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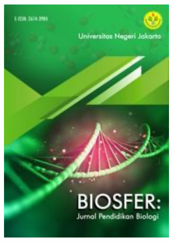

Scaffolding inquiry-based STEM: Enhancing problem-solving skills of preservice biology teachers

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ABSTRACT

Ecology courses demand the capacity to analyze complex environmental phenomena and to design innovative solutions. However, conventional ecology lectures often lack structured guidance to develop problem-solving skills. This research aims to evaluates the impact of inquiry-based STEM learning with scaffolding on the problem-solving skills of prospective biology teachers, focusing on the eutrophicated *Cengklik* Reservoir ecosystem. Employing a quasi-experimental pretest-posttest control group design, the sample consisted of 60 students, divided into an experimental group (n=30) received inquiry-based STEM with scaffolding and a control group (n=30) receiving standard inquiry. The experimental group designed a five-layer water filtration device as their engineering solution. Quantitative data were analyzed using ANCOVA with pretest scores as a covariate, partial eta squared (η^2) as the effect size and were integrated with qualitative interview data. The results indicate significant difference in problem solving skills between groups ($F(1,57)=24.356$; $p<0.001$; $\eta^2=0.391$), with the experimental group achieving a higher result (adjusted mean=3.74) than the control group (adjusted mean=3.03). The developed five layer filtration device reduced water turbidity (89.7%) and effectively bridged ecological theory with engineering practice. Thus, results demonstrate that inquiry-based STEM with enhances problem-solving capabilities through authentic product design. It is recommended that biology teacher education programs systematically integrate scaffolded STEM frameworks into ecological and environmental curricula to better prepare candidates for addressing real-world socio-scientific challenges.

INTRODUCTION

21st-century education demands that pre-service biology teachers have competencies that are in line with advances in science and technology, especially problem-solving skills (Kennedy et al., 2015; Gavrilas & Kotsis, 2025). These core skills enable future educators to adapt to rapidly changing educational landscapes and equip their future students with critical analytical capabilities (Tanti et al., 2021; UNESCO, 2022). These skills are key to addressing complex environmental problems, including water pollution and eutrophication in tropical reservoirs. *Cengklik* Reservoir in Boyolali, Central Java, for example, is facing serious eutrophication problems triggered by human activities, such as floating net cages and agriculture, leading to massive growth of water hyacinth and threatening the sustainability of water resources (Maharani et al., 2025; Lubis et al., 2026). Locally known as the *Waduk Cengklik* ecosystem, this artificial reservoir is a vital aquatic resource supporting local irrigation, freshwater aquaculture, and regional biodiversity, yet its hyper-eutrophicated state offers a rich, hands-on context for ecological inquiry. Thus, mastery of problem-solving skills is highly relevant for prospective biology teachers to address real ecological problems, such as the eutrophication of the *Cengklik* Reservoir.

Ecology learning in higher education should equip preservice biology teachers with the ability to analyze environmental problems scientifically and to design solution-oriented innovations (Cai & Wang, 2023; Schneider et al., 2021). However, problem-solving skills fail to develop optimally when instruction lacks critical thinking triggers (Achmetli et al., 2019; Zhao et al., 2025). Traditional learning devoid of authentic problems produces students who solve problems procedurally but lack real-world problem-solving skills (Brooks, 2022; Zhang et al., 2025). This issue is exacerbated by lecturer-centered methods and standardized practicums that limit student independence in designing, alternatives-evaluating, and reflecting on solutions (Boyd-Kimball & Miller, 2018; Flores-Lueg, 2022). This gap highlights the urgent need to reform ecological education toward autonomous, authentic problem-solving frameworks.

Scaffolded inquiry models mitigate these limitations by providing targeted assistance across scientific investigation stages (Chiu et al., 2022;Raes et al., 2020). Accumulated literature confirms that standard open inquiry without robust guidance often triggers cognitive overload, leaving students frustrated and unable to build systematic conclusions (Kirylo & Smith, 2021;Lai & Lai, 2018). While inquiry requires students to independently formulate questions, hypothesize, design experiments, and analyze data (Bembich & Bologna, 2025; Morris, 2025), many struggle to define problem focuses or interpret findings without intervention (Waked et al., 2024) Integrating structured scaffolding—such as trigger questions and tiered feedback overcomes these hurdles, acting as a crucial determinant for student success in autonomous scientific investigations (Lazonder & Harmsen, 2016; Shao et al., 2023; Rodríguez et al., 2022; Masava et al., 2022).

