

# Near-Field Electrospinning as a Project-Based Learning Tool Through Low-Cost 3D Printer Modification

Catzim-Rios, Kevin<sup>1</sup>; Ortega-Lara, Wendy<sup>1</sup>; Pérez Beltrán, Juan Pablo<sup>1</sup>; Sosa Fraga, Nicolas<sup>1</sup>; Orash Mahmoudsalehi, Amin<sup>1</sup>

<sup>1</sup>Instituto Tecnológico y de Estudios Superiores de Monterrey, Campus Monterrey, México, [catzimkevin@tec.mx](mailto:catzimkevin@tec.mx), [wlortega@tec.mx](mailto:wlortega@tec.mx), [jppb100304@gmail.com](mailto:jppb100304@gmail.com), [nicososfra@gmail.com](mailto:nicososfra@gmail.com), [A00836548@tec.mx](mailto:A00836548@tec.mx)

**Abstract**—Project-based learning has proven to be an effective strategy for developing technical and analytical competencies in engineering education, particularly when students are exposed to real-world systems integrating multiple disciplines. In this work, a hands-on educational project is presented in which undergraduate engineering students adapted a low-cost Cartesian 3D printer into a functional Near-Field Electrospinning (NFES) platform to explore the fundamentals of electrohydrodynamic fiber deposition. The system was modified through the integration of a syringe pump, a high-voltage power supply, and programmable motion control using open-source firmware and G-code-based positioning. The project involved students from nanotechnology and mechatronics engineering programs, promoting interdisciplinary collaboration in activities including system design, firmware modification, experimental setup, parameter exploration, and qualitative analysis. Rather than focusing on full material optimization, the educational experience emphasized understanding the relationships between processing conditions, jet stability, and fiber deposition behaviour, as well as the development of troubleshooting and problem-solving skills. Experimental validation demonstrated the successful generation of stable electrohydrodynamic jets and controlled fiber deposition using short tip-to-collector distances characteristic of NFES. Optical microscopy and scanning electron microscopy (SEM) observations confirmed the formation of continuous fibrous structures with predominantly linear morphology, allowing students to directly relate processing parameters with deposition outcomes. The results indicate that adapting accessible fabrication platforms to demonstrate advanced manufacturing techniques can significantly enhance student engagement and conceptual understanding, offering a replicable and low-cost framework for integrating complex engineering processes into educational environments.

**Keywords**— Near-Field Electrospinning, Project-Based Learning, Low-Cost Experimental Platforms, Engineering Education, Additive Manufacturing Adaptation.

## I. INTRODUCTION

Engineering education increasingly emphasizes the development of practical competencies alongside theoretical knowledge, particularly through active project-based learning [1]. These approaches allow students to engage directly with real systems, fostering a deeper understanding of complex concepts while strengthening skills such as problem-solving, system integration, and critical analysis. Within this context, the

incorporation of hands-on experimental platforms has become a key element in bridging the gap between classroom instruction and real-world engineering practice [2], [3].

Advanced manufacturing techniques are a valuable opportunity for experiential learning; however, their integration into undergraduate curricula is often constrained by high equipment costs, operational complexity, and safety requirements. As a result, many educational programs rely on simplified demonstrations or purely theoretical instruction, which can restrict students' exposure to emerging technologies and reduce opportunities for meaningful experimentation [4], [5], [6], [7].

Electrospinning is a representative example of such advanced techniques. Widely used in research and industrial applications for the fabrication of micro- and nanofibrous structures, electrospinning involves multidisciplinary principles including electrostatics, fluid dynamics, materials science, and motion control. Despite its educational potential, conventional electrospinning setups are rarely accessible in teaching laboratories, particularly in early-stage engineering programs [8], [9], [10], [11].

Near-Field Electrospinning (NFES), characterized by short tip-to-collector distances and reduced jet instabilities, offers additional advantages for educational use due to its improved spatial control and compatibility with programmable motion systems. These characteristics make NFES especially suitable for demonstrating direct-write fabrication concepts and process-parameter relationships in a controlled environment. Nevertheless, dedicated NFES systems remain uncommon in educational settings [12], [13], [14], [15].

In response to these challenges, this work presents an educational project in which students modified a low-cost Cartesian 3D printer to implement a functional NFES platform. The objective was not to optimize fiber properties, but to use the system as a learning tool that enables students to explore the fundamental principles of electrospinning through hands-on experimentation. By adapting an accessible and familiar fabrication platform, the project aimed to lower the barrier to entry for advanced manufacturing techniques while promoting active learning and interdisciplinary understanding.

