ASEAN Journal for Science and Engineering in Materials

Journal homepage: https://ejournal.bumipublikasinusantara.id/index.php/ajsem

Scientific Creativity in Materials Science Education among High School Students through Inquiry-Based Learning and Metacognitive Strategies

Pathomphong Boonpratham[1], Bovornpot Choompunuch[1,], Hisako Matsuo[2]*

[1]Mahasarakham University, Mahasarakham, Thailand;
[2]Saint Louis University, United States;
*Correspondence: E-mail: bovornpot.c@msu.ac.th

ABSTRACT

Materials science education requires high school students to connect abstract scientific concepts with the behavior and technological applications of materials. This study examined the effectiveness of inquiry-based learning integrated with metacognitive strategies in developing scientific creativity through electrostatics learning. A quasi-experimental two-group pretest–posttest design involved Grade 11 students assigned to experimental and control groups. The experimental group completed inquiry-based instruction incorporating planning, monitoring, and evaluating strategies, while the control group received conventional instruction. Scientific creativity was assessed through fluency, flexibility, and originality. ANCOVA results showed significantly higher adjusted posttest scores for the experimental group across all dimensions. The findings demonstrate the potential of inquiry–metacognition integration for fostering scientific creativity in materials science-oriented high school education.

ARTICLE INFO

Article History:
Submitted/Received 15 Feb 2026
First Revised 01 Jul 2026
Accepted 01 Aug 2026
First Available online 12 Aug 2026
Publication Date 01 Mar 2027

Keywords:
Electrostatics;
Inquiry-based learning;
Materials science education;
Metacognitive strategies;
Scientific creativity.

1. INTRODUCTION

Materials science connects fundamental scientific principles with the structure, properties, behavior, and technological use of materials. At the secondary-school level, introducing materials-related concepts can help students understand how abstract scientific principles are applied in functional systems and engineering contexts [1]. Electrostatics provides a relevant foundation for this purpose because electric charge, electric fields, potential, polarization, and capacitance directly influence the behavior of conductive and dielectric materials [2]. These concepts are particularly important for understanding how materials respond to electric fields and how such responses are utilized in capacitors, insulating systems, electronic devices, and other material-based technologies [3].

Despite its relevance, electrostatics is widely recognized as conceptually difficult because many of its central phenomena are invisible and require learners to construct mental models of charges, fields, forces, and potential differences [4]. Students may successfully apply mathematical formulas while retaining incomplete conceptual understanding of electric interactions [5]. Such difficulties become more important when electrostatic concepts are extended toward materials science, where learners must connect macroscopic observations with the electrical behavior of different materials. Therefore, instructional approaches are needed that move students beyond formula-based problem solving toward questioning, experimentation, interpretation, and application.

Inquiry-based learning provides such an environment by positioning learners as active constructors of scientific knowledge. Through questioning, investigation, evidence interpretation, and explanation, inquiry-based instruction has been shown to improve higher-order thinking and conceptual understanding in science [6]. The 5E instructional model (Engagement, Exploration, Explanation, Elaboration, and Evaluation) offers a structured inquiry framework that can support students in progressively developing and applying scientific concepts [7]. Recent evidence also indicates that inquiry-based approaches produce substantial positive effects on higher-order thinking skills across science disciplines [8]. However, inquiry alone may not ensure that students consciously regulate how they approach complex scientific problems. Metacognition, defined as awareness and regulation of one's own cognitive processes, provides an additional mechanism through which learners can plan strategies, monitor understanding, and evaluate the effectiveness of their reasoning [9]. These processes are particularly relevant when students encounter unfamiliar scientific and materials-related problems that allow multiple possible approaches. Metacognitive regulation can help learners reconsider ineffective strategies, explore alternative explanations, and refine emerging ideas [10].

The integration of inquiry and metacognitive strategies is therefore potentially important for developing scientific creativity. Scientific creativity involves generating scientifically meaningful ideas that demonstrate fluency, flexibility, and originality [11]. Unlike routine problem solving, creativity requires learners to generate multiple possibilities, shift between conceptual perspectives, and produce responses that are both novel and scientifically appropriate [12]. Metacognitive processes have been associated with stronger creative performance because monitoring and evaluation allow learners to organize, select, and refine ideas more effectively [13]. Similarly, metacognitive instruction has been shown to improve creative problem solving by supporting deliberate reflection on the quality of possible solutions [14].