One effective strategy for optimizing problem solving skills is by integrating a STEM approach into biology learning (Kelley & Knowles, 2016; Tan et al., 2023). The STEM approach focuses on authentic problem solving and the development of innovative solutions, as well as functioning as a bridge that connects abstract scientific concepts with real experiences in everyday life (English, 2023; Thibaut et al., 2029;Dyachenko et al., 2024). In the realm of ecology, STEM can be realized through designing engineering solutions to overcome environmental problems, for example the development of water filtration devices. One concrete example is a 5-layer water filtration device that combines scientific understanding of filtration mechanisms (science aspect), design optimization (engineering aspect), measurement of filtration parameters (technological aspect), and data analysis regarding reducing pollutant levels (mathematical aspect) (Peng et al., 2025; Tan et al., 2019). The integration of STEM into ecological learning, especially through the development of appropriate technology products such as 5-layer water filtration devices, has great potential to train prospective biology teachers to solve environmental problems scientifically.

Although a number of studies have proven that the integration of the STEM approach and inquiry-based learning is effective in improving problem-solving abilities, the majority of this research is still focused on the secondary education level (Erman et al., 2021; Hasancibi et al., 2021) and has not in depth touched on the tertiary context, especially in biology teacher candidate study programs. The current state of the art in ecological education underscores a heavy reliance on standard text-based fieldtrips or cookbook laboratory manuals, leaving a major gap in cross-disciplinary technological synthesis (Varadarajan & Ladage, 2022; Nuangchalerm et al., 2024). Previous research typically characterizes learners as passive recipients of science education in schools. At the university level, especially for prospective teachers, it is essential to address a critical gap: the simultaneous mastery of ecological content and the demonstration of advanced pedagogical strategies. In more detail, there are still a number of important gaps that represent the true novelty of this research, namely: (1) the lack of empirical evidence regarding how the application of Inquiry-Based STEM takes place in the educational context of prospective biology teachers which requires mastery of the material as well as pedagogical readiness; (2) there is no detailed description of the process of designing and implementing scaffolding in a structured manner at each phase in inquiry learning; and (3) the limited application of this approach in specific scientific disciplines such as aquatic ecology. Current STEM interventions in aquatic ecology frequently employ a trial-and-error approach that lacks sufficient scaffolding to support students' scientific reasoning. As a result, these interventions do not effectively connect macroscopic environmental phenomena with microscopic processes such as filtration and breakdown mechanisms. Thus, further research is needed to specifically examine the application of Inquiry-Based STEM with structured scaffolding in the context of aquatic ecology among prospective biology teachers. The urgency of this research arises from the imminent ecological collapse of the *Cengklik* Reservoir. Neglecting the development of technological problem-solving skills in future teachers perpetuates passive environmental education and hinders the generation of effective conservation solutions (Suprapto et al., 2023; Widiatmoko et al., 2024). In the absence of structured interventions, pre-service teachers are not adequately prepared to connect complex ecological theory with practical, field-based problem-solving.

To overcome this gap, this research aims to evaluate the impact of inquiry-based STEM learning with scaffolding on the problem-solving skills of prospective biology teachers, focusing on the eutrophicated *Cengklik* Reservoir ecosystem. This site was selected due to the critical condition of the *Cengklik* Reservoir, which is experiencing severe anthropogenic eutrophication. These challenges make it an ideal, though complex, natural laboratory for authentic problem-solving. Specifically, this research examines how systematically integrated scaffolding at each stage of inquiry facilitates knowledge construction, supports scientific reasoning, and encourages problem-solving through the development of a 5-layer water filtration tool as a real solution to eutrophication. Accordingly, this study addresses two primary research questions: (1) Does scaffolded inquiry-based STEM instruction significantly improve the ecological problem-solving skills of preservice biology teachers compared to standard inquiry methods? (2) In what ways does the integration of a five-layer filtration engineering task facilitate scientific reasoning that links observable reservoir degradation to mechanistic filtration outcomes?

METHODS

Research Design

This research uses a mixed-methods approach with an embedded design, in which quantitative data serve as the primary method and are supported by qualitative data to enrich the interpretation of the findings (Creswell, 2012). The quantitative component uses a quasi-experimental pretest-posttest control-group design with two groups. Both groups were given a pretest; the experimental group received treatment (inquiry-based STEM with scaffolding), and the control group received no special treatment (standard inquiry); both groups were given a posttest. This design was chosen to allow for causal inference about treatment effects while addressing the limitations of one-group pretest-posttest designs that lack a comparison group.

Although these quasi-experimental designs are more powerful than pre-experimental designs, they still have limitations, especially the lack of full randomization, which can affect internal validity. To minimize threats to internal validity such as history, maturation, and selection bias, several strategies were applied: (1) selecting a control group that had baseline characteristics equivalent to the experimental group based on pretest scores; (2) using the same instrument for pretest and posttest with controlled implementation time in both groups; (3) apply treatment consistently to all participants in the experimental group; (4) carry out an initial equality test (pretest) to ensure there are no significant differences between the two groups before treatment; and (5) integrating qualitative data (embedded design) to support and strengthen the interpretation of quantitative results. With these steps, the credibility of the findings is expected to increase even if full randomization is not carried out.