## II. MATERIALS AND METHODS

### A. Materials

Cellulose Acetate ( $C_{10}H_{16}O_8$ , Mn 50,000) was purchased from Sigma-Aldrich. Acetone ( $C_3H_6O$ , 99.65%) was purchased from CTR Scientific

### B. System Adaptation: 3D Printer Modification

The Near-Field Electrospinning system was developed by modifying a conventional three-axis Cartesian 3D printer (Figure 1), selected for its widespread availability in educational environments and its modular mechanical architecture. The printer is driven by four NEMA 17 stepper motors, which controls the motion of the extrusion system and the build platform. The X and Y axes employ GT2 belt-pulley mechanisms with linear rails and bearings to guide the motion of the extrusion head and collector. At the same time, the Z-axis utilizes a dual lead-screw configuration to convert rotational motion into precise linear displacement of the extrusion system.

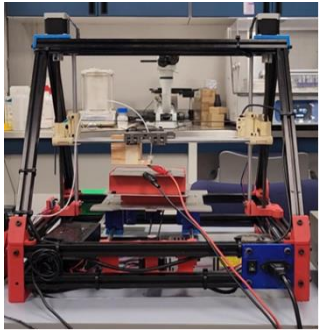


Figure 1. Modified Cartesian 3D printer adapted for Near-Field Electrospinning (NFES), showing the syringe-based extrusion system and the motion platform used for controlled fiber deposition.

Motion control is managed by an Arduino Mega 2560 microcontroller coupled with a RAMPS 1.4 control board. The system uses A4988 stepper motor drivers, which allow independent control of each motor and incorporate safety features, such as automatic deactivation when end-stop limit switches are activated. This hardware configuration was intentionally preserved during the adaptation process, allowing students to work within a familiar control framework while extending the printer's functionality beyond conventional thermoplastic extrusion.

The theoretical positional resolution of the system was calculated from the firmware step-per-millimeter configuration, yielding 80 steps/mm for the X and Y axes and 2064 steps/mm for the Z axis. These values correspond to minimum theoretical displacements of 0.0125 mm in X/Y and 0.000484 mm in Z.

Experimental verification of the practical resolution was conducted by applying controlled displacements measured with a digital caliper, confirming reproducible minimum movements of approximately 1 mm in X/Y and 0.1 mm in Z, with acceptable precision for NFES depositions. This validation process was incorporated into the student activity, reinforcing the relationship firmware parameters, mechanical behavior, and experimental outcomes.

To enable electrospinning, the original thermoplastic extrusion system was replaced with an external syringe-based extrusion setup driven by a syringe pump. A G26 metallic needle with an inner diameter of 0.45 mm was used as the spinneret, allowing controlled delivery of polymer solutions at low flow rates. The integration of this system required the design and fabrication of a custom syringe holder, developed with CAD tools and manufactured via additive manufacturing. This step provided students with hands-on experience in mechanical design, prototyping, and iterative refinement.

Given the importance of maintaining low temperatures during the fabrication of hydrogel-based materials, the standard heated build platform was modified. The original heated bed was replaced with a custom-designed double-bottom collector capable of containing dry ice, enabling passive cooling during deposition. The collector dimensions were  $136 \times 119$  mm, with an internal volume of approximately 125 cm<sup>3</sup>. The collector housing was designed using CAD software and fabricated through 3D printing (Figure 2), further reinforcing the integration of digital design and experimental implementation.

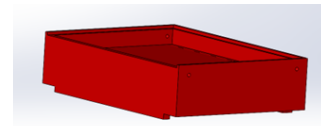


Figure 2. CAD model of the custom-designed collector base with a double-bottom structure, developed to allow passive cooling during the NFES process.

Additional structural reinforcements were introduced to enhance the system's mechanical stability. The printer frame consists of fifteen aluminum profiles connected using custom-designed brackets, which were redesigned and reprinted to enhance rigidity and ensure proper alignment during operation. Students participated in the redesign and replacement of these structural components, gaining insight into the impact of mechanical integrity on process stability and experimental reproducibility.