This relationship is especially relevant to electrostatics within materials science education. Concepts such as charge interaction, electric fields, potential, and capacitance provide opportunities for learners to examine how materials behave under electrical conditions and to consider alternative material-related applications. In the present study, the electrostatics unit included fundamentals of electricity, forces between charges, electric fields, electric potential and potential difference, work, electric potential energy, capacitors, and capacitor circuits. These topics provide a conceptual bridge between school physics and introductory materials science without changing the original instructional content or experimental variables.

Although inquiry-based learning and metacognitive strategies have independently been associated with higher-order thinking, fewer studies have examined their phase-specific integration for developing scientific creativity in an electrostatics context. Previous studies have more frequently emphasized conceptual understanding, critical thinking, or general higher-order thinking rather than fluency, flexibility, and originality as simultaneous outcomes [8, 13]. Moreover, limited attention has been given to positioning electrostatics learning as a foundation for materials science-oriented scientific reasoning at the secondary-school level.

To address this gap, the present study integrated metacognitive strategies specifically within the Elaboration phase of the 5E inquiry model. During this phase, students were required to apply electrostatic concepts to increasingly complex situations while explicitly planning their approaches, monitoring their reasoning, and evaluating their solutions. This phase-specific design was intended to promote the generation, reconsideration, and refinement of multiple scientifically grounded ideas.

Accordingly, this study aimed to: (i) design inquiry-based learning plans incorporating metacognitive strategies for electrostatics learning; (ii) compare students' scientific creativity before and after instruction within experimental and control groups; and (iii) compare scientific creativity between students receiving inquiry-based learning with metacognitive strategies and those receiving conventional instruction.

The novelty of the study lies in positioning electrostatics as a materials science-oriented learning context while integrating metacognitive regulation within a specific phase of the inquiry cycle. Rather than distributing metacognitive activities throughout instruction, planning, monitoring, and evaluation were deliberately embedded in the Elaboration phase. The study also evaluates scientific creativity through fluency, flexibility, and originality, providing empirical evidence on how structured inquiry and metacognitive regulation can support creative scientific reasoning relevant to introductory materials science education.

2. LITERATURE REVIEW

2.1. Materials Science Education and Electrostatics

Materials science education links fundamental scientific concepts with the behavior, properties, and technological application of materials. At the secondary level, electrostatics provides a relevant entry point because charge interaction, electric fields, electric potential, and capacitance underpin the electrical response and application of materials [2, 3]. These concepts support students in connecting abstract physics with materials-related systems such as conductors, insulators, capacitors, and electrical devices.

Electrostatics remains difficult for many learners because electric fields, charge distributions, and potential are not directly observable and require mental representations of interacting physical quantities [3, 4]. Students may therefore perform mathematical procedures correctly while retaining incomplete conceptual understanding [15]. This limitation becomes important in materials science-oriented learning, where students must apply electrostatic concepts to explain how materials behave in electrical environments.

In this study, electrostatics functions as the scientific context rather than as an experimental investigation of material properties. The instructional content covers fundamentals of electricity, forces between charges, electric fields, electric potential and potential difference, work, electric potential energy, capacitors, and capacitor circuits. This sequence provides a conceptual pathway from fundamental physics toward introductory understanding of electrical behavior in materials.

2.2. Inquiry-Based Learning

Inquiry-based learning positions students as active constructors of scientific knowledge through questioning, investigation, evidence interpretation, and explanation [6]. This approach provides opportunities for students to examine phenomena, test ideas, and justify conclusions rather than depend primarily on memorization.

The 5E model structures inquiry through Engagement, Exploration, Explanation, Elaboration, and Evaluation [7]. Engagement activates prior knowledge, Exploration supports investigation, Explanation develops evidence-based understanding, Elaboration extends concepts to new situations, and Evaluation assesses learning outcomes. This sequence is suitable for electrostatics because learners can progressively move from observing phenomena toward explaining and applying abstract concepts.