Population and Samples

The population in this study was all students in the 4th semester of the Biology Education Study Program at one of the state universities in Indonesia. The sampling technique used was purposive, as 4th-semester students had completed general biology prerequisite courses and had sufficient basic knowledge to engage in ecological inquiry. The research sample consisted of two groups that had been formed naturally (intact groups), namely the experimental group (n=30), which received Inquiry-based STEM treatment with scaffolding, and the control group (n=30), which received standard inquiry without structured STEM integration. The detailed demographic characteristics of the research sample are presented in Table 1.

Table 1
Demographic characteristics of the sample

Demographic variable	Category	Experimental group (n=30)	Control group (n=30)	Total (n=60)
Gender	Male	8 (26.7%)	7 (23.3%)	15 (25.0%)
	Female	22 (73.3%)	23 (76.7%)	45 (75.0%)
Prerequisite GPA	Medium (3.00-3.50)	20 (73.3%)	21 (70.0%)	43 (56.7%)
	High (>3.50)	8 (26.7%)	9 (30.0%)	17 (28.3%)

To provide an authentic ecological context, the research was situated at the *Cengklik* Reservoir ecosystem, an area heavily impacted by anthropogenic eutrophication, where participants gathered real-world water samples for their filtration projects.

Instrument

The main instrument is an essay test, which was developed based on indicators of problem-solving ability, which refer to (Polya, 1973) four stages, namely: (1) understanding the problem, (2) preparing a plan, (3) implementing the plan, and (4) checking again, which is then translated into operational indicators: problem identification, application of problem-solving procedures, generation and evaluation of solutions, justification of solutions, application in real-world contexts, as well as inductive and deductive reasoning (Greenstein, 2012).

Analyses of construct validity and reliability were conducted to ensure the psychometric quality of the essay test. Three expert panel judges evaluated content and construct validity using Aiken's V, yielding an average score of 0.87 ($V > 0.80$), indicating high contextual and theoretical appropriateness. The instrument was field-tested with an external cohort of 35 students who had previously completed the ecology course. Item validity was assessed using the Product-Moment Correlation, with all essay prompts demonstrating validity through correlation coefficients (xy) ranging from 0.42 to 0.76, exceeding the critical r_{table} value of 0.334. Reliability was measured using Cronbach's Alpha, yielding a coefficient α of 0.83, indicating high internal consistency and strong instrument dependability for academic measurement.

Qualitative data were collected through observation sheets and semi-structured interviews. Observations focused on student involvement, the inquiry process, and the form of scaffolding provided during learning. Interviews were conducted with 12 purposively selected students (6 from each of the high-, medium-, and low-ability groups) to explore their learning experiences, challenges, and perceptions of scaffolding. The qualitative protocols were validated through member checking and peer debriefing to ensure credibility and trustworthiness.

Procedure

This research was conducted over ten meetings (one semester) in the ecology course. The procedure consisted of four main stages: 1) preparation, 2) pretest, 3) treatment implementation, 4) posttest, and 5) data collection and analysis. The procedural workflow highlights the operational differences between groups, illustrated in Figure 1.

