support science career decisions and active learning,” CBE Life Sciences Education, vol. 6, no. 4, pp. 297–306, 2007.

[11] E. Seymour, A.-B. Hunter, S. L. Laursen, and T. DeAntoni, “Establishing the benefits of research experiences for undergraduates in the sciences: First findings from a three-year study,” Science Education, vol. 88, pp. 493–534, 2004.

[12] S. H. Russell, M. P. Hancock, and J. McCullough, “Benefits of undergraduate research experiences,” Science, vol. 316, no. 5824, pp. 548–549, 2007.

[13] J. Noguez, and L. Neri, “Research-based learning: a case study for engineering students”, International Journal on Interactive Design and Manufacturing (IJIDeM), vol. 13, pp. 1283–1295, 2019.

[14] R. N. Savage, K. C. Chen, and L. Vanasupa, “Integrating project-based learning throughout the undergraduate engineering curriculum”, Journal of STEM Education: Innovations and Research, vol. 8, pp. 29–39, 2008.

[15] K. Mayolo-Deloisa, A. M. Ramos-de-la-Peña, and O. Aguilar, “Research-based learning as a strategy for the integration of theory and practice and the development of disciplinary competencies in engineering”, International Journal on Interactive Design and Manufacturing (IJIDeM), 13(4), 1331–1340, 2019.

[16] J. L. D. Palencia, and Y. O. Ontiveros, “A classroom experience about the application of research-based learning for the teaching of probability in engineering”, STEM Education, vol. 4(2), 127–141, 2024.

[17] N. Intarawiset, S. Noulnoppadol, R. Jeenawong, and S. Akatimagool, “Development of research-based RRSDI learning model for telecommunication engineering education”, The impact of the 4th industrial revolution on engineering education, vol. 1134, pp. 674–683, 2020.

[18] N. Bartels, and K. Stolz, “Project- and research-based teaching in civil engineering”, International Journal of Engineering Pedagogy (iJEP), vol. 14(6), pp. 23–36, 2024.

[19] A. W. Setiawan, “Development of research-based learning in introduction to biomedical engineering course for undergraduate electrical engineering students”, 2020 10th Electrical Power, Electronics, Communications, Controls and Informatics Seminar (EECCIS), pp. 273–277, Malang, Indonesia, 2020.

[20] J. Strachan, C. Barnett, T. Maschmeyer, A. F. MastersAlice MotionAlexander K. L. Yuen, “Nanoparticles for Undergraduates: Creation, Characterization, and Catalysis”, Journal of Chemical Education, vol. 97, pp. 4166–4172, 2020.

[21] A. Vahedi and A. M. Farnoud, “Novel experimental modules to introduce students to nanoparticle characterization in a chemical engineering course,” Journal of Chemical Education, vol. 96, no. 9, pp. 2029–2035, 2019.

[22] A. E. Sweeney, P. Vaidyanathan, and S. Seal, “Undergraduate research and education in nanotechnology,” International Journal of Engineering Education, vol. 22, no. 1, pp. 157–170, 2006.

[23] K. E. Plass, J. J. Stapleton, J. L. Morford, R. E. Schaak, and A. C. T. van Duin, “Nanomaterials Research at a Primarily Undergraduate Institution: Transforming Nanorods, Undergraduate Research Communities, and Infrastructure,” ACS Nanoscience Au, vol. 4, no. 4, pp. 223–234, 2024.

[24] K. W. Kittredge, L. E. Russell, and M. C. Leopold, “A Series of Vertically Integrated Nanotechnology Experiments for the Undergraduate Curriculum,” The Chemical Educator, vol. 12, pp. 155–158, 2007.

[25] J. Lin, Z. Peng, Y. Liu, F. Ruiz-Zepeda, R. Ye, E. L. G. Samuel, M. J. Yacaman, B. I. Yakobson, and J. M. Tour, “Laser-induced porous graphene films from commercial polymers,” Nature Communications, vol. 5, Article 5714, 2014.

[26] H. Liu and Y. Chen, “Laser-induced graphene film and its applications in flexible electronics,” Applied Sciences, vol. 12, no. 21, Article no. 11233, 2022.

[27] B. Singleton, T. V. S. N. Vuddagiri, J. A. Z. Maldonado, M. Williams and S. Das, “Flexible Graphene Tactile Sensors with Spider Web Designs for Human-Computer Interaction,” IEEE SoutheastCon 2026, pp. 1-6, 2026.

[28] V. Braun, and V. Clarke, “Using thematic analysis in psychology”, Qualitative Research in Psychology, vol. 3(2), 77–101, 2006.