Inquiry-based approaches have demonstrated positive effects on higher-order thinking in science [8]. Similar evidence indicates that inquiry can strengthen students' thinking performance when learning activities require active analysis and knowledge construction [16]. However, completing inquiry procedures does not automatically ensure that students consciously regulate their reasoning. Metacognitive support is therefore needed to strengthen reflection and strategic control during complex scientific problem solving.

2.3. Metacognitive Strategies in Inquiry Learning

Metacognition refers to awareness and regulation of one's own cognitive processes [9]. Its regulatory components commonly include planning, monitoring, and evaluation [10]. Planning involves selecting goals and strategies, monitoring involves checking understanding and progress, and evaluation involves judging the effectiveness of reasoning and outcomes.

These processes can strengthen inquiry learning because students are required not only to investigate scientific problems but also to regulate how they approach them. Metacognitive support can encourage learners to reconsider assumptions, identify weaknesses in reasoning, compare alternative strategies, and revise solutions. Metacognition-based approaches have been associated with stronger higher-order thinking because they require deliberate control over cognitive processes [17].

In this study, metacognitive strategies were embedded specifically within the Elaboration phase of the 5E model. Students applied established electrostatic concepts to increasingly complex problems while explicitly planning, monitoring, and evaluating their reasoning. The instructional relationship is summarized in **Table 1**.

Table 1. Integration of the 5E inquiry model and metacognitive strategies.

5E PHASE	MAIN LEARNING ACTIVITY	CONTRIBUTION TO SCIENTIFIC CREATIVITY
Engagement	Identifying phenomena and generating initial ideas	Stimulates idea generation
Exploration	Investigating phenomena and evidence	Expands possible explanations
Explanation	Constructing evidence-based explanations	Refines scientific understanding
Elaboration	Applying concepts with planning, monitoring, and evaluation	Promotes alternative and refined solutions
Evaluation	Assessing understanding and outcomes	Consolidates scientific reasoning

The phase-specific integration distinguishes the present intervention from approaches that distribute metacognitive activities throughout the entire instructional sequence. Positioning planning, monitoring, and evaluation within Elaboration allows students to regulate their thinking precisely when concepts are transferred to unfamiliar situations.

2.4. Scientific Creativity

Scientific creativity refers to the generation of ideas that are both novel and scientifically meaningful. Hu and Adey conceptualized scientific creativity as a multidimensional capacity that includes divergent production within scientific contexts [11]. In this study, it is operationalized through fluency, flexibility, and originality. Fluency represents the number of relevant ideas generated, flexibility represents variation across conceptual categories, and originality represents the relative novelty of responses.

Scientific creativity requires more than factual knowledge. Learners must generate alternatives, shift perspectives, and evaluate whether their ideas remain scientifically appropriate [12]. Consequently, instructional environments dominated by predetermined answers may provide limited opportunities for creativity, whereas inquiry provides greater space for divergent reasoning.

Metacognition further supports creative performance by regulating the generation and refinement of ideas. Monitoring and evaluation help learners identify weak responses, reconsider possible solutions, and improve the quality of emerging ideas [13]. Recent evidence also indicates that effective metacognitive monitoring is an important condition for higher levels of creative performance [18].

2.5. Conceptual Framework

The conceptual framework of this study proposes that inquiry-based learning provides opportunities for scientific exploration and idea generation, while metacognitive regulation supports the deliberate refinement of those ideas. Electrostatics serves as the instructional context and provides a conceptual connection to introductory materials science, whereas scientific creativity represents the measured outcome.

The proposed relationship is: Inquiry-Based Electrostatics Learning + Metacognitive Regulation → Scientific Creativity.

Inquiry activities support questioning, investigation, and generation of alternative explanations, while planning, monitoring, and evaluation during Elaboration help students regulate and refine their reasoning. Scientific creativity is subsequently evaluated through fluency, flexibility, and originality.

This framework supports the comparison between inquiry-based learning integrated with metacognitive strategies and conventional instruction while maintaining the original variables and assessment structure of the study.

3. METHODS

3.1. Research Design and Participants

A quasi-experimental two-group pretest-posttest design was employed to examine the effect of inquiry-based learning integrated with metacognitive strategies on scientific creativity. The design is presented in **Table 2**.

Table 2. Two-group pretest-posttest research design.