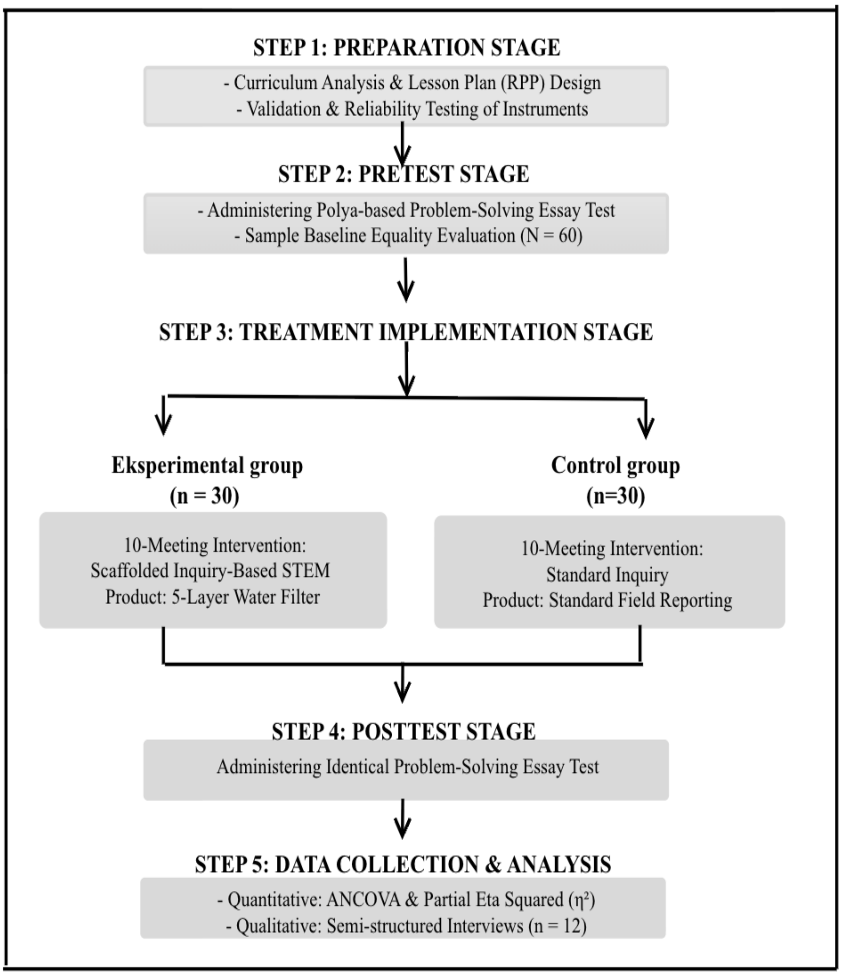

Figure 1. Operational flowchart of the mixed-methods embedded experimental procedure, tracking the sequential stages of the research.

The intervention was carried out over ten meetings (two learning cycles) in the Ecology course, following the stages of inquiry: inquisition, acquisition, supposition, implementation, summation, and exhibition (Ormanci & Cepni, 2025). The conceptual integration of STEM fields and specific scaffolding mechanisms across each Inquiry-Based Learning stage is systematically operationalized in Table 2.

Table 2
Integration of STEM and forms of scaffolding in ecological inquiry learning

Inquiry Stage	Learning Activities	STEM Integration	Scaffolding Form
Inquisition	Identifying the eutrophication .phenomenon in *Cengklik* Reservoir, formulating research questions.	Science: Eutrophication concept, nutrient pollution	Trigger question, initial concept clarification, video presentation of reservoir conditions.
Acquisition	Brainstorming possible solutions for water purification.	Science: Mechanisms of filtration, adsorption; Techniques: Filtration system design ideas	Concept map, guided discussion, filtration technology literature study.
Supposition	Formulate a hypothesis about the effectiveness of filtration layers.	Science: Relationship of variables; Mathematics: Cause-and-effect reasoning, prediction of removal percentage	Example of a hypothesis, lecturer feedback on hypothesis testability.
Implementation	Design and construct a 5-layer filtration device, test it on water samples.	Technique: Design layer arrangement; Technology: Measuring tools; Science: Experimental methods	Experiment templates, guided demonstrations, procedural checklists.

Summation	Collect, process, and analyze data on turbidity, pH, and pollutant reduction.	Mathematics: Data tables, graphs, percentage calculations; Science: Interpretation of filtration results	Analysis guide questions, data interpretation examples, statistical guidance.
Exhibition	Presenting the results of filtration tools and recommendations for the Cengklik Reservoir.	Technology: Digital presentations, scientific reports; Science: Scientific communication	Formative feedback, peer assessment rubrics, self-reflection prompts.

Data Analysis Techniques

The study employs both quantitative and qualitative data analysis methodologies, organized as follows:

1. Descriptive statistics are used to calculate the mean, standard deviation, and normalized gain score (N-gain) for the experimental and control groups.
2. Preliminary tests are conducted before inferential analysis, including the Shapiro-Wilk test for residual normality, Levene's test for homogeneity of variance, the linearity test, and the homogeneity of slopes test.
3. Inferential statistics include Analysis of Covariance (ANCOVA), using pretest scores as a covariate to assess differences in problem-solving skills between groups. When the homogeneity-of-slopes assumption is violated, the Johnson-Neyman procedure or a separate-group analysis is used as an alternative.
4. Effect size is measured using Partial Eta Squared (η^2) and 95% confidence intervals are calculated to determine the practical significance of the treatment effect.
5. Thematic analysis is conducted through data reduction, coding, categorization, and interpretation to integrate qualitative insights that support and illustrate students' quantitative problem-solving processes.

RESULTS AND DISCUSSION

The effectiveness of integrating a structured STEM approach with tiered scaffolding was assessed by monitoring the progression of problem-solving proficiency among pre-service biology teachers. The descriptive statistics and adjusted posttest mean scores for the inquiry-based STEM with scaffolding and standard inquiry groups are presented in Table 3.

Table 3
Descriptive statistics of problem-solving skills.

