



NANOFIBER MEMBRANES FOR RENEWABLE ENERGY: A STEM APPROACH TO CREATIVE THINKING IN EDUCATION

**Leni Marlina,
Ardi,
Mardiah Afifa,
Ida Sriyanti,
Meilinda**

Introduction

Nanofiber membranes are innovative materials produced through nanofiber technology using the *electrospinning* method. This process generates fibers at the nanometer scale, which are significantly finer than those produced by conventional spinning methods. *Electrospinning* utilizes an electric field force to draw out a polymer solution or melt into micro- or nanoscale fibers, unlike traditional *melt-spinning* processes that rely solely on mechanical forces (Sriyanti et al., 2024). Nanofiber membranes, composed of nanometer-scale fibers, show great potential for various renewable energy applications (Wang et al., 2023; Wei et al., 2020). Nanofiber membranes, particularly those derived from lignocellulose, possess distinctive properties such as expansive surface areas and significant porosity. These characteristics make them suitable for utilization in various energy-related applications, including solar cells, batteries, and fuel cells (Almafie et al., 2022; Jauhari et al., 2021). Lignocellulose-based nanofiber membranes offer high conductivity because of their carbon content, flexibility, and biodegradability, making them suitable for integration into renewable energy learning (Wang et al., 2023; Wei et al., 2020). Utilizing nanofiber membranes in learning allows students to explore scientific principles, material characteristics, and potential applications in solving sustainable energy challenges. Particularly on the topic of renewable energy and Coulomb's law.

Several studies have explored innovative learning methods for renewable energy topics, such as the use of learning videos (Nugraha & Widiana, 2021; Torres-Ramírez et al., 2014), learning module (Ashnam et al., 2022; Karlina et al., 2024), and worksheets (Ayuni et al., 2022). Common technology addresses for renewable energy in STEM activity are a solar project (Mayasari et al., 2019) and a wind project (Anderson et al., 2019). However, the integration of renewable energy using nanofiber materials into STEM learning remains largely underexplored in previous research. Implementing nanofiber technology in educational settings can offer students a more practical and significant learning experience. Learning with nanofiber membrane can foster

Abstract. *The development of renewable energy technology is increasing rapidly, one of which is the nanofiber membrane, which has the potential to be an innovative material for various applications, including renewable energy. Its utilization in learning, especially STEM-based approach, to improve students' understanding of renewable energy and its applications, is still limited. This study contributes by introducing a novel approach that integrates nanofiber membranes into STEM-based approach in current educational practices. This study aimed to describe and evaluate the effectiveness of STEM-based approach that integrates a nanofiber membrane to improve students' creative thinking skills on the topic of renewable energy. A quasi-experimental design with pre-test and post-test design was employed, involving 120 tenth-grade high school students. The findings indicated that implementing nanofiber membrane within STEM-based learning improved students' creative thinking skills compared to traditional teaching methods. In the experimental group, no students achieved medium-level n-gain, while 45.45% attained high-level n-gain. Conversely, in the control group, 13.64% of students had low-level n-gain, 86.36% reached medium-level, and none achieved high-level n-gain. This research highlights the importance of linking current technologies, such as nanofiber membranes, with classroom learning to enhance students' understanding of renewable energy and to prepare them for future sustainable development challenges.*

Keywords: *creative thinking skills, experimental research, nanofiber membrane, science and technology education for sustainable development, STEM approach*

**Leni Marlina, Ardi, Mardiah Afifa,
Ida Sriyanti, Meilinda**
Sriwijaya University, Indonesia



the creative thinking skills (Luo et al., 2025). Students' creative thinking skills regarding energy-related material are still low (Muflikhun & Setyarsih, 2022). The low prevalence of creative thinking skills is often a consequence of classroom instruction being predominantly characterized by conventional learning models, emphasis on teacher domination and doctrinal methodologies, which frequently prove inadequate in stimulating creative thought processes (Hasanah et al., 2019; Handayani et al., 2020). Despite evidence indicating the positive impact of innovative pedagogical strategies, such as discovery learning, project-based learning, and mind mapping, the enhancement of creative thinking skills has shown moderate improvement (Smith et al., 2023). However, this progress has not been substantial, primarily due to the suboptimal integration of renewable technologies within the implemented learning models. This approach not only enhances students' awareness of energy sustainability but also prepares them to tackle future challenges in this field. Consequently, it is essential to integrate technological advancements in education, particularly in the field of renewable energy (Hilmi & Yusof, 2024).

Research has demonstrated that incorporating technology into educational practices can enhance students' abilities in both creative thinking (Bereczki & Kárpáti, 2021) and critical analysis (Karuru et al., 2024). Implementing technology in learning can significantly improve students' critical thinking skills (Agasi, 2024). Hidayah et al. (2022) also demonstrated that implementing STEM-based e-learning could enhance students' ability to collaborate. Nevertheless, there has been a lack of studies to date that explore the use of nanofiber technology in STEM-based renewable energy education to improve students' creative thinking skills.

Creative thinking skills are among the most important competencies in the era of globalization (Nurhamidah et al., 2018). These skills reflect an individual's ability to generate diverse solutions to a problem by exploring new perspectives or innovative combinations of concepts (Afifa et al., 2024). In the context of education, creative thinking can be identified through four main indicators: flexibility, fluency, originality, and elaboration (Torrance, 1977). In physics learning, creative thinking skills play an important role in understanding concepts, developing mathematical modeling, and applying physics principles in real life (Wahyu et al., 2020). Therefore, these skills must be developed so that students can be actively involved in the learning process to achieve optimal learning objectives (Cahyaningsih et al., 2023).