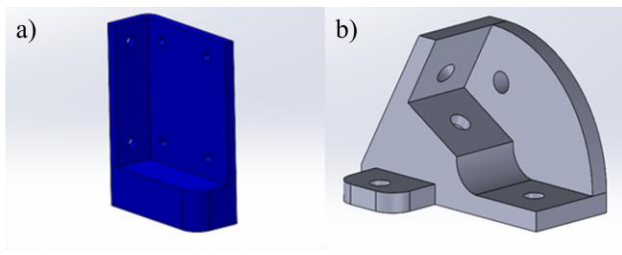


Figure 3. CAD models of custom-designed adapters and structural components fabricated to modify and reinforce the 3D printer for NFES operation.

The complete experimental setup consisted of the adapted 3D printer, a syringe pump configured to deliver flow rates as low as 0.03 mL/h, and a high-voltage power supply rated at 6 kV, operated at 5 kV for NFES experiments. This configuration allowed students to safely explore interactions among electrical and material parameters while maintaining an accessible, modular system suitable for instructional use.

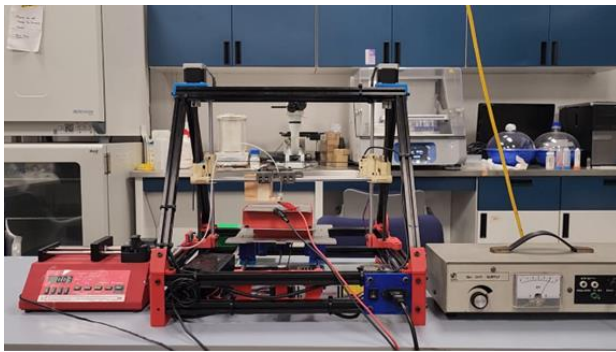


Figure 4. Complete experimental setup for Near-Field Electrospinning, integrating the modified 3D printer, high-voltage power supply, and syringe pump.

### C. Educational Methodology

The educational activity was designed as a project-based learning experience to introduce students to Near-Field Electrospinning by modifying and operating a low-cost experimental platform. The project was implemented within an engineering course related to materials processing and manufacturing technologies, involving undergraduate students with prior exposure to basic concepts of mechanics, electronics, and digital fabrication [16], [17], [18].

The project was conducted by two undergraduate students with complementary academic backgrounds: one enrolled in Nanotechnology Engineering and the other in Mechatronics Engineering. This interdisciplinary composition was intentionally selected to promote collaborative problem-solving and to mirror real-world engineering environments. The student specializing in nanotechnology focused primarily on understanding the electrospinning and near-field electrospinning principles, solution preparation, and qualitative analysis of fiber morphology. In contrast, the mechatronics

engineering student was primarily responsible for hardware modifications, motion-control configuration, firmware adaptation, and the integration of external components, such as a syringe pump and a high-voltage power supply.

Beyond experimental execution, the project incorporated multiple engineering activities, including literature review on NFES principles, computer-aided design (CAD) of custom mechanical components, firmware modification, experimental parameter definition, and iterative testing. This structure allowed students to engage in the complete engineering workflow from conceptual understanding and system design to experimental validation and analysis reinforcing both technical competencies and transversal skills such as teamwork, documentation, and critical evaluation of results.

Rather than presenting the NFES system as a fully assembled instrument, students were guided through a structured sequence of tasks that emphasized active participation and progressive understanding. The project was divided into three main stages: system analysis and modification, parameter exploration, and experimental validation. During the initial stage, students analyzed the 3D printer's original architecture and identified the mechanical, electrical, and control components relevant to its adaptation for NFES. This stage emphasized system-level thinking and encouraged students to consider safety, alignment, and functional integration.

In the second stage, students interacted directly with the modified platform by configuring motion parameters, flow rates, and applied voltage under instructor supervision. Simple, controlled experiments were conducted to observe the formation and stability of the electrospinning jet, as well as the effects of the tip-to-collector distance and tip velocity on fiber deposition. The short working distances characteristic of NFES enabled students to visually correlate parameter changes with immediate experimental outcomes, reinforcing theoretical concepts through direct observation [19], [20], [21].

The final stage focused on experimental validation and troubleshooting. Students were tasked with evaluating the repeatability of controlled movements, identifying sources of instability, and proposing adjustments to improve deposition consistency. Measurement tools such as digital calipers were used to verify displacement accuracy, linking firmware configuration and mechanical behavior to practical results. This stage promoted critical thinking and problem-solving, as students were required to interpret deviations between expected and observed behavior [22], [23].

