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Analysis of a STEM Based Flipped Classroom Learning Model for Enhancing Metacognition and Student Learning Outcomes in Buffer Solution Topic

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Abstract. In the current era of globalization, science education requires instructional strategies that not only improve student achievement but also develop metacognitive abilities essential for complex problem solving. However, traditional teaching models are still predominantly used, often limiting students' understanding of abstract scientific concepts such as buffer solutions. This study aims to examine the effectiveness of a STEM based flipped classroom model in enhancing students' metacognitive skills and learning outcomes. A quasi-experimental design with a pre-test and post-test control group was employed, involving 60 senior high school students divided into experimental and control groups. The instruments used were a learning outcome test and a metacognitive awareness questionnaire, both of which had been validated and proven reliable. The results revealed that students in the experimental group showed significantly higher improvements in both metacognitive awareness and academic performance compared to the control group. These findings suggest that the integration of technology, scientific inquiry, and real world problem solving through a STEM based flipped classroom model positively impacts students' conceptual understanding and learning achievements. This study highlights the urgent need for pedagogical transformation in science education and provides evidence supporting the implementation of innovative, technology enhanced learning models to better prepare students for future challenges.
Keywords: Flipped classroom; metacognition; learning outcomes; buffer solution.

Introduction

In today's digital era, education plays a crucial role in improving the quality of human resources. All aspects of life, including education, have been transformed by advances in information and communication technology. These advancements have led to the development of various technology based learning media. Such media are highly beneficial for teachers in transferring knowledge to students (Rahman, 2021). Additionally, learning innovation is essential to minimizing the obstacles faced in education. One model that has gained significant attention in learning innovation is the flipped classroom. This model provides teachers with opportunities to integrate various supporting features, such as assessments in learning, inquiry based approaches, and differentiation strategies. Consequently, the flipped model offers a more flexible learning environment compared to conventional classroom learning (Pratiwi, 2022).

The flipped classroom model, initially developed in the United States, has been widely adopted and implemented in high schools and universities worldwide. Although it was first introduced at the secondary education level, this approach has subsequently been embraced by higher education institutions (Wang et al., 2024). The flipped classroom model continues to gain popularity due to its potential to shift passive learning into active, student centered engagement. This pedagogical approach allows students to explore content outside of class and apply their understanding during in class activities. Recent findings by Casselman et al. (2022) demonstrate that students benefit most during in class, interactive sessions rather than during at home video viewing. The findings from their study, which was carried out in a controlled chemistry learning environment, showed that students achieved cognitive engagement and significant learning improvements mainly when they were actively involved in classroom activities conducted through direct, in person instruction. These results highlight the importance of intentional classroom interaction in promoting deeper understanding and retention of chemical concepts. These results support the core design of flipped classrooms that prioritize active learning and collaborative problem solving as central to improving student outcomes in science education, including complex topics such as buffer solutions.

The flipped classroom model represents a major pedagogical innovation in recent decades. This instructional approach shifts the traditional learning paradigm by allowing students to independently access theoretical materials outside the classroom through various media, including educational videos, online resources, and interactive platforms. Consequently, in class sessions are optimized for the application of concepts, collaborative problem solving activities, and comprehensive discussions to deepen students' understanding of the subject matter (Katona & Gyonyoru, 2020; Hodges, 2020)

Recent developments in education technology have significantly shaped the flipped classroom model, making it more adaptable and effective in diverse learning contexts emphasized that integrating metacognitive and self regulated learning components within flipped classroom settings enhances learners' autonomy and reflective thinking. This integration is especially crucial in STEM learning environments that demand high level problem solving and conceptual understanding (Shen et al., 2025). Additionally, a meta analysis by Gong & Cheng (2023) found that flipped classrooms significantly improve student achievement in STEM disciplines, particularly when combined with formative feedback and active learning strategies.

In the context of chemistry learning, Hartandi & Mawardi (2023) demonstrated that combining guided inquiry with flipped classroom models on buffer solution material effectively enhances students' conceptual understanding and engagement. Moreover, Clark et al. (2024) highlighted the importance of regular metacognitive reflection activities in a flipped STEM course, which led to significant improvements in students' planning and monitoring skills. Complementing this, Musva & Abdullah (2023) confirmed that a problem based flipped classroom approach in teaching buffer solutions contributes not only to better learning outcomes but also promotes independent thinking among high school students.

