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Enhancing Experiment Planning Skills Using Unguided Experiment Worksheets: Indicator-Based Analysis, Learner Autonomy, and Theoretical Insights

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Abstract

This study aims to analyze the effectiveness of using Unguided Experiment Worksheets (UEWs) to enhance university students' experiment planning skills. Employing a one-group pretest-posttest design with 15 biology education students, the descriptive analysis showed an increase in average scores from 11.0 (pretest) to 17.3 (posttest), accompanied by improved uniformity in student understanding. The paired sample t-test yielded a t-value of 34.49 ($p < 0.05$), indicating a statistically significant improvement. Per-indicator analysis revealed substantial progress in hypothesis formulation, experimental variable identification, and scientific procedure design. The findings are discussed within the frameworks of Cognitive Load Theory, Self-Regulated Learning, constructivism, and the cognitive apprenticeship model, emphasizing the importance of balancing student autonomy with instructional scaffolding. This study offers novel contributions by demonstrating that UEWs benefit not only high-achieving students but also support lower-performing students in improving their skills, thereby promoting equitable science learning outcomes. The study recommends lecturer training, curriculum integration, multi-institutional research, and long-term retention evaluations to strengthen UEW implementation across educational levels.

Keywords: Unguided Experiment Workshee, Experiment Planning Skill, Learner Autonomy, Cognitive Load Theory, Self-Regulated Learning

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INTRODUCTION

The ability to plan experiments is a crucial element in science education, contributing significantly to students' understanding of concepts and development of scientific thinking. In the context of science learning, this ability not only involves applying the scientific method in practice but also encourages students to think critically, systematically, and reflectively skills at the core of scientific inquiry. Effective experiment planning includes steps such as formulating hypotheses, identifying variables, designing experimental procedures, and analyzing observational data. These activities foster an understanding of cause-and-effect relationships in scientific phenomena and strengthen students' capacity to organize logical reasoning and draw conclusions based on empirical evidence.

Existing pedagogical techniques in science education, such as Problem-Based Learning (PBL), Inquiry-Based Learning (IBL), and Discovery Learning (DL), have been shown to improve students' scientific literacy and foster curiosity, as well as support independent learning through solving real-world problems requiring systematic experimental planning (Worachak et al., 2023; Nurlaela et al., 2018; Mao, 2023). PBL, for example, cultivates critical thinking by presenting students with realistic, open-ended problems that require deep inquiry and analytical reasoning (Tapilouw, 2020). IBL engages students in structured question formulation and investigation, enhancing creativity and fostering ownership of learning (Nurlaela et al., 2018). DL offers opportunities for autonomous exploration, promoting independent thought and problem-solving (Mao, 2023). Despite the demonstrated strengths of these approaches, there is a pressing need to address a critical research gap: how do we enhance students' autonomy and higher-order thinking specifically in the context of experiment planning, beyond what is already supported by PBL, IBL, or DL?

While these methods emphasize exploration and problem-solving, they often still operate within guided frameworks that provide significant scaffolding to students. This overreliance on guided worksheets or structured activities can inadvertently suppress students' creative thinking and independent decision-making. Studies such as Chutami & Suhartini (2021) and Mahyuna et al. (2024) suggest that overly directive instructional designs limit students' opportunities to develop their own experimental strategies, diminishing critical and analytical thinking. This aligns with Kirschner et al. (2006), who warn that while minimal guidance approaches can seem appealing, without thoughtful design they risk leaving students overwhelmed and disengaged, particularly when working with novel and complex content.

One promising alternative is the use of Unguided Experiment Worksheets (UEWs), which offer students the freedom to plan and conduct experiments with minimal prescriptive direction. This approach shifts the responsibility for inquiry onto students, encouraging them to apply prior knowledge, reason independently, and reflect critically on their learning processes (Erasanti & Juandi, 2017; Melawati et al., 2022). Importantly, UEWs can serve as a tool to enhance student autonomy a key predictor of engagement and learning success in science classrooms (Deliveli & Balçikanli, 2023). Syamsudin (2023) emphasizes that when learners are empowered to construct their own experimental paths, they develop not only confidence but also the critical inquiry skills foundational to scientific literacy. Similarly, Pujani (2022) finds that self-directed experimental tasks enhance concept retention and deepen understanding.