Throughout the project, the instructional approach prioritized competency development over quantitative optimization. Key competencies targeted included understanding of electrohydrodynamic processing principles, basic instrumentation and hardware integration, interpretation of process-parameter relationships, and collaborative problem-solving. The open and modular nature of the modified 3D printer allowed students to refine the system, fostering engagement and ownership of the learning process.

By integrating NFES into a hands-on, project-based framework, the methodology provided students with an accessible entry point to advanced manufacturing techniques. The combination of low-cost hardware, active experimentation, and guided reflection enabled meaningful understanding of both the underlying physical phenomena and the practical challenges of experimental system design.

### III. RESULTS AND DISCUSSION

The adapted Near-Field Electrospinning platform allowed students to successfully generate stable electrohydrodynamic jets and perform directed fiber deposition under controlled conditions. Using short tip-to-collector distances characteristic of NFES, continuous jets were established at applied voltages of 4–5 kV, significantly reducing the whipping instabilities commonly observed in conventional electrospinning setups. This stability enabled clear visual identification of the jet trajectory and deposition point, which proved essential for instructional purposes.

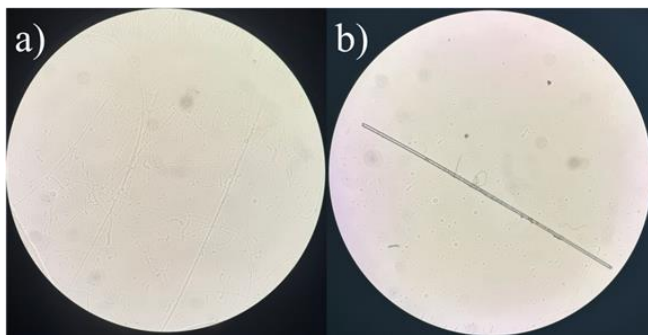


Figure 5. Optical microscopy images of fibers obtained during initial NFES experiments using an 8% cellulose acetate solution at a flow rate of 0.03 mL/h, a short tip-to-collector distance, and an applied voltage of 6 kV: (a) 10 $\times$  magnification showing localized and relatively ordered fiber deposition; (b) 40 $\times$  magnification highlighting regions of aligned fibers resulting from reduced jet instabilities.

Experiments conducted with low flow rates, on the order of 0.03 mL/h, resulted in consistent material delivery through the syringe-based extrusion system (Figure 5). Students observed that deviations from this flow regime led to either intermittent jet formation or excessive material accumulation at the needle tip, reinforcing the importance of parameter balance in electrohydrodynamic processes. These observations were used to qualitatively examine the relationship among solution flow, the applied electric field, and jet stability.

The integration of Cartesian motion control through G-code programming enabled the deposition of fibers along predefined paths. Linear, simple patterns were reproducibly generated (Figure 6), demonstrating the feasibility of guided fiber placement using the modified 3D printer platform. While

the resulting fibers were not subjected to detailed morphological or mechanical characterization, their spatial arrangement and continuity were sufficient to illustrate the transition from random fiber mats toward controlled, printing-like deposition behavior.

The reduced working distance between the needle and the collector enabled students to directly correlate positional accuracy with deposition outcomes. Misalignment in the Z-axis or variations in the tip-to-collector distance resulted in immediate, observable changes in deposition quality, including jet interruption or loss of fiber continuity. These effects were intentionally discussed during experimental sessions to emphasize the sensitivity of NFES systems to geometric configuration.

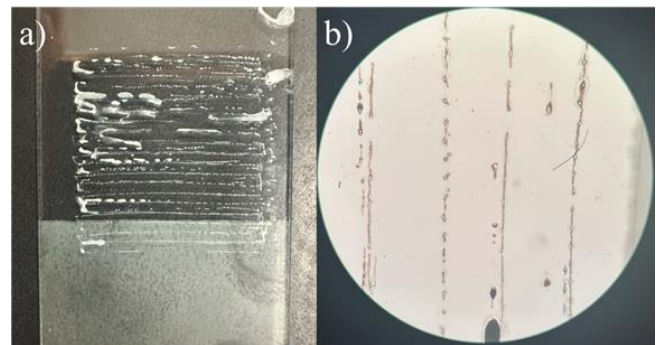


Figure 6. Optical microscopy images of fibers deposited following the implementation of a predefined motion pattern resembling a multilayer 3D printing strategy: (a) low-magnification view illustrating ordered linear deposition across multiple passes; (b) higher-magnification view (40 $\times$ ) revealing localized variations in fiber continuity associated with flow and solvent evaporation effects.