Educational outcomes in schools aim to equip students with the capacity to address global challenges and actively participate in finding solutions. These competencies encompass observing, inquiring, and forecasting, designing and executing investigations, handling and examining data and information, assessing and contemplating, and conveying findings through basic projects or visual representations. These activities employ readily available technological applications focused on alternative energy sources, aiming to accomplish sustainable development goals. Through the development of knowledge, noble characters, and scientific attitudes such as honesty, objectivity, critical reasoning, creativity, independence, innovation, mutual cooperation, and global diversity (Kemendikbud, 2022). The STEM approach is an appropriate strategy to achieve these goals because it can integrate various disciplines and provide students with the necessary competencies to address energy sustainability challenges (Okonkwo et al., 2024). The STEM approach to learning not only helps students understand issues related to energy availability but also hones skills in the exploration and utilization of renewable energy sources (Okonkwo et al., 2024; Saputro et al., 2022; Colmenares-Quintero et al., 2023). The STEM approach can also significantly improve students' creative thinking skills by integrating interdisciplinary knowledge and providing real-life problem-solving experiences (Gracia et al., 2024). Thus, this approach can foster creativity and problem-solving skills, both of which are crucial for developing more innovative and sustainable energy solutions.

Students can enhance their ability to think creatively through engaging in active and innovative learning experiences. These experiences provide opportunities for learners to practice approaching problem-solving from multiple perspectives, thereby developing their creative thinking abilities (Nurhamidah et al., 2018). One is the implementation of nanofiber membrane in learning, which actively involves students in the learning process.

Research Problem

Nanofiber technology, especially nanofiber membranes, holds a significant promise for bolstering STEM-based learning, particularly in the realm of renewable energy materials. Integrating this technology into education can foster a more engaging and innovative learning atmosphere, raise awareness about energy sustainability, and equip students to tackle global challenges. Nevertheless, the application of nanofiber membranes in school learning remains quite limited. Furthermore, creative thinking skills, a crucial 21st-century competency, still require enhancement. Prior research indicates that incorporating technology into learning can elevate critical thinking, higher-order thinking, and collaboration skills. However, a lack of studies has integrated nanofiber membrane into STEM-based



learning to improve students’ creative thinking skills, especially regarding renewable energy materials. Previous studies have explored innovative learning methods for renewable energy topics, such as the use of learning videos (Nugraha & Widian, 2021; Torres-Ramírez et al., 2014), learning module (Ashnam et al., 2022; Karlina et al., 2024), and worksheets (Ayuni et al., 2022) but not using nanofiber membrane. Learning with nanofiber membrane can foster the creative thinking skills (Luo et al., 2025). This shows a great opportunity to develop innovative STEM-based learning by utilizing nanofiber membranes to improve students’ creative thinking skills while filling the gap in previous research and presenting relevant innovations in education.

Research Focus

This study has examined and described the application of STEM-based approach incorporating nanofiber membranes to enhance students’ creative thinking abilities in the field of renewable energy materials. The research has emphasized the potential of nanofiber membranes as effective educational tools in physics, particularly for teaching about renewable energy materials. It has focused on how this educational approach supports the development of creative thinking, emphasizing core indicators such as fluency, flexibility, originality, and elaboration.

Research Aim and Research Questions

The aim of this research was to explore how the application of nanofiber membranes within a STEM context can enhance students’ creative thinking skills in classroom learning activities focused on renewable energy. In particular, this study sought to assess the effectiveness of this educational approach in fostering students’ creative thinking skills by concentrating on specific indicators.

The questions explored in this study were as follows:

- 1. How does the application of nanofiber membranes within a STEM context manifest in classroom learning activities focused on renewable energy?
- 2. What is the effectiveness of integrating renewable energy education, facilitated by nanofiber membranes within a STEM pedagogical framework, in fostering the development of students’ creative thinking skills?

Research Methodology

General Background

An experimental research with quasi-experimental design was used in this study. This research was intended to examine the causal relationship between a specific intervention, treatment, or stimulus and the subject of the research (Barrett & Anderson, 2017). This study was conducted using two groups: an experimental group that received X treatment, namely using a nanofiber membrane in a PBL-STEM-based approach, and a control group that did not receive the treatment, only using a PBL-STEM-based approach. To evaluate the effectiveness of the educational process on students’ creative thinking abilities, identical pre-tests and post-tests were administered to both groups. Table 1 illustrates the experimental design employed in this study, which was implemented over a total of 35 teaching hours. The design involved 5 lesson hours distributed across two meetings in a week for each class, conducted in 7 different tenth-grade classes, resulting in a total of 35 lesson hours conducted from August to October.

Table 1
Research Design

Group	Pre-test	Treatment	Post-test
Experimental	√	X	√
Control	√		√

Note: X: Treatment in the STEM learning process using nanofiber membranes for tenth-grade students was conducted from August to October (Fahrissa & Parmin, 2022).



Sample

Drawing upon a population of 198 tenth-grade students from private upper-secondary schools in Palembang, namely Ahlul Quran Islamic Boarding School and PGRI 1 Senior High School, this study involved a sample of 120 participants selected via purposive sampling (Thomas, 2022). This sampling technique was employed to ensure the inclusion of students suitable for the research aims, namely those who had experienced STEM learning with carbon nanofiber membranes and those who had not, thereby allowing for an assessment of the treatment's effectiveness and yielding relevant and meaningful data to address the research questions.

A sample size of 120 students is statistically adequate for the generalization of the study findings. However, since purposive sampling was employed, generalization is made in an analytical sense where findings apply to similar contexts with comparable characteristics, rather than to the broader population. The sample was evenly split into two groups: a control class and an experimental class, each consisting of 60 students. Ethical considerations were ensured through informed consent, participant anonymity, and compliance with institutional ethical standards. The two groups are clearly outlined in Table 2.