To ground these arguments theoretically, Cognitive Load Theory (Sweller, 1988) and the Self-Regulated Learning (SRL) model (Zimmerman, 1989) offer valuable insights. Cognitive Load Theory (CLT) posits that working memory has limited capacity, and excessive cognitive demands can hinder learning (Sweller et al., 1998). Tasks that are too complex or insufficiently structured can impose high intrinsic cognitive load, overwhelming students and impeding the acquisition of new knowledge. Conversely, instructional strategies that manage cognitive load effectively such as segmenting content, using worked examples, or providing minimal but targeted guidance can optimize schema development and foster deep learning (Merriënboer & Sluijsmans, 2008). Within this framework, UEWs balance the cognitive demands of experimentation by offering students autonomy without overwhelming them with excessive instructions or irrelevant details.

Zimmerman's SRL theory complements this perspective by focusing on students' active regulation of their own learning processes (Zimmerman, 1989; Schunk & Zimmerman, 2006). SRL involves a cycle of forethought (planning and goal setting), performance (monitoring and strategy use), and self-reflection (evaluating outcomes and adjusting behaviors). In the context of science education, UEWs provide an ideal platform for practicing self-regulation, as they require students to set experimental goals, monitor their progress, and revise their approaches based on observed outcomes. Research shows that students who effectively engage in SRL strategies, such as goal setting and self-monitoring, tend to achieve higher levels of academic success and demonstrate greater engagement and intrinsic motivation (Pintrich & Groot, 1990; Greene et al., 2011). Managing cognitive load effectively through instructional design can thus directly enhance students' ability to regulate their learning and exercise autonomy (Panadero, 2017).

This dual-theoretical lens helps explain why traditional guided worksheets, despite their structured clarity, often fail to foster deep cognitive engagement and self-directed learning behaviors. While guided inquiry can improve process skills (Sulistyani et al., 2022; Yusuf et al., 2023), it can also reduce opportunities for students to take ownership of their learning. In contrast, UEWs encourage students to develop metacognitive strategies, apply prior knowledge creatively, and explore alternative solutions skills essential for navigating the complexities of real-world scientific inquiry (Dignath & Büttner, 2008; Greene et al., 2011).

It is also essential to situate this study within the ongoing international debate on minimal guidance learning. Kirschner et al. (2006) caution that minimally guided instructional designs can fail if they lack sufficient scaffolding, especially for novice learners. They argue for the necessity of guided instruction to help students process new information effectively. On the other hand, Hmelo-Silver et al. (2007) highlight that strategic scaffolding in inquiry-based environments can significantly enhance student engagement and learning, supporting the gradual development of independent inquiry skills. The key, then, lies in balancing autonomy with scaffolding a balance that UEWs aim to achieve by providing minimal, carefully designed support to guide students' independent exploration.

Comparing UEWs with other pedagogical approaches underscores their distinctiveness. While PBL emphasizes problem-solving in real-world contexts, it often lacks an explicit focus on experimental planning. Similarly, IBL fosters inquiry and exploration but typically involves teacher-provided questions or structured investigative paths. Discovery Learning offers students open exploration opportunities but can risk cognitive overload without sufficient scaffolding (Kirschner et al., 2006). In contrast, UEWs specifically target the development of experiment planning skills, guiding students through the entire scientific cycle from hypothesis generation and variable identification to procedural design and data analysis while maintaining a high degree of learner autonomy.