Scanning Electron Microscopy (SEM) analysis was performed to further examine the morphology of fibers produced using the adapted NFES platform. Figure 7 shows representative SEM images at 500X and 1000X, revealing continuous well-defined fiber structures with predominantly linear geometry. The absence of severe jet instabilities, such as pronounced bead formation or random coiling, supports observations from optical microscopy and confirms the effective suppression of whipping behavior due to the reduced tip-to-collector distance characteristic of NFES.

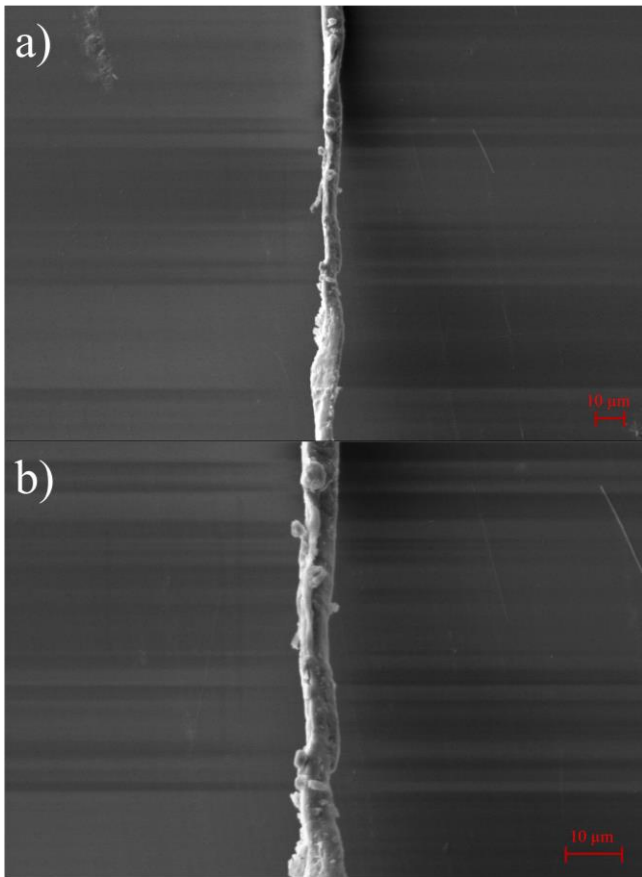


Figure 7. SEM images of fibers produced using the adapted Near-Field Electrospinning system: (a) 500X magnification showing continuous fiber formation with predominantly linear geometry; (b) 1000X magnification highlighting surface features and localized diameter variations along the fiber length.

Surface irregularities and localized diameter variations were observed along the fiber length, attributed to fluctuations in solvent evaporation and minor variations in flow stability during deposition. Rather than representing a limitation, these features provided an opportunity for students to relate processing conditions to morphological outcomes, reinforcing discussions on solution properties, electric field strength, and mass transport phenomena. The SEM observations thus served as a complementary qualitative validation of the system's capability to produce controlled fibrous structures while maintaining an accessible and instructive experimental framework.

The results obtained in this work demonstrate that the proposed low-cost adaptation of a conventional 3D printer can be effectively used as a platform for Near-Field Electrospinning (NFES) in an educational context. The ability to generate stable jets and achieve controlled fiber deposition confirms that the system is functionally capable of reproducing key aspects of the NFES process, despite its simplified design and reduced operational complexity. A key observation is the strong correlation between process parameters such as applied voltage, flow rate, and tip-to-collector distance and the resulting fiber

deposition behavior. These relationships were consistently observed by students during experimentation, particularly due to the reduced whipping instability inherent to NFES. This characteristic allowed direct visualization of the jet trajectory and facilitated intuitive understanding of electrohydrodynamic principles, which are typically difficult to grasp in conventional electrospinning setups.

The SEM analysis further supports the system's capability to produce continuous fibrous structures with predominantly linear morphology. While surface irregularities and diameter variations were observed, these features are consistent with the exploratory nature of the experiments and reflect typical sensitivities to process conditions such as solvent evaporation and flow stability. Importantly, these observations provided valuable opportunities for students to connect theoretical concepts with real experimental outcomes.