Table 2*Sample of a Control and an Experimental Group*

Group	Grade	Age		Gender	
		15 Years-old	16 Years-old	Female	Male
Experimental	10 th	34	26	40	20
Control	10 th	31	29	39	21

Instrument and Procedures

This study used several instruments to collect data, namely, expert validation sheets, PBL-STEM-based E-Worksheet, and pre-test and post-test creative thinking skills instruments. In this study, validated and practical PBL-STEM-based E-Worksheets integrating nanofiber membrane technology were implemented throughout the learning process in experimental classes. The validation results indicate that the E-Worksheet is of high quality, with scores of 4.5 for design (very valid), 3.72 for STEM aspects (valid), 4.5 for material (very valid), 4.0 for language (valid), and 3.8 for the PBL model (valid). The developed E-Worksheet is also very practical, with the results of a one-to-one evaluation of 4.5 (very practical) and a small group evaluation of 4.5 (very practical). PBL-STEM-based E-Worksheet developed as a strategy to enhance creative thinking. Then, a pre-test post-test instrument was developed, which was used to measure students' creative thinking skills. This study employed four key indicators of creative thinking: fluency, flexibility, originality, and elaboration (Handayani et al., 2021). The pre-test and post-test instruments for measuring creative thinking skills, which consisted of eight questions, were validated using the Pearson product-moment correlation, with items deemed valid when their Pearson correlation values exceeded r_{table} (.444). This aligns with the statement by Nurmala and Rahmiati (2024), who argue that an item is considered valid if its Pearson correlation value exceeds the r_{table} threshold. The reliability of the instrument was assessed using Cronbach's alpha, which produced a value of .715, indicating that the instrument was reliable. An instrument is considered reliable when its Cronbach's alpha value exceeds .7 (Shrestha, 2021). These validated and reliable instruments were utilized as pre-test and post-test assessments to evaluate students' creative thinking skills. Table 3 provides the details of the pre-test and post-test instruments for assessing creative thinking skills.

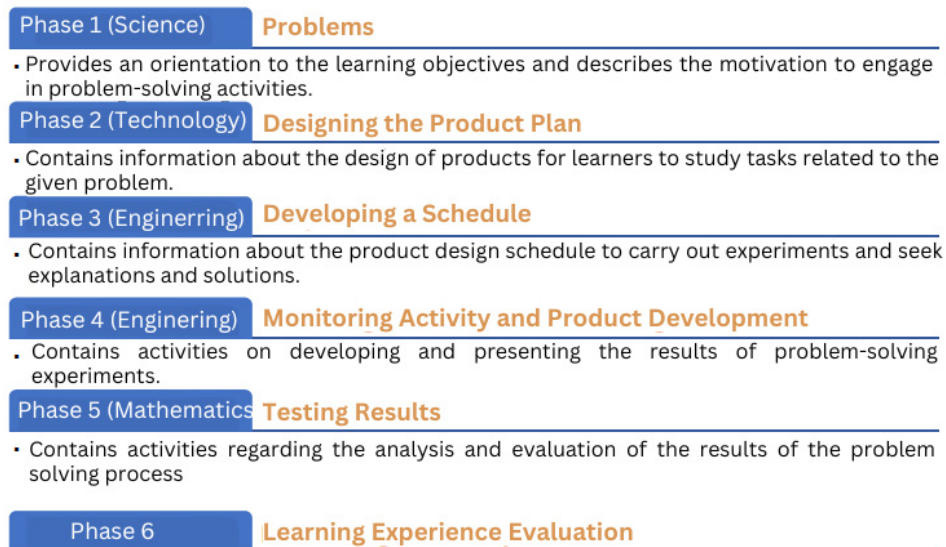


Table 3
Pre-test and Post-test Instruments of Creative Thinking Skills for Control and Experiment Group

No	Question	Creative Thinking Indicators
Take a look at the following picture to answer questions 1-3!		
1	 Source: https://www.anakteknik.co.id/farhanhf/articles/apa-itu-boiler-pada-pltu In your city, there is a company that produces electricity from fossil fuels. Many residents around the company complain about pollution and other negative impacts of the power plant. As a student, your task is to think of alternative uses of renewable energy that can be used by the company. What are the renewable energy alternatives that can be used by the company?	Fluency
2	What are the advantages and disadvantages of the renewable energy alternatives you mentioned?	Flexibility
3	How will you convince companies to switch to renewable energy?	Originality
4	 Source: https://www.idntimes.com/travel/destination/riyan-sumarno/air-terjun-di-pagar-alam-c1c2 Pagaralam City has a 10 m high waterfall. The waterfall is utilized by the community as a power plant. The villagers installed a wheel at a height of 5 m. The electricity generated by the waterfall is still not enough to meet the needs of the population. What is the solution given so that electricity needs can be met? Explain!	Elaboration

The learning process was performed using the PBL-STEM with a nanofiber membrane. The learning steps are illustrated in Figure 1.



Figure 1
Learning Steps*Data Analysis*

This study employed quantitative analysis of the collected data. The research assessed students' creative thinking abilities through pre-tests administered before using the E-Worksheet and post-tests conducted after learning with the PBL-based E-Worksheet incorporating a STEM-based approach. The pre-test and post-test results were evaluated using the *n*-gain normality test and ANCOVA hypothesis test, which involved several prerequisites: 1) normality test, 2) homogeneity test of data variation, and 3) independent t test. ANCOVA was utilized to examine the treatment effect differences between the control and experimental groups. The experimental group engaged with a PBL-STEM-based E-Worksheet assisted by nanofiber membranes, while the control group used a PBL-STEM-based E-Worksheet without nanofiber membranes. The enhancement in students' creative thinking skills was then calculated based on the normalized *n*-gain score using SPSS version 27. Table 4 outlines the criteria for *n*-gain interpretation.

Table 4
N-Gain Criteria

Score	Category
$g \leq .3$	Low
$.3 < g \leq .7$	Moderate
$.7 < g \leq 1$	High

Note: The *n*-gain criteria were adapted from (Doyan et al., 2020).

Research Results*Renewable Energy Learning Process Using Nanofiber Membrane in STEM-based Approach to Improve Creative Thinking Skills*

The learning process was performed using the PBL-STEM approach with a nanofiber membrane. Before learning activities are carried out, each student is given a pre-test, which is then continued with learning activities; learning activities refer to the learning steps. The learning steps can be seen in Figure 1.



In phase 1, students were presented with a problem by showing a video, and students were asked basic questions. This is a form of orientation about learning objectives and describes the motivation to engage in problem-solving activities. The phase 1 activities are shown in Figure 2.

Figure 2

Activity Phase 1: Problem

1 **PROBLEM** **Info Sciences**

Fundamental question?