GROUP	PRETEST	TREATMENT	POSTTEST
Experimental	T_1	X_1	T_2
Control	T_1	X_2	T_2

Note: X_1 = inquiry-based learning with metacognitive strategies; X_2 = conventional instruction.

The population comprised 142 Grade 11 students in the Science-Mathematics program at a university-affiliated demonstration school in Northeast Thailand. Cluster random sampling yielded 69 participants: 30 in the experimental group and 39 in the control group.

3.2. Instructional Intervention

Both groups studied the same electrostatics content for 16 hours across eight lesson plans: fundamentals of electricity, forces between charges, electric fields, electric potential and potential difference, work in moving a charge, kinetic and electric potential energy, capacitors, and capacitor circuits.

The experimental group followed the 5E inquiry sequence described in **Table 1**. Metacognitive regulation was explicitly embedded in the Elaboration phase through planning, monitoring, and evaluating. Students planned solution strategies, monitored their reasoning, and evaluated the effectiveness and accuracy of their solutions. The control group received conventional instruction using identical content and instructional duration.

Five experts evaluated the instructional plans using a five-point scale. The final plans achieved mean appropriateness ratings of 4.51-5.00 before implementation.

3.3. Scientific Creativity Assessment

Scientific creativity was assessed using three open-ended problem scenarios adapted from literature [11]. The assessment measured fluency, flexibility, and originality. Fluency represented the number of relevant non-repetitive responses, flexibility represented the number of conceptually distinct response categories, and originality was determined by response rarity.

The three tasks addressed hypothetical scientific consequences, bio-inspired invention using spider-silk properties, and technological innovation involving artificial intelligence. The instrument therefore measured general scientific creativity rather than materials-specific creativity, while electrostatics and materials science orientation constituted the instructional context.

Content validity was evaluated by five experts using the Index of Item-Objective Congruence (IOC), with final values ranging from 0.60 to 1.00. A preliminary test involving 73 students produced item discrimination indices of 0.30-1.00 and a Cronbach's alpha of 0.837, indicating satisfactory internal consistency.

3.4. Data Collection and Analysis

Both groups completed the same creativity pretest before instruction and posttest after the 16-hour intervention. Responses were scored using the predetermined rubric under equivalent testing conditions. Means and standard deviations were calculated descriptively. Paired-samples *t*-tests examined within-group pretest-posttest differences. ANCOVA compared posttest scores between groups while controlling for pretest scores. The homogeneity-of-regression-slopes assumption was examined before ANCOVA, and statistical significance was set at $p \leq 0.05$.

4. RESULTS AND DISCUSSION

4.1. Development of the Instructional Plans

Eight inquiry-based lesson plans integrated with metacognitive strategies were developed for 16 instructional hours. The content covered fundamentals of electricity, forces between charges, electric fields, electric potential and potential difference, work, kinetic and electric potential energy, capacitors, and capacitor circuits.

The plans followed the 5E sequence summarized in **Table 1**, with planning, monitoring, and evaluation explicitly incorporated into the Elaboration phase. During Exploration, students investigated electrostatic phenomena through simulations, while Explanation required evidence-based interpretation. During Elaboration, increasingly complex problems required students to apply concepts while regulating their reasoning.

Expert evaluation indicated a high level of instructional appropriateness, with an overall mean of **4.74 ± 0.17**. Key concepts received the highest rating (M = 4.90, SD = 0.10), followed by learning objectives (M = 4.80, SD = 0.20), content (M = 4.80, SD = 0.14), instructional media (M = 4.76, SD = 0.15), learning process (M = 4.68, SD = 0.19), and assessment (M = 4.55, SD = 0.08). These results indicate that the intervention was considered structurally coherent and suitable for implementing electrostatics within a materials science-oriented learning context.

4.2. Within-Group Changes in Scientific Creativity

4.2.1. Experimental Group

As shown in **Table 3**, students receiving inquiry-based learning with metacognitive strategies demonstrated significant improvement in all dimensions of scientific creativity. The total score increased from 18.23 ± 6.03 to 27.30 ± 11.02, $t(29) = 4.13$, $p < 0.001$. Significant gains were also observed in fluency, flexibility, and originality. The simultaneous improvement across these dimensions suggests that the intervention supported not only greater idea generation but also greater diversity and novelty of scientific responses.