Addressing the practical urgency of this research, science classrooms often face systemic constraints such as limited time, packed curricula, and scarce resources. These constraints can hinder the meaningful implementation of inquiry-based learning activities. UEWs present a practical solution: they allow teachers to promote student-centered experimentation without the heavy demands of elaborate instructional design or extensive teacher intervention (Fatimah & Bramastia, 2021). By equipping students with a flexible, minimal-structure tool, UEWs enable dynamic, responsive learning environments that better meet diverse learner needs.

Despite the promising potential of UEWs, prior research has paid insufficient attention to their comparative effectiveness and the specific mechanisms by which they enhance experiment planning skills. What specific aspects such as hypothesis formulation, variable control, or procedural design are most impacted by unguided worksheets compared to guided approaches or other learning models? This study seeks to fill this research gap by empirically investigating the use of UEWs in science education, analyzing their impact on students' experiment planning skills, and articulating the mechanisms through which autonomy and self-regulation contribute to scientific learning.

This study aims to advance the theoretical and practical discourse on instructional design in science education by providing empirical evidence for the effectiveness of UEWs. By examining how UEWs influence the development of students' experiment planning skills, this research not only addresses a critical gap in the existing literature but also offers insights for educators seeking to implement more autonomous, student-centered pedagogical strategies. Ultimately, this work contributes to the ongoing reform of science education by promoting innovative, evidence-based approaches that empower students as active participants in their own learning journeys.

METHODS

This study employed a pre-experimental approach using a one-group pretest-posttest design. This design involved only one group of students who were first given a pretest to assess their initial experiment planning skills. Following this, the group received an intervention in the form of learning activities using Unguided Experiment Worksheets (UEWs) worksheets without detailed instructions, designed to require students to independently plan and design experiments. After the intervention, the group completed a posttest to evaluate any improvement in their skills. This design was selected because it is appropriate for preliminary or pilot studies aimed at exploring the potential impact of an educational intervention before applying it on a larger scale (Creswell, 2012).

Although the one-group pretest-posttest design allows researchers to gauge the effectiveness of an intervention within the same group over time, it is important to acknowledge its methodological limitations. As Creswell (2012) explains, this design lacks random assignment and control groups, making it susceptible to threats to internal validity, such as maturation effects, testing effects, and external influences. Bhattacherjee (2012) further emphasizes the importance of clearly defining the problem, hypotheses, and context when selecting such a design to maximize the precision and clarity of interpretations. While this study provides valuable early insights, future research with stronger experimental designs is needed to confirm causal relationships more rigorously.

Participants

The research participants consisted of 15 undergraduate students enrolled in the Biology Education Study Program at Universitas Pendidikan Mandalika. The participants were selected using purposive sampling based on the following criteria: (1) students had prior foundational knowledge of experimental methodology, ensuring they were prepared to engage meaningfully with the intervention; (2) they were in a semester relevant to learning about experiment planning, meaning they were developmentally aligned with the study's learning objectives; and (3) the class selected was available and willing to participate in the entire research process. Establishing clear participant profiles is essential for ensuring the validity and applicability of the findings (Ohreen et al., 2021), as well as for conducting stratified analyses that can yield nuanced insights.

Data Collection Techniques

Data were collected using a combination of pretest and posttest assessments. Before the intervention, students completed an initial test to measure their baseline experiment planning abilities. After engaging with the UEW-based learning activities, they completed a final test to assess progress. Both tests were designed to evaluate five key indicators of experiment planning skills, as summarized in Table 1.

Table 1. Test Indicators

No.	Indicator
1	Ability to formulate a research problem in the form of a clear research question
2	Ability to develop an appropriate hypothesis using an "if… then…" statement
3	Ability to accurately identify independent, dependent, and control variables
4	Ability to list all necessary tools and materials relevant to the research objective
5	Ability to design a systematic, logical, and detailed experimental procedure that others can follow

Research Instruments

The main research instrument was a set of five open-ended essay questions aligned with the indicators listed above. These questions were designed to elicit students' reasoning, analytical thinking, and practical planning abilities, providing both qualitative and quantitative data for analysis.