Basic Question: You already know the various sources of energy, such as electricity, heat, motion, solar energy and so on. But have you ever thought if used continuously whether the energy source will run out?. Try to see the material in the video entitled "Will the oil in the world run out? And what terrible effects will occur if petroleum runs out?"

Watch the video link below !

Source: <https://www.youtube.com/watch?v=AI454Vrww&list=PL>

Based on the video link you watched, what do you think the problem is? Please write your answer in the column below

Then, the learning activities continued in Phase 2, namely, designing product planning. At this stage, a learning video was provided in the form of carbon nanofibers from palm oil shells as renewable energy, which can be used as a reference for students to develop their own products. The phase 2 activities are shown in Figure 3.

Figure 3

Phase 2 Activity: Design Product Planning

2 **PRODUCT DESIGN** **Info Technology**

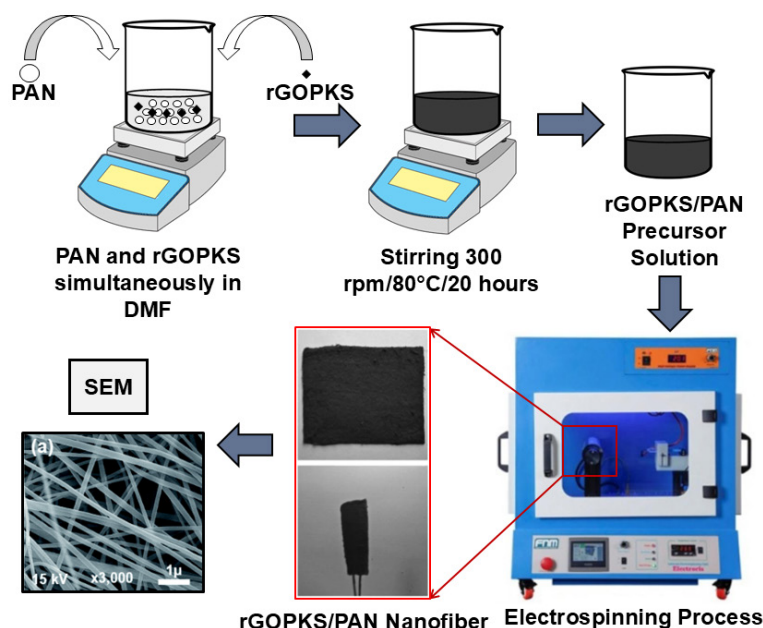
One of the impacts if the world's oil runs out is in the transportation sector. As the future generation we must think creatively to find a more environmentally friendly renewable energy solution, watch the video link below !!!!

Source : <https://www.youtube.com/watch?v=g2RWtGss3D0>

After watching the video above on making carbon nanofibers from palm shells, can palm shells become renewable energy to become an alternative energy to replace petroleum? To answer this question, you can read or watch other references.



After Phase 2 activities are carried out, then proceed with the activities in Phase 3, namely, developing a schedule. In this phase, students follow a schedule to work on their products, carry out experiments, and look for explanations and solutions. Subsequently, it continues with Phase 4, which monitors the activeness and development of the product. The learning process was emphasized through the integration of STEM aspects—science, technology, engineering, and mathematics. In this STEM approach, the technological aspect was represented by the introduction of nanofiber membrane technology to students.

Figure 4*Illustration of Nanofiber Technology*

Note: Photograph courtesy of Mardiah Afifa. Copyright 2025

Figure 4 presents a nanofiber membrane produced using nanofiber technology through the electrospinning method. In this learning activity, students are introduced to the process of producing fine nano-sized fibers from a polymer solution using the electrospinning technique. This method is known for its effectiveness in fabricating nanofibers with high flexibility and superior mechanical properties (Aruan et al., 2017). The process utilizes a single-needle system connected to a syringe filled with a previously dissolved polymer solution. The syringe is mounted on a plunger system to ensure a stable and controlled flow rate (Huang et al., 2003).

A direct current (DC) voltage source is used to create an electric potential difference between the needle and the collector plate. Within the learning context, students are guided to understand that the needle acts as the positive electrode, while the collector functions as the negative electrode. The polarity of these electrodes can be reversed depending on the experiment. When a high voltage is applied, the initially neutral polymer solution becomes polarized due to the applied potential difference (Ramakrishna et al., 2005). If the needle tip is connected to the positive terminal, positive ions accumulate at the surface of the solution, while negative ions are repelled inward. Conversely, when the polarity is reversed, the charge distribution is altered accordingly. This charge distribution generates electrostatic repulsion forces, or Coulomb forces, which push the polymer solution out of the needle tip, forming thin fibers that travel toward the collector and deposit as a nanofiber membrane (Huang et al., 2003). Through this activity, students not only learn the basic physics concepts such as electric charge and Coulomb force but also gain insight into modern material engineering technologies. Furthermore, this process incorporates the mathematics aspect of the STEM approach, as it can be quantitatively explained using the Coulomb force equation:

$$\vec{F}_c = k \frac{q_1 q_2}{r^2}$$



In addition, an electric force due to the applied field between the electrodes acted on the charges:

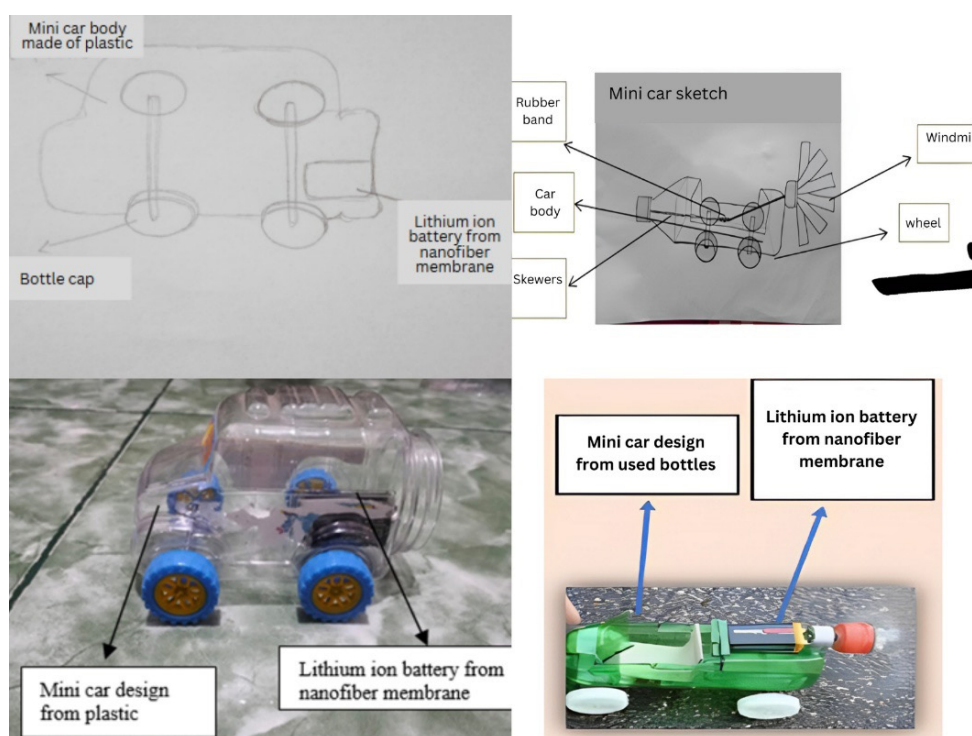
$$\vec{F}_e = q\vec{E}$$

With this approach, students not only learn the theory but also directly observe how physics and mathematics concepts are applied in real-world technologies, such as the production of advanced materials like nanofibers (Ramakrishna et al., 2005). The science aspect of this STEM approach is reflected in physics concepts such as Coulomb force, electric force, and energy. The combination of Coulomb and electric forces pulls the polymer solution into a conical shape. Coulomb force and electric force have been previously studied by students and are related to energy. When the resultant of the electrostatic and electric forces exceeded the counteracting surface tension and intermolecular forces, the charged polymer solution was ejected toward the collector. The solution elongated as it traveled, and the solvent evaporated due to the high voltage, resulting in the formation of solid fibers on the collector's surface that are called as a nanofiber membrane. The nanofiber membrane can be used as an energy storage material that can store more energy. This is attributed to its characteristics, including small size, high surface area, and flexibility, which allow it to store more energy compared to conventional batteries.

After successfully producing nanofiber membranes, students modified them to build a mini car powered by energy stored in the nanofiber-based system. This product development process highlights the engineering aspect of the STEM-based approach. One example of the student-developed product is presented in Figure 5.

Figure 5

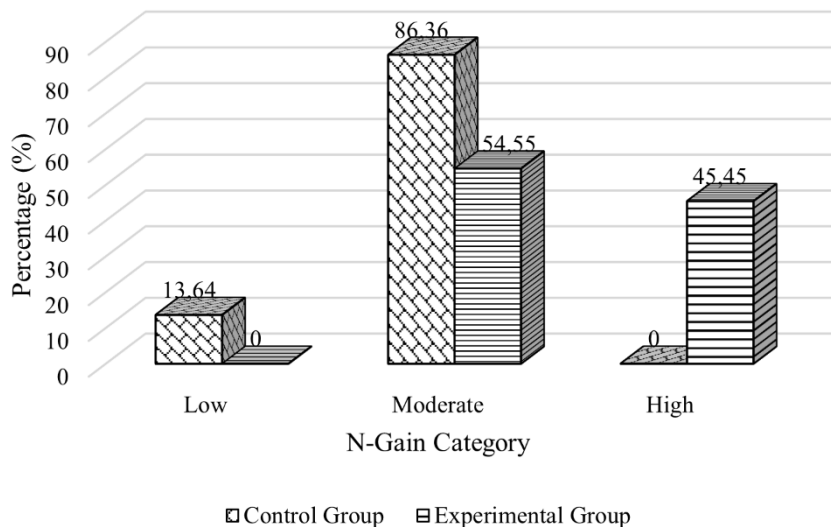
Product Development Results using Nanofiber Membrane



At this stage, students successfully developed a mini car design from used bottles by using nanofiber membranes from palm shells as batteries used in mini cars. Lithium-ion batteries from nanofiber membranes can store more electric charges than ordinary batteries. This is because nanofiber membranes have properties such as a small size, a large surface area, and flexibility. After Phase 4 activities were carried out, the activities continued in Phase 5, namely, testing the results. Experiments using mini cars show good results, in which mini cars can move with the help of batteries from nanofiber membranes. Thus, this learning process involves all aspects of STEM, namely science, technology, engineering, and mathematics. The final activity was Phase 6, which evaluated the learning experience.

The Effect of Renewable Energy Learning with Nanofiber Membrane in STEM-based Approach on Creative Thinking Skills

The last activity was Phase 6, which evaluated the learning experience. At this stage, the final evaluation is carried out in the form of a post-test to see the improvement that occurs in students' creative thinking skills using *n*-gain analysis. The results of the *n*-gain analysis are shown in Figure 6.

Figure 6*Experimental Group Student's Pre-test Answers Result*

According to Figure 6, the experimental class showed no students in the low *n*-gain category ($\leq .3$), 54.55% in the moderate category ($.3 < g \leq .7$), and 45.45% in the high category ($.7 < g \leq 1$). The control class had 13.64% of students in the low *n*-gain category, 86.36% in the moderate category, and none in the high category. While both classes demonstrated improvement, only the experimental class achieved high *n*-gain values, suggesting that the nanofiber membrane in education more effectively enhances students' creative thinking abilities. To determine significant differences between the experimental and control classes, normality, homogeneity, and independent *t* tests were performed.

The normality test yielded a *p* of .200 for both classes, indicating that the data were normally distributed ($p > .05$). The homogeneity test showed homogeneous data distribution with a *p* of .657, exceeding $p .05$. Based on these results, an independent sample *t*-test was conducted on the pre-test and post-test scores to evaluate differences in the average performance between the unpaired experimental and control classes. Table 5 displays the independent sample *t*-test results for the creative thinking skills pre-test scores.