It is important to emphasize that the results presented in this study are intentionally qualitative and exploratory. The primary objective of this work is not the optimization or full characterization of electrospun materials, but rather the use of NFES as a pedagogical tool for introducing advanced manufacturing concepts. In contrast to conventional electrospinning research, which often focuses on material properties and extensive quantitative analysis, this work prioritizes accessibility, system understanding, and hands-on learning.

From an educational perspective, the integration of system modification, parameter control, and experimental observation allowed students to engage with the complete engineering workflow. This includes problem identification, hardware adaptation, process tuning, and interpretation of results. The interdisciplinary nature of the project combining nanotechnology and mechatronics further reinforced collaborative learning and the application of complementary skill sets.

Although no direct comparison with conventional electrospinning systems was performed, the results suggest that the proposed platform provides a viable approximation for instructional purposes. Future work may include comparative studies and extended material characterization; however, within the scope of this work, the emphasis remains on educational impact and the development of practical competencies.

#### IV. CONCLUSION

This work presented the adaptation of a low-cost Cartesian 3D printer into a functional Near-Field Electrospinning (NFES) platform intended for educational and project-based learning applications. Through the integration of a syringe pump, high-voltage power supply, and programmable motion control, the modified system enabled the generation of stable electrohydrodynamic jets and directed fiber deposition under controlled conditions.

The experimental observations obtained through optical microscopy and SEM imaging confirmed the capability of the

platform to produce continuous fibrous structures while allowing direct visualization of process behavior. Although the results are exploratory and qualitative in nature, they successfully demonstrated the relationship between operational parameters and deposition stability, providing students with meaningful exposure to advanced manufacturing concepts.

TABLE I. Input and Outcome Skills Developed Through the NFES Project.

| Skill Area                               | Input Skills (Before Project)                                                                                              | Outcome Skills (After Project)                                                                                                                        |
|------------------------------------------|----------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Fundamental Engineering Knowledge</b> | Basic understanding of physics, introductory materials science, and electrical concepts acquired through early coursework. | Applied understanding of electric field effects, material behaviour, and process–structure relationships through hands-on experimentation.            |
| <b>Mechanical and System Design</b>      | Introductory exposure to mechanical components and basic use of CAD software.                                              | Ability to design, adapt, and fabricate custom mechanical components for experimental systems using CAD and additive manufacturing.                   |
| <b>Electronics and Instrumentation</b>   | Basic familiarity with electronic components and microcontroller-based platforms.                                          | Practical experience integrating external devices (syringe pump and high-voltage power supply) into a mechatronic system under supervised conditions. |
| <b>Programming and Motion Control</b>    | Introductory programming skills and limited experience with motion control systems.                                        | Improved understanding of motion coordination, parameter adjustment, and firmware-based control for precise material deposition.                      |
| <b>Experimental Design</b>               | Limited experience following predefined laboratory protocols.                                                              | Ability to define experimental parameters, perform iterative testing, and observe the effects of process variations on experimental outcomes.         |
| <b>Data Observation and Analysis</b>     | Qualitative observation skills with limited exposure to microscopy-based analysis.                                         | Enhanced capability to interpret optical and SEM images and relate morphological features to processing conditions.                                   |
| <b>Research and Literature Review</b>    | Introductory exposure to scientific literature with guided interpretation.                                                 | Improved ability to consult, interpret, and contextualize technical literature related to Near-Field Electrospinning.                                 |
| <b>Teamwork and Communication</b>        | Experience in small academic team assignments.                                                                             | Strengthened interdisciplinary collaboration, task distribution, technical discussion, and                                                            |

|                            |                                                              |                                                                                                                      |
|----------------------------|--------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|
|                            |                                                              | documentation of results.                                                                                            |
| <b>Engineering Mindset</b> | Primarily theoretical understanding of engineering concepts. | Increased confidence in tackling open-ended engineering problems and connecting theory with real-world applications. |

From an educational perspective, the project promoted interdisciplinary collaboration between students from nanotechnology and mechatronics engineering backgrounds, integrating activities such as literature review, CAD design, firmware modification, system integration, experimentation, and analysis. This approach enabled students to engage with the complete engineering workflow while developing practical and analytical competencies.

Overall, the proposed platform represents an accessible alternative for introducing NFES concepts in instructional environments where conventional electrospinning equipment may be economically inaccessible. Future work may include comparative studies with conventional electrospinning systems, additional process optimization, and extended material characterization.

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