Table 3. Pretest-posttest scientific creativity scores in the experimental group.

COMPONENT	TEST	N	M	SD	t	df	p
Fluency	Pretest	30	8.70	3.03	4.40	29	<0.001
	Posttest	30	14.63	6.71			
Flexibility	Pretest	30	4.50	0.93	5.20	29	<0.001
	Posttest	30	5.80	1.42			
Originality	Pretest	30	5.03	3.13	2.16	29	0.039
	Posttest	30	6.87	3.68			
Total score	Pretest	30	18.23	6.03	4.13	29	<0.001
	Posttest	30	27.30	11.02			

Note: $p \leq 0.05$ indicates statistical significance.

Inquiry activities provide repeated opportunities to generate and compare explanations, whereas metacognitive regulation encourages learners to reconsider and refine those ideas [13]. The results therefore support the proposed mechanism in which inquiry promotes idea generation while planning, monitoring, and evaluation strengthen the quality of creative reasoning.

4.2.2. Control Group

The control group showed a more limited pattern of improvement, as presented in **Table 4**. Significant increases occurred only for fluency and the total score. Flexibility ($p = 0.270$) and originality ($p = 0.348$) did not change significantly. Conventional instruction may therefore increase the number of ideas available to learners but appears less effective for promoting diverse and original scientific reasoning, which generally requires opportunities for exploration and perspective shifting [12].

Table 4. Pretest-posttest scientific creativity scores in the control group.

COMPONENT	TEST	N	M	SD	t	df	p
Fluency	Pretest	39	7.94	4.98	5.04	38	<0.001
	Posttest	39	10.05	5.06			
Flexibility	Pretest	39	4.56	2.56	1.12	38	0.270
	Posttest	39	4.79	2.99			
Originality	Pretest	39	4.51	0.97	0.95	38	0.348
	Posttest	39	5.08	0.95			
Total score	Pretest	39	17.03	2.45	3.66	38	<0.001
	Posttest	39	19.92	3.11			

Note: $p \leq 0.05$ indicates statistical significance.

4.3. Between-Group Comparison

ANCOVA was conducted using pretest scores as covariates. The homogeneity-of-regression-slopes assumption was satisfied because group-by-pretest interactions were nonsignificant for fluency ($p = 0.125$), flexibility ($p = 0.102$), originality ($p = 0.831$), and total creativity ($p = 0.352$).

After controlling for pretest differences, the experimental group obtained significantly higher scores across all dimensions, as shown in **Table 5**. The strongest adjusted difference occurred for flexibility (partial $\eta^2 = 0.169$), followed by fluency (0.164), total creativity (0.160), and originality (0.062). Inquiry-based learning combined with metacognitive regulation produced advantages beyond initial group differences.

Table 5. ANCOVA results for scientific creativity.

COMPONENT	F	df	p	PARTIAL η^2	ADJUSTED EXPERIMENTAL M	ADJUSTED CONTROL M
Fluency	12.97	1, 66	<0.001	0.164	14.49	10.15
Flexibility	13.40	1, 66	<0.001	0.169	5.81	4.78
Originality	4.38	1, 66	0.040	0.062	6.83	5.10
Total score	12.56	1, 66	<0.001	0.160	27.06	20.10

Note: Pretest scores were entered as covariates; $p \leq 0.05$ indicates statistical significance.

The pattern is theoretically consistent with inquiry-based learning, which provides opportunities to generate and test alternative scientific ideas [8]. Metacognitive monitoring and evaluation may further support students in comparing alternatives and refining responses, thereby strengthening flexibility and originality [9, 13]. In the context of this study, electrostatics provided the scientific content through which these cognitive processes were developed, while scientific creativity remained the measured outcome.

4.4. Effect of Inquiry-Metacognition Integration on Scientific Creativity

The stronger performance of the experimental group can be explained by the complementary functions of inquiry and metacognitive regulation. Inquiry provided opportunities to investigate electrostatic phenomena, generate explanations, and consider alternative solutions, while metacognitive strategies required students to plan, monitor, and evaluate their reasoning. This combination supported both idea generation and deliberate refinement.