Group	n	Pretest	Std. deviation	Posttest	Std. deviation	Average Adjusted
Inquiry-based STEM with scaffolding	30	2.48	0.487	3.72	0.59	3.74
Standard inquiry	30	2.50	0.503	3.05	0.57	3.03

All parametric prerequisites for ANCOVA were rigorously met, as shown in Table 3. Included residual normality as assessed by the Shapiro-Wilk test ($p = 0.203 > 0.05$); homogeneity of variances via Levene's test ($p = 0.372 > 0.05$); homogeneity of regression slopes F (1.56) = 0.845; $p = 0.362 > 0.05$); and a verified linear relationship between the covariate (pretest) and the dependent variable (posttest) ($p < 0.05$). Advancing students from 'moderate' to 'excellent' problem-solving proficiency. While unguided environments imposed high extraneous cognitive load, leading to mechanical execution (Sweller, 2020), the 5-layer filtration task externalized abstract ecology into concrete engineering variables. This scaffolding acted as a cognitive prosthesis (Lazonder & Harmsen, 2016), preventing overload and refining the reasoning loops required to address ecological crises (English, 2016; Tan et al., 2023).

An ANCOVA was conducted to assess whether the pedagogical differences between the two cohorts had statistically significant effects, controlling for students' initial abilities as measured by the pretest. The inferential statistics summarising the treatment's effect on students' problem-solving skills are presented in Table 4.

Table 4
Results of the analysis of covariance test (ANCOVA) of the effect of treatment on problem solving skills

Sources of variance	df	F	p	η^2	Adjusted Mean (SE)
Treatment	1	24.356	<0.001	0.391	
- Inquiry-based STEM with scaffolding					3.74 (0.09)
- Standard inquiry					3.03 (0.09)
Error	57				

Unguided environments in standard inquiry imposed high extraneous cognitive load, hindering the control group's ability to synthesize reservoir data (Sweller, 2020; Kirschner & Hendrick, 2020). In contrast, scaffolded STEM integration in the experimental group prevented cognitive overload and enabled students to master ecological concepts alongside advanced engineering problem-solving strategies (Janssen et al., 2019; Lazonder & Harmsen, 2016; English, 2016; Tan et al., 2023). To evaluate the magnitude of this intervention, the operational effect-size parameters distinguishing the two instructional approaches are presented in Table 5.

Table 5
Effect size of difference in problem-solving skills (pretest-posttest)

Variable	Comparison	Effect size	Value	95% CI (Lower)	95% CI (Upper)	Interpretation
Problem solving	Inquiry-based STEM with scaffolding-Standard inquiry groups	Partial Eta Squared (η^2)	0.391	0.221	0.532	Large
		Cohen's d	1.19	0.65	1.73	Large

This large effect size is driven by marked improvements in students' problem identification and procedural application, confirming that integrated scaffolding successfully anchored their cognitive frameworks during initial problem mapping and device design (Kim et al., 2019). Furthermore, the experimental cohort's superior capacity for solution justification indicates a significant epistemic shift. Rather than generating unsupported claims common in conventional inquiry, interdisciplinary STEM tasks compelled learners to validate technical designs with rigorous biochemical reasoning. Consequently, this tiered support reinforced the evidence-based argumentation required for pre-service biology teachers to address complex socio-scientific challenges (Hmelo-Silver et al., 2019; Kelley & Knowles, 2016).

A standardized metric of growth across distinct cognitive dimensions was established by normalizing the absolute gains (Δ) for each problem-solving indicator to the maximum ideal score of the assessment rubric and converting the resulting values into growth percentages. The normalized percentage improvement across all six problem-solving indicators for both cohorts is presented in Figure 2.

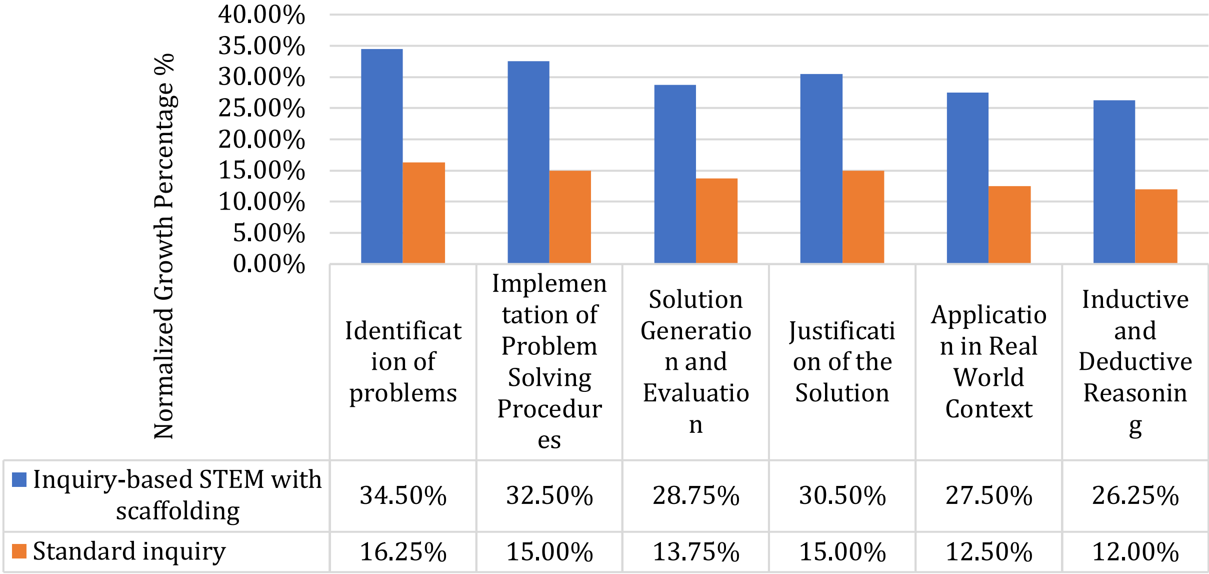

Figure 2. Comparison of percentage problem-solving skills indicators between groups