Table 5*Differences in Experimental and Control Group Results: Pre-test Score*

Group	<i>M</i>	<i>SD</i>	<i>t</i>	<i>p</i> (2-tailed)	Interpretation
Experimental	43.81	12.14	.662	.512	No significant difference
Control	41.27	13.33	.662	.512	

Table 5 illustrates that there were no significant differences between the control and experimental groups in their pre-test results. This suggests that, at the time of the pre-test, both groups had comparable creative thinking abilities. Following this, an independent sample *t*-test was performed on the creative thinking skills post-test scores, with the results presented in Table 6.



Table 6*Difference in Experimental and Control Group Results: Post-test Score*

Group	<i>M</i>	<i>SD</i>	<i>t</i>	<i>p</i> (2-tailed)	Interpretation
Experimental	80.72	8.333	5.252	< .001	There is a significant difference
Control	60.90	7.849	5.252		

As shown in Table 5, the post-test results revealed a significant difference between the control and experimental groups. This suggests that the creative thinking abilities of the students in both groups varied considerably at the time of the post-test. Subsequently, an ANCOVA test was conducted, with the results presented in Table 7.

Table 7*ANCOVA Test Results*

Class	<i>F</i>	<i>SD</i>	<i>p</i> (2-tailed)	Interpretation
Experiment	138.44	13.38	< .001	There is a significant effect
Control		8.33		

Based on Table 7, a significant impact was observed on students' creative thinking skills in both the experimental and control classes. This indicates that the implementation of nanofiber membranes in learning had a substantial effect on enhancing students' creative thinking abilities. The effect is evident from the students' responses in the pre-test and post-test. The results of the students' answers during the creative thinking skills pre-test are presented in Figure 6.

Figure 6*Experimental Group Student's Pre-test Answers Results*

1. What are the alternative uses of renewable energy that can be used by the company? (**Fluency**)

Alternatif energi terbarukan tidak menggunakan bahan bakar yang menghasilkan polusi udara yang berbahaya. Bisa menggunakan tenaga kincir angin
Renewable energy alternatives do not use fuels that produce harmful air pollution. You can use windmill power

2. What are the advantages and disadvantages of the renewable energy alternatives you mentioned? (**Flexibility**)

1. Menghemat energi 2. Mudah untuk digunakan
1. Save energy 2. Easy to use

In Figure 6, it can be seen that the answers given by the students are still simple. However, after being treated with learning using a nanofiber membrane, there were changes in students' answers. The results of the students' answers in the post-test are shown in Figure 7.



Figure 7*Control Group Student's Pre-test Answers Results*

1. What are the alternative uses of renewable energy that can be used by the company? **(Fluency)**

Energi alternatif yang dapat digunakan oleh perusahaan tersebut diantaranya: 1. Pembangkit listrik tenaga surya 2. Pembangkit tenaga listrik tenaga angin 3. Pembangkit listrik tenaga air 4. Pembangkit listrik tenaga panas bumi 5. Pembangkit listrik tenaga biomasa
Alternative energy that can be used by the company includes: 1. Solar power plants 2. Wind power plants 3. Hydroelectric power plants 4. Geothermal power plants 5. Biomass power plants

3. What are the advantages and disadvantages of the renewable energy alternatives you mentioned? **(Flexibility)**

Keuntungan listrik tenaga surya : sumber energi terbarukan yang tidak terbatas, tidak menghasilkan emisi gas rumah kaca. Kerugian listrik tenaga surya : membutuhkan ruang yang cukup luas untuk membangun turbin angin, efektivitas tergantung pada intensitas sinar matahari

Advantages of solar power: unlimited renewable energy source, does not produce greenhouse gas emissions. Disadvantages of solar power: requires a large enough space to build a wind turbine, effectiveness depends on the intensity of sunlight

Based on Figure 7, it can be seen that students' answers became more complex. Students are better able to explain their answers more fluently and flexibly. This shows a significant effect on students' creative thinking skills after learning to use a nanofiber membrane in a STEM-based approach.

Discussion

Renewable Energy Learning Process Using Nanofiber Membrane in a STEM-based approach to Improve Creative Thinking Skills

In this study, learning on the topic of renewable energy was carried out using a nanofiber membrane. During the learning process, learning activities were conducted with the media of a PBL-STEM-based E-Worksheet using nanofiber membranes. Learning was carried out with PBL syntax consisting of six phases: (1) problems, (2) designing project planning, (3) preparing a schedule, (4) monitoring activeness and product development, (5) testing results, and (6) evaluating the results of the experience (Setiawan & Takaoka, 2020). During learning, students are given an energy problem that is intended to enable them to analyze problems and try to solve problems creatively. Students are faced with the problem of fossil energy, which is becoming increasingly depleting and can cause environmental problems (Zhang et al., 2024). Fossil energy contributes significantly to CO₂ emissions and global warming; therefore, a transition to renewable energy is needed for energy sustainability (Ghose et al., 2024). Therefore, students were asked to overcome these problems by using renewable technology in the form of nanofiber membranes.

Learning using nanofiber membranes as a form of renewable energy is closely related to the concepts of Coulomb's law and energy storage. The application of Coulomb's law in the electrospinning process during the formation of nanofiber membranes provides a strong conceptual foundation for understanding energy storage mechanisms at the nanoscale. The high electric field used in electrospinning generates electrostatic forces between charges, which stretch and align the polymer solution into charged nanofibers (Noll et al., 2024). This process not only reflects the fundamental principles of Coulombic force but also produces nanofiber structures with high surface area and optimal mass transfer efficiency—two key characteristics in enhancing the performance of energy storage systems such as



fuel cells and supercapacitors (Nada et al., 2020). The integration of nanotechnology into physics education enables students to observe how theoretical concepts are applied in renewable energy technologies, while also fostering critical and creative thinking skills in designing solutions to future global energy challenges (Buonomenna & Bae, 2015).