The flipped classroom learning model provides an opportunity for classroom time to be utilized more effectively for interactive exercises and engaging activities rather than solely for delivering instructional content. This method encourages students to take a more active role in constructing knowledge and developing a deeper understanding of the material. According to Wannapiroon & Petsangsri (2020), the integration of digital technology in this model supports a more flexible and adaptive learning environment that caters to students with varying levels of comprehension. The implementation of the flipped classroom model is also motivated by the need to improve learning outcomes and to cultivate higher order thinking skills (HOTS), including metacognition. Traditional instructional approaches often hinder meaningful teacher student interaction, thus reducing their effectiveness in facilitating deep and comprehensive learning. Additionally, the flipped classroom model supports differentiated instruction by allowing students to review material at their own pace, making the learning process more inclusive and responsive to diverse learning preferences.

Various studies have examined the effectiveness of the flipped classroom learning model. In general, these studies indicate that this approach can positively impact students' conceptual understanding and thinking skills. Research by Khumairah et al. (2020) at SMAN 5 Bengkulu City revealed that The application of the flipped classroom model significantly improved students' chemistry learning outcomes on buffer solution material. Compared to the average pre-test score, the average post-test score increased, demonstrating the effectiveness of this model in chemistry learning. Putri et al. (2021) examined the effect of the flipped classroom model supported by the schoology e-learning platform on student learning outcomes on buffer solution material. The results showed that students who learned through this model had higher average learning outcomes compared to students taught through conventional methods.

The integration of technology within the flipped classroom model is aimed at streamlining the time allocated for instructional delivery while simultaneously enhancing student involvement throughout the learning process (Zainuddin et al., 2019). This study applies a flipped classroom approach grounded in STEM, focusing on student participation through interdisciplinary problem solving that incorporates science, technology, engineering, and mathematics. Learning outcomes are likely to improve when students are actively engaged and given the flexibility to participate in the learning experience (Purwasila, 2024). Utilizing a STEM based flipped classroom model serves as an effective response to various pedagogical challenges, as it encourages learner centered instruction and cultivates essential 21st century competencies, including critical thinking, creativity, and the ability to solve authentic problems (Lo & Hew, 2021). Recent empirical findings in integrated STEM education highlight the significant role of design. Design serves as a bridge between STEM learning and real world contexts, enabling students to more effectively apply disciplinary knowledge from each STEM field in practical, everyday situations (Hallström & Ankiewicz, 2023; Lin et al., 2021; Hallström et al., 2022; Sung & Kelley, 2022).

Although prior research has demonstrated the success of the STEM based flipped classroom in diverse subject areas, there is still a limited understanding of its effectiveness in fostering metacognitive skills and enhancing academic performance in the context of high school chemistry, particularly in the buffer solution topic. Previous studies have primarily focused on students' cognitive development, while the metacognitive dimension specifically their ability to plan, monitor, and evaluate their thinking processes has received comparatively little attention. Additionally, while the flipped classroom and STEM approaches have each been applied in isolation, research combining both strategies in chemistry learning especially in the area of buffer solutions is still lacking.

The characteristics of chemistry as a subject involve the interrelationship between concepts within each topic, where these concepts progress from simple to more complex ones. As a result, many students find chemistry challenging and require higher reasoning processes. This necessitates innovation in the learning process that not only focuses on conceptual understanding but also fosters HOTS, including metacognition. Metacognition, which refers to an individual's awareness and regulation of their own thinking process, plays a crucial role in enhancing student learning outcomes (Zohar & Barzilai, 2021). Metacognition plays a crucial role in science learning, particularly in chemistry, as it enables students to plan, monitor, and evaluate their understanding of complex concepts, such as buffer solutions.

Despite its critical role in chemistry education, the topic of buffer solutions continues to be a source of difficulty for many students. This is mainly due to the complex and abstract nature of concepts such as acid base interactions, equilibrium, and pH calculations, which necessitate not only theoretical comprehension but also proficiency in multiple forms of representation (Herunata et al., 2024). Moreover, active student engagement is essential to achieving meaningful learning. However, in practice, students tend to engage with learning materials outside of school only when required to complete assignments, which often results in superficial understanding (Khumairah, 2020).

Based on this background, this study aims to measure the extent to which the flipped classroom learning model can help students develop their metacognitive skills, such as planning, monitoring, and evaluating the learning process, compared to the conventional learning model. In addition, this research also seeks to evaluate the impact of the flipped classroom model on improving student learning outcomes, both in the cognitive domain and in conceptual understanding, as well as examining how the implementation of this model can provide a more meaningful and interactive learning experience. The results of this study are expected to contribute to the development of more effective and innovative learning strategies, especially in chemistry education, and serve as a foundation for educators in implementing methods that better adapt to student needs.