Data Analysis Techniques

The data analysis process involved two stages: descriptive analysis and inferential analysis.

Descriptive Analysis included calculating the mean, standard deviation, minimum and maximum scores, and score ranges for both pretest and posttest results. This provided an overview of overall improvement and the distribution of scores among participants, aligning with the descriptive statistics presented in Table 2 of the Results section.

Inferential Analysis involved conducting a paired sample t-test to determine whether the difference between pretest and posttest scores was statistically significant. Since the same participants were tested before and after the intervention, the paired sample t-test was an appropriate choice. However, to ensure the validity of the t-test, the assumptions underlying this statistical method were first examined. Specifically, the normality of the difference scores was assessed using the Shapiro-Wilk test, which is particularly reliable for small sample sizes (Glenn et al., 2013). In cases where larger samples are available, the Kolmogorov-Smirnov test can complement normality assessments (Budiharto & Basuki, 2021). Additionally, graphical methods such as Q-Q plots were consulted to provide a comprehensive understanding of data distribution.

It is crucial to note that the paired sample t-test assumes that the paired differences are normally distributed. If the data were found to violate normality assumptions, nonparametric alternatives such as the Wilcoxon signed-rank test would be considered, as it does not assume normality and is effective in evaluating differences between paired medians. Fortunately, in this study, the data met the normality assumption, allowing the paired sample t-test to be applied confidently.

Methodological Transparency and Limitations

In line with Bhattacherjee (2012), this study openly acknowledges the limitations of its methodological design. The absence of a control group means that external factors, such as the Hawthorne effect (Chen et al., 2015), maturation effects, or practice effects from taking the pretest, cannot be ruled out as alternative explanations for the observed improvements. While the findings provide promising evidence regarding the potential of UEWs, they should be interpreted cautiously and understood as preliminary. Future research should consider employing randomized controlled trials or quasi-experimental designs with comparison groups to enhance the robustness of causal claims.

RESULTS AND DISCUSSION

The results of this study demonstrate that the use of Unguided Experiment Worksheets (UEWs) has a significant positive impact on students' abilities to plan experiments. Descriptive analysis shows that the average pretest score of the students was 11.0, which increased to 17.3 in the posttest. The score range also improved, shifting from 8–14 in the pretest to 15–19 in the posttest. This indicates not only an overall improvement in students' experimental planning skills but also a more homogeneous distribution of understanding among participants, as reflected by the reduction in standard deviation from 1.70 (pretest) to 1.40 (posttest) (see Table 2).

Table 2. Descriptive Analysis of Experiment Planning Skills

Statistic	Pretest	Posttest
Number of Students	15	15
Mean	11.0	17.3
Highest Score	14	19
Lowest Score	8	15
Standard Deviation (SD)	1.70	1.40

Figure 1 (Comparison of Pretest and Posttest Scores of Students) visually presents this improvement, showing a consistent upward pattern across all participants. The orange line (posttest) consistently stays above the blue line (pretest), reinforcing the statistical evidence that the intervention was effective in enhancing students' skills. Notably, students who initially performed poorly, such as Student 5 and Student 6, displayed the largest improvements, with gains of up to 7 points, suggesting that the intervention was beneficial not only for high- and mid-performing students but also for those with lower initial abilities.