In learning activities, students design mini cars that use nanofiber membranes as lithium-ion batteries that function as renewable energy sources. This is consistent with the results reported by Huang et al. (2020); Xu et al. (2022), which state that nanofiber membranes can be used as lithium-ion batteries. Lithium-ion batteries from the resulting nanofiber membranes can store more electric charge compared to ordinary batteries. This is due to the unique properties of nanofiber membranes, including their small size, expansive surface, and flexibility, which enhance ion conductivity and charge storage capacity (Liu et al., 2025; Nasikhudin et al., 2023). Based on the learning results, the students can design a minicar that uses nanofiber membranes as a lithium-ion battery, as shown in Figure 5. After the learning was conducted, the effect of learning using a nanofiber membrane on students' creative thinking skills was evaluated.

The Effect of Renewable Energy Learning with Nanofiber Membrane in STEM-based Approach on Creative Thinking Skills

The assessment of the impact of nanofiber-technology-based learning on students' creative thinking skills commenced with the analysis of data normality test results. Both the experimental group, which implemented PBL-STEM incorporating nanofiber membranes, and the control group, which applied PBL-STEM without nanofiber membranes, exhibited a p of .200 in the normality test, indicating a normal data distribution. This aligns with Isroani et al. (2022), who suggest that data is categorized as normally distributed when the p value surpasses .05. Following confirmation of normality, a homogeneity test was performed to assess the differences between the two groups. The test yielded a p of .657, confirming the homogeneity of the data. This result was consistent with that reported by Mustofa and Hidayah (2020), who state that data is considered homogeneous when the p exceeds .05. After verifying both normality and homogeneity, an independent t -test was performed to compare the mean scores of the experimental and control groups. This procedure aligns with Kim (2015), who explains that t -tests are employed to analyze the differences in means between two independent groups.

The analysis of pre-test data using an independent t -test yielded a p of .512 for both the experimental and control groups. This finding indicates that no substantial difference existed in the creative thinking skills of the two classes before the implementation of the educational intervention. According to Gómez-de-Mariscal et al. (2021); Williams et al. (2023), a p greater than .05 signifies the absence of a significant difference between groups. Following the implementation of PBL-based E-Worksheets with a STEM approach utilizing nanofiber membranes for renewable energy education, post-test results revealed a significant difference, with a p of $< .001$. This aligns with findings from Otero et al. (2025); Williams et al. (2023), who state that a p below .05 denotes a meaningful difference. The disparity is further evidenced by the mean scores: 80.72 for the experimental class versus 60.90 for the control class. This outcome suggests that the PBL-STEM E-Worksheet approach, incorporating nanofiber membranes, was more effective in enhancing student performance compared to traditional methods. To further examine the impact of this learning approach, an analysis of covariance (ANCOVA) was conducted on the application of PBL-STEM-based E-Worksheets with nanofiber membranes in educational activities.

The analysis using ANCOVA produced a p of $< .001$, indicating that students' creative thinking abilities significantly impacted the learning process. This finding is consistent with Shuvo et al. (2022), who state that a p below .05 indicates a substantial impact of the independent variable on the dependent variable. As a result, the experimental group using PBL-STEM-based E-Worksheet with nanofiber membranes showed a substantial impact on enhancing students' creative thinking skills. The marked difference in impact between the experimental and control classes can be attributed to the former's implementation of PBL-STEM-based E-Worksheet using palm kernel shell nanofiber membrane media (CPS). In contrast, the control class employed E-Worksheet with PBL-STEM alone, without incorporating the nanofiber membrane media (PKS) in classroom learning. The PBL-based E-Worksheet, which incorporates phases such as (1) problem orientation, (2) learning organization, (3) guided investigation, (4) development and presentation of results, and (5) analysis and evaluation of problem-solving, integrated with STEM, has been proven to enhance students' creative thinking skills (Romli et al., 2018). However, research conducted by Muskita et al. (2020) found that E-Worksheet based on PBL-STEM had a p of 1.70, suggesting no significant effect on improving students' creative thinking skills.

The experimental class's higher mean value can be attributed to the utilization of nanofiber membranes, suggesting superior creative thinking skills compared to the control class. Nanofiber membranes are appealing in form



and readily accessible (Almafie et al., 2022; Jauhari et al., 2021). Other studies also state that nanofiber membranes are easily available and environmentally friendly (Sriyanti et al., 2020). Consequently, incorporating nanofiber membrane media (PKS) in PBL-STEM-based instruction enhances learning engagement and comprehension. This is further evidenced by the student *n*-gain results. In the experimental group, 0% of students had low *n*-gain ($\leq .3$), 54.55% had moderate *n*-gain ($.3 < g \leq .7$), and 45.45% had high *n*-gain ($.7 < g \leq 1$). Conversely, in the control group, 13.64% of students had low *n*-Gain, 86% and 36% had moderate *n*-gain, and 0% had high *n*-gain. This aligns with Doyan et al. (2020), who categorize *n*-gain values as low ($\leq .3$), moderate ($.3 < g \leq .7$), and high ($.7 < g \leq 1$). While both groups showed improvement, only the experimental class achieved high *n*-gain values, demonstrating that the nanofiber membrane is more effective in enhancing students' creative thinking abilities. This improvement is also reflected in the pre-test and post-test responses. Initially, students provided simple answers, as illustrated in Figure 7. However, after exposure to the nanofiber membrane, their responses became more sophisticated, exhibiting greater fluency and flexibility with diverse alternative answers. This underscores the significant impact of nanofiber membranes on students' creative thinking skills in a STEM-based approach. The ability to provide fluent answers is a creative thinking skill, where students can generate numerous ideas or solutions (Kurniawan et al., 2024).

The teaching design in the STEM worksheet on renewable energy using nanofiber membranes can enhance students' creative thinking skills through steps involving problem-solving, product design, and evaluation. This learning syntax includes several key components:

1. Problem Orientation
Presenting real-world problems related to the application of renewable energy, which increases motivation and relevance in problem-solving activities.
2. Product Design Planning
Providing students the opportunity to design renewable energy-based solutions, such as nanofiber technology, which encourages creative thinking through the planning and conceptualization of their projects. This approach connects theoretical knowledge with practical applications, supporting the development of innovative thinking skills (Wulanningtyas & Ratnasari, 2022).
3. Development Schedule
Providing a clear timeline for renewable energy experiments, allowing students to explore various solutions and explanations. This structured approach also helps students manage their time and their creative processes in a disciplined manner.
4. Monitoring and Presentation
Incorporating continuous assessment of product development and refinement of ideas based on feedback. Presenting findings promotes communication and collaboration skills among students, further stimulating their creativity.