The improvement in fluency indicates that students became more capable of generating multiple scientifically relevant responses. Open-ended inquiry encourages learners to explore alternative hypotheses rather than converge immediately on a single predetermined answer [12]. This interpretation is consistent with the significantly higher adjusted fluency score of the experimental group shown in **Table 5**.

The largest effect was observed for flexibility (partial $\eta^2 = 0.169$). Metacognitive monitoring may have contributed to this result by encouraging students to recognize ineffective approaches and shift toward alternative reasoning strategies. Metacognition supports the regulation and adaptation of cognitive strategies [9], while deliberate monitoring contributes to creative performance [18]. The integration of these processes during Elaboration therefore provides a plausible mechanism for the observed increase in flexible scientific thinking.

Although originality also differed significantly between groups, its effect was smaller (partial $\eta^2 = 0.062$), as shown in **Table 5**. Original ideas generally require both divergent generation and subsequent evaluation. Metacognition can facilitate this process by helping learners assess and refine emerging ideas rather than accepting their initial responses [13].

The smaller effect suggests that originality may require longer and repeated exposure to open-ended scientific problems.

Inquiry and metacognition perform complementary roles. Inquiry expands opportunities for scientific idea generation, whereas metacognitive regulation helps students examine, modify, and refine those ideas. This interpretation is consistent with evidence that explicit metacognitive instruction can improve creative problem-solving performance [14].

4.5. Relevance to Materials Science Education

The findings also have implications for introductory materials science education. Electrostatics requires students to reason about charge interactions, electric fields, potential, energy, and capacitance, which provide foundations for understanding electrical behavior in materials [2]. The instructional sequence used in this study progressed from fundamental electrical concepts toward capacitors and capacitor circuits, allowing abstract physics concepts to be connected with materials-related technological applications.

However, the results should be interpreted carefully. The creativity instrument measured general scientific creativity, not the experimental characterization or design of materials. Therefore, the present findings do not demonstrate improved knowledge of dielectric properties, conductivity, polarization, or other measurable material characteristics. Instead, they indicate that an electrostatics learning environment relevant to introductory materials science can support fluency, flexibility, and originality when inquiry is combined with structured metacognitive regulation.

This distinction strengthens the educational interpretation of the study. Materials science education requires not only disciplinary knowledge but also the ability to consider alternatives and connect scientific principles with technological problems. Inquiry-metacognition integration provides a pedagogical mechanism for developing these reasoning processes without overstating the materials-specific outcomes measured in the present experiment.

4.6. Pedagogical Implications

Metacognitive strategies should be integrated purposefully rather than added as general reflection activities. In this study, planning, monitoring, and evaluation were concentrated within the Elaboration phase, where students applied established concepts to increasingly complex problems. This phase-specific structure allowed students to regulate their reasoning at the point where conceptual transfer was required.

For materials science-oriented instruction, teachers can similarly use electrostatic phenomena and material-related applications as contexts for open-ended problem solving. Students can be encouraged to propose alternatives, justify choices using scientific principles, monitor the consistency of their explanations, and evaluate possible solutions. Such activities maintain disciplinary grounding while creating opportunities for scientific creativity.

4.7. Limitations and Future Research

Several limitations should be considered. First, the study involved 69 Grade 11 students from a single university-affiliated demonstration school, limiting generalizability. Second, the quasi-experimental design cannot control all teacher- and classroom-related factors. Third, outcomes were measured immediately after the intervention; therefore, the persistence of creativity gains remains unknown.

Most importantly for the materials science framing, the assessment measured general scientific creativity rather than materials-specific knowledge or creativity. Future research should therefore incorporate tasks directly involving material selection, electrical properties, dielectric behavior, or materials-based technological design. Such studies could determine whether the creativity gains observed here transfer specifically to materials science problem solving.

Future studies should also involve larger and more diverse samples, delayed posttests, and mixed-method approaches. Interviews, classroom observations, and student reflections could clarify how planning, monitoring, and evaluation influence the generation and refinement of scientific ideas. Extending the approach to materials-related topics in physics and chemistry would further establish its applicability to materials science education.