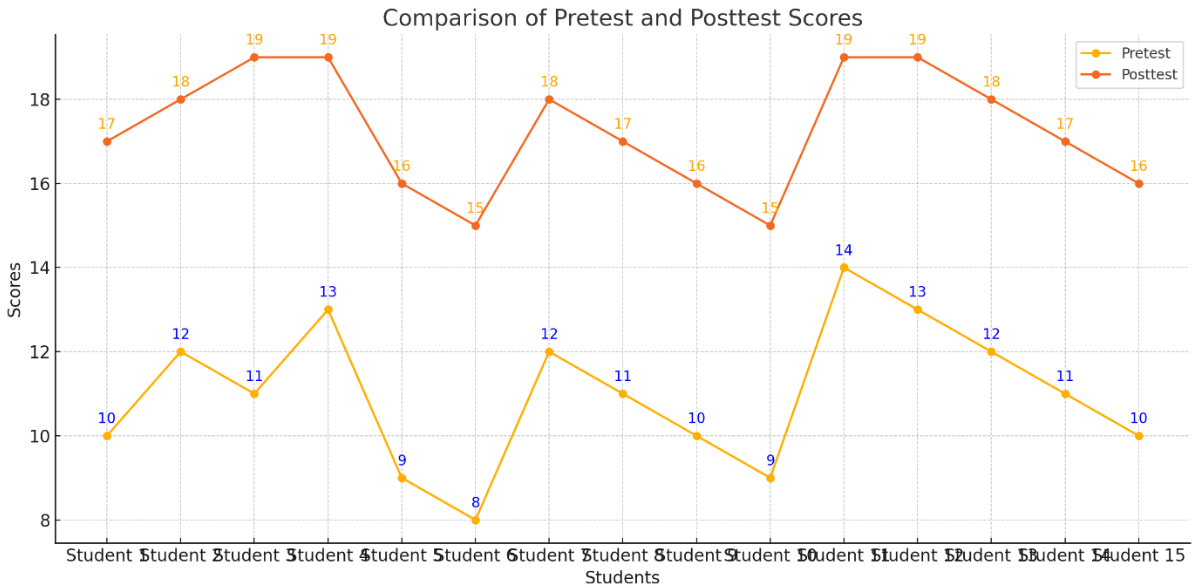

Figure 1. Comparison of Pretest and Posttest Scores of Students

Inferential analysis using the paired sample t-test revealed a t-value of 34.49 with a p-value of 6.07×10^{-15} (Table 3), far below the significance level of 0.05. This result confirms that the improvement in students' performance was statistically significant. Importantly, the data were first assessed using the Shapiro-Wilk test to ensure normality, yielding a p-value > 0.05, which confirmed the validity of the t-test assumptions.

Table 3 . Paired Sample t-Test Results

Statistic	**Value**
t- statistic	34.49
p-value	6.07×10^{-15} (highly significant)
Degrees of freedom (df)	14
Significance level (α)	0.05

To gain deeper insight, we conducted a per-indicator analysis of the experimental planning components: hypothesis formulation, identification of experimental variables, and design of scientific procedures. These aspects are critical for the development of students' scientific process skills and align with previous research.

Hypothesis formulation is widely recognized as a foundational skill in scientific inquiry. Andini et al. (2018) emphasize that assessing this skill is key to understanding students' scientific proficiency. Demkanin et al. (2019) argue that structured practice in hypothesis formulation promotes logical inference and enhances students' ability to make predictions based on prior knowledge. In this study, students who initially struggled to articulate clear, testable hypotheses showed marked improvement post-intervention, demonstrating enhanced scientific reasoning and analytical thinking.

Identifying experimental variables represents another vital dimension of experimental design. According to Rahmawati et al. (2022) and Numa & Martini (2022), guided inquiry interventions significantly improve students' capacity to identify and classify independent, dependent, and controlled variables. In our findings, many students initially failed to distinguish between manipulated and responding variables or overlooked the importance of control variables. After the UEW intervention, students displayed notable progress, indicating that engaging independently with experimental tasks helped solidify their understanding of experimental structures.

Designing scientific procedures involves applying theoretical knowledge to create a logical sequence of experimental steps. Fahlevi et al. (2022) and Sukarmin et al. (2018) have shown that structured interventions can help students translate abstract concepts into concrete experimental actions. In this study, post-intervention student work revealed enhanced capability in designing feasible and systematic procedures, anticipating sources of error, and predicting outcomes—all of which are essential elements of scientific inquiry.