The inquiry-based STEM with Scaffolding group achieved double the growth of the standard inquiry group across all dimensions. Structured scaffolding reduced cognitive friction, allowing students to decompose environmental crises into technical requirements and transforming their reasoning from intuitive assertions into evidence-based models (Ryu & Sandoval, 2020; Sampson & Clark, 2018).

To assess the practical implementation of students' inquiry loops, the experimental cohort transformed their conceptual frameworks into functional engineering prototypes. Provides context for the range of project foci, layer configurations, and operational optimization metrics attained by student representatives in Table 6.

Table 6
Project characteristics of 5-layer filtration equipment

Project focus	**Layer configuration**	**Key findings**	**Turbidity reduction**
Comparison of natural vs synthetic filter media	Layers 1-2: gravel-sand; Layer 3: active carbon; layer 4: -coconut fiber; Layer 5: cotton	The combination of coconut fiber + activated carbon is most effective for removing organic pollutants	89.70%
Optimization of activated carbon thickness	Variation of activated carbon layer thickness (2cm, 4cm, 6cm, 8cm)	6cm thickness is optimal for adsorption balance and flow rate of	86.30%
Effect of filter media order on filtration efficiency	Testing 5 configurations with different media arrangements	Descending particle size order (coarse→fine) essential to prevent clogging	87.50%
Multi-stage filtration for nutrient reduction	Addition of zeolite layer for ammonia adsorption; Carbon modification with chemical treatment	Modified activated carbon increases phosphate removal by 23%	91.20%

The experimental group engaged in authentic iterative engineering optimization rather than replicating predefined setups. By integrating complex aquatic chemistry with physical engineering constraints, students successfully internalized abstract ecological data, translating it into functional, evidence-based physical parameters (Brophy et al., 2018). Furthermore, their diverse configuration strategies reflected advanced inductive and deductive reasoning. This iterative optimization process bridged the gap between scientific literacy and technical agency, fostering the cross-disciplinary problem-solving competencies necessary for future biology educators to promote environmental activism (Pleasants et al., 2021; Roehrig et al., 2021).

To evaluate the mechanical realization of the students' designs, the physical spatial organization of the filtration prototypes was systematically documented. The structural stratification and operational layout of the finalized 5-layer filtration device engineered by the students illustrated in figure 3.

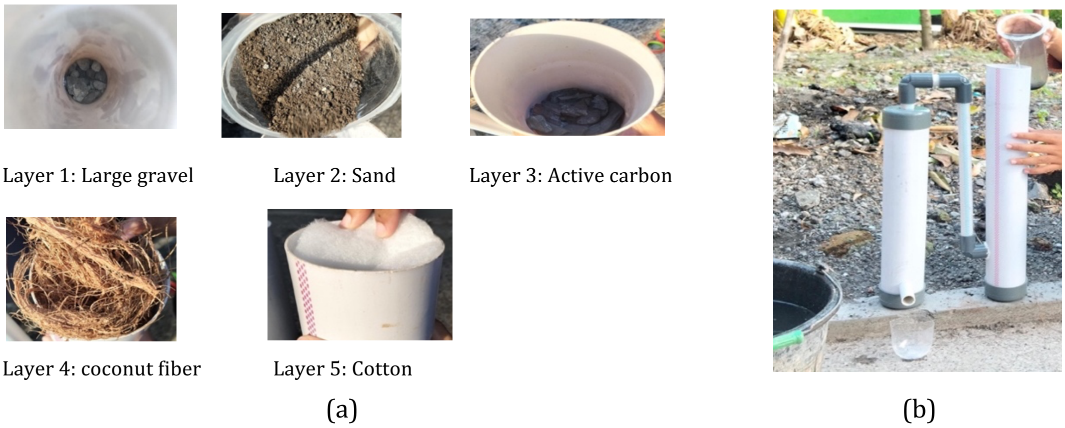

Figure 3. (a) exemplifies the effective application of fluid, (b) demonstrates the development of technical agency

The sequential media arrangement (Figure 2a) exemplifies the application of fluid dynamics, functioning as an externalized cognitive tool that transforms abstract hydraulic concepts into practical spatial configurations. Similarly, the empirical testing phase (Figure 2b) demonstrates the development of technical agency. By actively regulating fluid dynamics using reservoir inputs, students bridged the divide between scientific literacy and engineering practice, fostering the cross-disciplinary skills necessary for future biology educators to support authentic classroom investigations (Capraro et al., 2016; Guzey et al., 2016).