5. CONCLUSION

Inquiry-based learning integrated with metacognitive strategies effectively enhanced students' scientific creativity in electrostatics learning. Students receiving the intervention demonstrated significant improvements in fluency, flexibility, originality, and overall scientific creativity and significantly outperformed those receiving conventional instruction after controlling for initial differences. The phase-specific integration of planning, monitoring, and evaluation within the Elaboration stage provided a structured mechanism for generating, examining, and refining scientific ideas. The study further demonstrates the potential of electrostatics as a learning context for introductory materials science education by connecting fundamental electrical concepts with materials-related phenomena and applications. However, the measured outcome was general scientific creativity rather than materials-specific competence. Future studies should therefore examine whether this instructional approach can enhance creativity in tasks involving material properties, material selection, dielectric behavior, and materials-based technological design.

6. ACKNOWLEDGMENTS

This research project was financially supported by Mahasarakham University, Thailand.

7. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

REFERENCES

[1] Gogotsi, Y., Burnside, H., Choi, M. Y., and Ferroni, J. (2005). Materials science in secondary education: Non-MRSEC initiatives. *Nature Materials, 4*, 357.

[2] Stamopoulos, D. (2024). Electrostatics in materials revisited: The case of free charges combined with linear, homogeneous, and isotropic dielectrics. *Materials, 17*(20), 5046.

[3] McDermott, L. C., and Shaffer, P. S. (1992). Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding. *American Journal of Physics, 60*(11), 994-1003.

[4] Hestenes, D. (1987). Toward a modeling theory of physics instruction. *American Journal of Physics, 55*(5), 440-454.

[5] Hasanah, R., Hidayat, A., Sutopo, and Fawaiz, S. (2025). Electrostatics conceptual test as an assessment instrument for undergraduate student's conceptual mastery on static electricity. *Jurnal Pendidikan Sains, 13*(1), 8-19.

[6] Urdanivia Alarcon, D. A., Talavera-Mendoza, F., Rucano Paucar, F. H., Cayani Caceres, K. S., and Machaca Viza, R. (2023). Science and inquiry-based teaching and learning: A systematic review. *Frontiers in Education, 8*, 1170487.

[7] Melgarejo, T., Atanacio, L., Leandro, A., Faustino, L., Rivarola, M., López, J., and Chavez, J. (2024). The 5E instructional model in the meaningful learning of science and technology. *Frontiers in Education, 9*, 1435530.

[8] Antonio, R. P., and Prudente, M. S. (2024). Effects of inquiry-based approaches on students' higher-order thinking skills in science: A meta-analysis. *International Journal of Education in Mathematics, Science and Technology, 12*(1), 251-281.

[9] Flavell, J. H. (1979). Metacognition and cognitive monitoring: A new area of cognitive-developmental inquiry. *American Psychologist, 34*(10), 906-911.

[10] Schraw, G., and Moshman, D. (1995). Metacognitive theories. *Educational Psychology Review, 7*(4), 351-371.

[11] Hu, W., and Adey, P. (2002). A scientific creativity test for secondary school students. *International Journal of Science Education, 24*(4), 389-403.

[12] Kind, P., and Kind, V. (2007). Creativity in science education: Perspectives and challenges for developing school science. *Studies in Science Education, 43*(1), 1-37.

[13] Jia, X., Li, W., and Cao, L. (2019). The role of metacognitive components in creative thinking. *Frontiers in Psychology, 10*, 2404.

[14] Hargrove, R. A., and Nietfeld, J. L. (2014). The impact of metacognitive instruction on creative problem solving. *The Journal of Experimental Education, 83*(3), 291-318.

[15] Duit, R., and Treagust, D. F. (2003). Conceptual change: A powerful framework for improving science teaching and learning. *International Journal of Science Education, 25*(6), 671-688.

[16] Damopolii, I., Nunaki, J. H., Nusantari, E., and Kandowangko, N. Y. (2020). The effectiveness of inquiry-based learning to train students' thinking skill based on SOLO taxonomy. *Journal of Physics: Conference Series, 1567*(4), 042025.

[17] Hamzah, H., Hamzah, M. I., and Zulkifli, H. (2022). Systematic literature review on the elements of metacognition-based higher order thinking skills teaching and learning modules. *Sustainability, 14*(2), 813.

[18] Urban, M., and Urban, K. (2025). Do we need metacognition for creativity? A necessary condition analysis of creative metacognition. *Psychology of Aesthetics, Creativity, and the Arts, 19*(6), 1467.