The theoretical underpinnings of these improvements can be explained using two major frameworks: Cognitive Load Theory (CLT) and Self-Regulated Learning (SRL). CLT (Sweller et al., 1998) posits that working memory has limited capacity, and excessive cognitive demands can impede learning. The UEW used in this study was carefully designed to balance cognitive load: by minimizing extraneous load (e.g., redundant instructions) while maintaining a level of intrinsic load that challenges students to engage actively with the material and develop new mental schemas. This aligns with Merriënboer & Sluijsmans (2008), who emphasize the importance of well-designed instructional materials in supporting complex learning tasks.

From the SRL perspective, Zimmerman (1989) defines self-regulated learning as a cyclic process involving forethought, performance, and self-reflection. The UEW intervention required students to set goals, monitor their progress, and evaluate outcomes independently. Prior research by Pintrich & Groot (1990) and Greene et al. (2011) has shown that students who effectively apply self-regulation strategies are more engaged and achieve better learning outcomes. Our findings support this, as students reported increased ownership over their learning process and demonstrated heightened metacognitive awareness in planning and evaluating their experimental work.

The social dimension of learning, as highlighted by Vygotsky's Constructivist Learning Theory (Wang & Bonk, 2019), also played a crucial role in this study. Although the UEW approach emphasizes independence, students frequently engaged in peer discussions, shared ideas about hypothesis generation, and collaboratively evaluated experimental designs. This aligns with Vygotsky's assertion that knowledge is co-constructed through social interactions and that collaborative problem-solving enriches cognitive development.

The Cognitive Apprenticeship Model (Collins et al., 1989) extends this idea by emphasizing modeling, scaffolding, coaching, and reflection in authentic learning contexts (Parscal, 2009). Although the UEW approach reduces direct teacher scaffolding, it encourages students to observe, imitate, and practice the behaviors of scientists, effectively internalizing expert strategies through self-directed exploration.

Visual analysis of Figure 1 further strengthens these interpretations. Low-performing students, particularly Student 5 and Student 6, showed substantial posttest gains, closing the gap with their peers. This suggests that the UEW approach supports not only high achievers but also helps weaker students catch up, contributing to a more equitable learning environment. Moreover, the reduction in posttest score variation indicates that the intervention not only improved individual performances but also fostered more uniform comprehension across the cohort.

Despite these promising results, it is important to acknowledge the study's limitations. First, the one-group pretest-posttest design lacks a control group, which restricts causal inferences. As Chen et al. (2015) and Fernald et al. (2012) highlight, the Hawthorne effect—where participants alter their behavior because they know they are being studied—can inflate perceived intervention effects. Without a control group, it is impossible to fully isolate the impact of the UEW intervention from external factors such as students' increased motivation or maturation over time (undefined, 2017).

Second, the small sample size (n = 15) limits the generalizability of the findings. Brownell et al. (2013) and Besekar et al. (2024) caution that small-sample educational research is prone to statistical and interpretive limitations, including volunteer bias and insufficient power to detect small-to-moderate effects. This underscores the need for future research with larger, more diverse samples to validate the findings and extend them to broader educational contexts.

Third, unguided learning approaches inherently present challenges, especially for students with low initial self-regulation or confidence. Fatimah & Bramastia (2021) and Murtalib et al. (2022) note that minimal guidance can result in confusion or anxiety among less independent learners, potentially reducing motivation and learning outcomes. Providing formative feedback (Hernani et al., 2009) and fostering collaborative learning opportunities (Suyitno, 2021) may mitigate these risks, ensuring that students receive the necessary support while maintaining autonomy.

In practical terms, the study suggests several levels of recommendations. Short-term, faculty development programs can train instructors to design and implement UEWs effectively, integrating them into existing laboratory modules. Mid-term, curriculum revisions could systematically incorporate UEWs as part of experimental and inquiry-based learning units. Long-term, multi-institutional experimental studies are needed to test the scalability and adaptability of UEWs across different educational settings and levels, including primary and secondary education for vertical generalization.