The interview results showed that scaffolding during the exhibition stage helped students increase their self-confidence and ability to defend scientific arguments. Student E-7 (Inquiry-based STEM with scaffolding group) stated:

> "*During the presentation, we were asked to explain the reasoning behind our filter layer arrangement and how it would apply to Cengklik's water conditions. I was nervous at first, but as we have been guided through data collection and analysis, I can confidently explain why our design works.*" (E-7)

Students also demonstrate the ability to relate their filtration device designs to real-world applications. E-12 students said:

> "*Discussions with other groups made us realize that our filtration design had the potential to be scaled for household use by communities around the Cengklik Reservoir. We started thinking about materials that were cheap and easily accessible to local communities.*" (E-12)

In contrast, control group students showed a lower ability to relate their findings to broader applications. Student C-4 stated:

> "*We followed the steps of inquiry and got results, but I'm not sure how this applies outside of this course. The experiment was interesting, but I didn't feel confident to design my own investigation.*" (C-4)

Through a process of scientific communication, reflection, and validation of data-based answers, the exhibition stage in this study serves as an integrative platform to solidify the problem-solving abilities of aspiring biology teacher students. The study's findings demonstrate that the use of scaffolding in problem-based learning (PBL), which is currently integrated with the STEM approach, plays a strategic role in assisting students in methodically communicating the findings of investigations, defending solutions in an argumentative manner, and demonstrating their preparedness to apply solutions in real-world contexts, such as the *Cengklik* Reservoir's eutrophication problem through the design of a seven-layer water filtration device.

According to (Belland et al., 2016) and (Lazonder & Harmsen, 2016) scaffolding in the form of scientific presentation guides, assessment rubrics, reflective questions, and formative feedback from peers and lecturers serves as a metacognitive support that enables students to construct arguments that are rational, grounded in facts, and compliant with the standards of scientific communication. These results demonstrate that the exhibition stage serves as a venue for critical reflection and improving the calibre of the problem-solving process in addition to being a platform for showcasing final results (Zhang et al., 2025; Shao et al., 2023).

The ability of students in the experimental group to explain the rationale behind the arrangement of water filter layers, relate empirical data to the designs created, and respond to questions in an argumentative manner as demonstrated by student E-7's statement clearly demonstrates the development of indicators for maintaining solutions and communicating results. It has been demonstrated that scaffolding in the form of presentation flow guides and trigger questions helps lower anxiety and boost students' confidence in defending scientific arguments, reflecting the development of solution-evaluation and solution-justification skills as crucial elements in problem-solving (Brooks, 2022; Mercan & Köseoğlu, 2022).

Additionally, indicators of the practical application of problem-solving abilities emerged from critical group discussions that prompted students to consider the real-world applications of research findings, such as household-scale filtration designs used in the community surrounding the *Cengklik* Reservoir. The statements made by E-12 students demonstrate that they go beyond technical fixes and begin to take into account factors such as material accessibility and affordability for nearby populations. According to Tan et al. (2023), Tripon (2025), and Zhang et al. (2025), this process demonstrates that the presentation stage serves as a link between academic knowledge and the practical demands of society.

Students in the control group, who did not receive systematic scaffolding, demonstrated poorer problem-solving skills, particularly in relating their results to broader applications. According to Student C-4's remark, even though they followed the phases of inquiry, the lack of metacognitive assistance during the learning process led to poor knowledge transfer to other settings and low confidence in conducting autonomous inquiries. According to earlier studies (Haruehansawasin & Kiattikomol, 2018; Hendrayana & Mutaqin, 2025; Kim et al., 2019; Varadarajan & Ladage, 2022), scaffolding is crucial for maximizing problem-solving abilities and autonomous learning in inquiry-based learning and PBL.

In addition, the experimental group seems to have more developed inductive and deductive thinking capabilities as part of their problem-solving abilities. Students can infer from filtering experiment data and connect these inferences to the scientific ideas that underpin their designs. This demonstrates how the gradual scaffolding aids students in developing a methodical scientific approach to addressing environmental issues (Achmetli et al., 2019; Gao et al., 2026; Mercan & Köseoğlu, 2022) Overall, the results at this exhibition stage support the idea that scaffolding used gradually and adaptively in STEM-based PBL learning greatly enhances the development of problem-solving abilities in aspiring biology teachers, particularly with regard to problem identification, strategy application, solution evaluation, solution justification, real-world application, and scientific reasoning (Pinar et al., 2025; Zviel-Girshin & Rosenberg, 2025).

The cognitive progression from open-ended environmental observation to targeted empirical experimentation was explicitly documented through students' self-generated research questions. What a specific student-led inquiries systematically resulted in validated technological solutions, and the integration of STEM disciplines show in Table 7.