The experimental group shows greater improvement in creative skills because they not only assemble renewable energy-based vehicle models but also create a power source based on nanofiber technology. In contrast, the control group only assembles vehicle models using commercially available power sources. This difference highlights the significant impact of nanotechnology-based learning in fostering innovation and creativity among students within the context of renewable energy.

The integration of sophisticated technological modalities, exemplified by nanotechnology, presents a salient opportunity to potentiate both creative ideation and critical reasoning faculties within a Science, Technology, Engineering, and Mathematics (STEM)-centric pedagogical paradigm (Husseiny & Saab, 2024). This innovative confluence serves to enrich conventional instructional methodologies by cultivating advanced technological literacy, fostering substantive cognitive engagement, and affording exposure to veridical, real-world applications. Through such a synergistic and judicious integration, educators are empowered to architect immersive and interdisciplinary learning environments strategically designed to equip students with the requisite competencies for navigating future exigencies. The intrinsic interdisciplinarity inherent within the STEM-based approach facilitates a holistic epistemic acquisition through the convergence of foundational academic disciplines. By way of illustration, the incorporation of nanotechnology enables students to rigorously examine scientific phenomena at the molecular stratum, thereby engendering a more profound and nuanced conceptual comprehension (Fidan & Winter, 2025). Furthermore, interdisciplinary pedagogical frameworks demonstrably cultivate advanced creative problem-solving capacities by establishing substantive intellectual linkages across disparate yet complementary domains, as evidenced by the emergent integration of Nanoart within Science, Technology, Engineering, Arts, and Mathematics (STEAM) education, effectively bridging traditionally discrete scientific and artistic epistemologies (Suchikova & Kovachov, 2024).¹ When students are actively engaged in addressing authentic and complex problems, such as the practical application of



nanofiber membrane technology, they are intrinsically motivated to operationalize theoretical knowledge within tangible, real-world contexts. This pedagogical process not only refines the depth and breadth of conceptual mastery but also cultivates crucial innovation and sophisticated creative thinking proficiencies (Suchikova & Kovachov, 2024; Fidan & Winter, 2025). In summation, the judicious implementation of a Project-Based Learning (PBL)-oriented Electronic Worksheet (E-Worksheet) predicated upon a STEM-based pedagogical approach, and specifically leveraging nanofiber membranes for applications in renewable energy materials, demonstrably exhibits a positive and statistically significant effect on the enhancement of students' creative thinking proficiencies.

Conclusions and Implications

Nanofiber membranes are innovative materials produced through nanofiber technology using the electrospinning method. Integrating nanofiber membranes into STEM-based renewable energy education presents a novel and effective approach to enhancing students' creative thinking skills by connecting advanced materials science with real-world sustainability challenges. This integration offers students meaningful, interdisciplinary learning experiences that foster innovation and 21st-century competencies. This research demonstrates empirically that a STEM-based approach, incorporating nanofiber membrane and renewable energy materials, substantially enhances students' creative thinking skills. The *n*-gain analysis revealed that the experimental group experienced a moderate to high increase in creative thinking skills, while the control group only achieved a low to moderate improvement. This outcome highlights the effectiveness of a STEM-based approach that integrates cutting-edge technologies like nanotechnology in fostering students' creative thinking capabilities. The study's implications suggest a need for developing innovative science education methods that emphasize a more contextual and technology-driven STEM approach to cultivate 21st-century skills in students.

The research has limitations in terms of material scope, presenting opportunities for future studies to investigate this method's efficacy across various educational settings. It is recommended that subsequent research broaden the range of technologies incorporated into STEM learning and assess their impact on additional higher-order thinking skills, such as problem-solving and critical thinking. Future investigations should also examine contextual factors that may influence the effectiveness of STEM-based learning with nanofiber membranes, including resource availability and teacher support.

Therefore, the findings of this study can provide a strong basis for designing more innovative and flexible learning strategies suited to the demands of the Industrial Revolution 4.0 era. The results also make a valuable contribution to efforts aimed at enhancing science education quality in Indonesia, particularly in equipping young individuals with strong creative thinking skills to address global energy and sustainability challenges.

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Declaration of Interest

The authors declare no competing interest.

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**Leni Marlina**

Associate Professor, Lecturer in Master's Program in Physics Education, Faculty of Teacher Training and Education, Sriwijaya University, Palembang, Indonesia.
E-mail: leni_marlina@fkip.unsri.ac.id
ORCID: <https://orcid.org/0000-0002-7874-7089>

Ardi

Master's of Education, Master's Program in Physics Education, Faculty of Teacher Training and Education, Sriwijaya University, Palembang, Indonesia.
E-mail: alzakiyunardi97@gmail.com
ORCID: <https://orcid.org/0009-0008-0444-4318>

Mardiah Afifa

Master's of Education, Master's Program in Physics Education, Faculty of Teacher Training and Education, Sriwijaya University, Palembang, Indonesia.
E-mail: mardiahafifa231@gmail.com
ORCID: <https://orcid.org/0000-0002-1186-2349>

Ida Sriyanti

(Corresponding author)

Professor, Lecturer in Master's Program in Physics Education, Faculty of Teacher Training and Education, Sriwijaya University, Palembang, Indonesia.
E-mail: ida_sriyanti@unsri.ac.id
ORCID: <https://orcid.org/0000-0001-8011-8866>

Meilinda

Associate Professor, Lecturer in Department of Biology Education, Faculty of Teacher Training and Education, Sriwijaya University, Palembang, Indonesia.
E-mail: meilinda@fkip.unsri.ac.id
ORCID: <https://orcid.org/0000-0002-9436-730X>