The findings also hold broader educational policy implications. Implementing UEWs aligns with the goals of competency-based education frameworks, such as Indonesia's Merdeka Curriculum, which emphasizes student autonomy, project-based learning, and the development of 21st-century skills. By cultivating independent, scientifically literate learners, UEWs contribute to national educational reforms that aim to prepare students for complex global challenges.

Reflectively, this study confirms the initial hypothesis that learner autonomy significantly enhances cognitive engagement, higher-order thinking skills, and conceptual understanding. The intervention's success supports constructivist and cognitive apprenticeship perspectives, suggesting that when students are given ownership of their learning process, they become more engaged, motivated, and capable of critical scientific inquiry.

For future research, we recommend: (1) conducting controlled experimental studies to strengthen causal claims, (2) assessing the long-term retention effects of UEW interventions, (3) adopting mixed-methods approaches to capture both quantitative outcomes and qualitative insights into student experiences, and (4) exploring the adaptation of UEWs in lower educational levels, such as secondary or even primary education, to evaluate vertical scalability.

The study expands our understanding of how instructional designs that balance autonomy and support can strengthen science education. By integrating theoretical frameworks (CLT, SRL, constructivism, cognitive apprenticeship) with empirical evidence, this research provides a strong foundation for designing innovative, contextually relevant pedagogical interventions that enhance student learning and empowerment in science classrooms.

CONCLUSION

This study concludes that the implementation of Unguided Experiment Worksheets (UEWs) significantly enhances students' skills in planning scientific experiments. The findings demonstrate substantial improvements not only in overall scores but also across specific indicators, including hypothesis formulation, identification of experimental variables, and the design of scientific procedures. By providing minimal yet purposeful guidance, UEWs foster student autonomy, encourage critical inquiry, and promote self-regulated learning. The success of this intervention confirms theoretical predictions drawn from Cognitive Load Theory, Self-Regulated Learning frameworks, and constructivist learning models, particularly emphasizing that when cognitive load is balanced and students are given ownership of their learning process, they engage more deeply and achieve better educational outcomes. Moreover, the study highlights that UEWs are effective not only for high-achieving students but also for those who initially demonstrate lower performance, thus contributing to a more equitable learning environment. While the study was limited by its small sample size and the absence of a control group, its results nonetheless provide strong preliminary evidence supporting the pedagogical value of unguided, student-centered learning strategies in science education.

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RECOMMENDATIONS

Based on the findings, several practical and research recommendations are proposed. In the short term, universities and science educators should consider incorporating UEWs into laboratory courses and experimental modules. Faculty development programs should focus on equipping instructors with the skills to design effective UEWs that balance challenge and cognitive load. In the medium term, curriculum developers are encouraged to integrate UEWs systematically into inquiry-based and project-based learning frameworks, ensuring that students across various courses gain opportunities to practice independent scientific investigation. For the long term, future research should address the limitations of the current study by employing larger sample sizes, introducing control groups, and using mixed-methods designs to capture both quantitative impacts and qualitative insights into students' learning experiences. Furthermore, exploring the application of UEWs at different educational levels, including secondary and primary education, could help assess the vertical scalability and generalizability of this approach. Finally, future studies should investigate the long-term retention effects of UEWs to determine whether improvements in experimental planning skills are sustained over time, thereby ensuring that these interventions contribute meaningfully to the development of lifelong scientific literacy.

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AUTHOR CONTRIBUTIONS

Eka Citra Gayatri Kerihi acted as the principal investigator who designed the entire study, developed the Unguided Experiment Worksheet, and drafted the initial draft of the article. Nur Aini Bunyani contributed to the instrument validation process, conducted quantitative data analysis including t-tests and descriptive analysis, and drafted the discussion and recommendations section of the study. Meanwhile, Hunaepi played a role in implementing classroom learning interventions, compiling theoretical foundations and literature studies, conducting final editing of the article manuscript, and providing academic supervision during the research implementation process. The three authors worked collaboratively in every stage of the study to ensure the validity and quality of the research output.

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