Table 7
Student representative project ideas and resulting solutions

Research questions asked by students	Demonstrated results	Demonstrated STEM integration
What is the effect of the combination of activated carbon and coconut fiber on reducing the turbidity of the *Cengklik* Reservoir water?	The combination of coconut fiber + activated carbon achieved a turbidity reduction of 89.7%, compared to 76.2% for activated carbon alone	Science: Adsorption mechanism; Technique: Material combination design
What is the optimal thickness of the	6cm activated carbon layer is optimal;	Technique: Design

Research questions asked by students	Demonstrated results	Demonstrated STEM integration
activated carbon layer for maximum pollutant removal with adequate flow rates?	thinner layers lower removal efficiency, thicker layers reduce excessive flow rate	optimization; Mathematics: Rate calculations
Can the addition of a zeolite layer increase ammonia reduction in eutrophic water?	The addition of the zeolite layer increased ammonia removal by 41.3% compared to the standard configuration	Science: Ion exchange; Technology: Water quality testing
How does the sequence of filtration layers affect the removal of various particle sizes?	The descending order of particle size is essential; reversing the order causes rapid blockage within the first 5 minutes	Science: Particle dynamics; Engineering: System design

The matrix in Table 7 demonstrates that the experimental group advanced toward high-level epistemic questioning by formulating precise inquiries concerning material synergy, 6cm layer optimization, and zeolite ion-exchange loops to translate the macro-environmental degradation of the *Cengklik* Reservoir into testable empirical variables (Chiu et al., 2022). This systematic translation underscores a coordinated multidisciplinary thinking process in which students integrated mathematical flow-rate calculations with biochemical principles to optimize and justify their engineering designs. These findings indicate that integrated STEM modules, anchored by robust inquiry supports, effectively equip future biology educators with the structural frameworks necessary to address complex socio-scientific challenges (Miller & Krajcik, 2023).

The experimental cohort's heightened problem-solving proficiency aligns with Vygotsky's Zone of Proximal Development, where targeted scaffolding bridges the gap between actual and potential capabilities (Chin & Osborne, 2016; Belland et al., 2016). Early-stage guidance effectively helps learners pinpoint ecological challenges in the reservoir context, while mathematical integration fosters robust, evidence-based justification (Lazonder & Harmsen, 2016; Shao et al., 2023; Tan et al., 2023; Raes et al., 2020). Furthermore, the 5-layer filtration device functions as a mediating artifact that functionally links cross-disciplinary STEM knowledge to optimize practical solutions for real-world environmental issues (Kelley & Knowles, 2016; Gavrilas & Kotsis, 2025).

Theoretical and Practical Contributions

Theoretically, this research conceptualizes staged scaffolding in inquiry-based STEM, demonstrating gradual support reduction as student competency develops while providing empirical evidence within preservice ecology education (Belland et al., 2016; Cai & Wang, 2023). Practically, it offers an authentic learning model. Biology educators should implement clear, fading scaffolding, integrate meaningful STEM components, utilize relatable local environmental crises, and mandate physical engineering products to validate conceptual application (Miswami & Nurcahyo, 2020; Tripon, 2025).

Limitations and Future Research

Some limitations need to be acknowledged. First, this study used a quasi-experimental design and a relatively small sample from a single university, limiting generalizability. Second, the ten-meeting intervention duration may not fully capture long-term skill retention. Third, 5-layer filtration devices, although effective, may not address all dimensions of the reservoir eutrophication. Fourth, this study did not assess the development of pedagogical content knowledge, which is essential for teacher candidates.

Future research should use larger, multi-site samples to establish broader generalizations. Longitudinal studies are needed to examine the ongoing impact of inquiry-based STEM with Scaffolding on teacher candidates' professional competencies as they enter teaching practice. Additionally, research needs to investigate how preservice teachers transfer their STEM inquiry experiences into their own instructional designs, examining the relationship between these experiences and the development of pedagogical capacity for STEM teaching.

CONCLUSION

This research demonstrates that scaffolded inquiry-based STEM learning significantly enhances the problem-solving skills of prospective biology teachers within ecological contexts. Driven by a robust quasi-experimental design, the intervention yielded a substantial treatment effect ($\eta^2 = 0.391$), operationalized through student-engineered 5-layer water filtration devices that effectively resolved the authentic eutrophication crisis in the *Cengklik* Reservoir. Theoretically, these findings advance socio-constructivist frameworks by establishing continuous scaffolding as a dynamic epistemic tool that bridges scientific inquiry with engineering design constraints. Practically, this study provides vital curricular implications for teacher training institutions, offering a scalable pedagogical model to transition traditional science labs into high-order thinking environments that equip future educators with the technological agency and evidence-based reasoning necessary to foster authentic environmental activism in their future classrooms.

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