Methods

Recent research in chemistry education has examined the comparative effectiveness of flipped classroom methods across diverse learning environments. Williams, & Kearns (2024) conducted a study evaluating student outcomes across traditional, hybrid, and fully online flipped classroom formats using a consistent set of instructional materials. Their findings revealed that all flipped modalities led to notable improvements in student performance, with minimal variance across delivery modes, thus demonstrating the robustness of the flipped approach in enhancing comprehension and problem solving skills in undergraduate chemistry courses. This aligns with our results, reinforcing the notion that the STEM based flipped classroom model can effectively improve conceptual understanding, regardless of the instructional context.

The research design used a pre-test and post-test design to measure the improvement of metacognition and student learning outcomes. The research was conducted in two classes, namely the experimental class and the control class. This research was conducted at SMA Negeri 1 Pronojiwo, Lumajang Regency, using a random sampling technique while considering classes with relatively homogeneous academic characteristics, namely class XI-1 with 30 students and class XI-2 with 30 students. One class acts as an experimental group that is given a STEM based flipped classroom learning model and another class is a control group that uses conventional learning.

The instruments used in this study included teaching modules, written tests in the form of multiple choice questions, and questionnaires. The data collection methods comprised several techniques, namely learning outcome tests, tests to measure students' metacognitive abilities, and questionnaires as instruments to evaluate students' activities in the problem solving process. The data analysis techniques employed included descriptive analysis and inferential statistical analysis. Inferential analysis was conducted through normality tests, homogeneity tests, and the N-gain test (Yuniar & Hadi, 2023).

Results and Discussion

Each study is conducted to reveal facts based on systematically obtained data and analyzed objectively. In this chapter, the research findings obtained through various tests of the STEM based flipped classroom learning model, aimed at improving students' metacognition and learning outcomes on the buffer solution material, are presented. Data collected through pre-test, post-test, and questionnaires were analyzed to address the research problem and test the formulated hypothesis. Using a quantitative approach, this study explores how the implementation of the learning model affects students' conceptual understanding and reflective skills.

Data collection was conducted systematically, beginning with a pre-test to measure students' initial abilities, followed by a learning intervention using a STEM based flipped classroom. After the intervention, a post-test was conducted to assess the extent of students' learning improvement. Additionally, to measure metacognitive development, students completed a questionnaire designed based on metacognitive skill indicators.

The data analysis was conducted using inferential statistical methods to examine the significance of differences before and after the implementation of the learning model. The results of this analysis provide insights into the extent to which the STEM based flipped classroom enhances students' learning outcomes and metacognitive skills compared to conventional learning models. Thus, this study not only contributes empirical evidence on innovations in chemistry education but also offers important implications for more effective instructional design. The findings from the data analysis will be further discussed in the following sections, focusing on differences in pre-test and post-test scores, improvements in students' metacognitive skills, and the statistical significance of the results.

In this study, students participated in the learning process of buffer solution material over three class meetings. In the first meeting, students conducted a practicum, while in the second and third meetings, they engaged in discussions with the teacher about the material they had learned. Before the class sessions began, the teacher provided teaching materials that students were required to study independently at home. Additionally, students were given the freedom to seek additional references from various sources, such as youtube, google, e-books, and others. At the beginning of the first meeting, students took a pre-test to assess their prior understanding of the material. Then, at the end of the second meeting, a post-test was administered to evaluate the improvement in learning outcomes after the implementation of the flipped classroom learning model.

Descriptive Statistics Test

After the implementation of the pre-test and post-test, the results of descriptive statistical analysis are presented in Table 1.

Table 1. Descriptive statistics of learning outcomes

Group	Test type	Minimum	Maximum	Mean	Standard Deviation
Experiment class	Pre-test	24	68	48.00	10.02
	Post-test	55	100	72.13	12.41
Control class	Pre-test	24	68	48.27	9.57
	Post-test	45	86	62.93	10.62

The results of the descriptive statistical tests in this study provide an overview of students' metacognition and learning outcomes before and after the implementation of the STEM based flipped classroom learning model on the buffer solution topic. This analysis includes the minimum, maximum, mean, and standard deviation values of the pre-test and post-test results for both the experimental and control groups.

Before learning began, the experimental group's pre-test scores ranged from 24 to 68, with an average of 48.00 and a standard deviation of 10.021. Meanwhile, the control group had the same score range (24 to 68) but a slightly higher average of 48.27 and a standard deviation of 9.566. The nearly identical pre-test scores between the two groups indicate that students' initial abilities were relatively balanced, with no significant difference before the treatment.

After the learning intervention was applied, the post-test scores in the experimental group increased significantly, ranging from 55 to 100, with an average of 72.13 and a standard deviation of 12.406. Meanwhile, the control group also showed improvement, but with lower results, as their scores ranged from 45 to 86, with an average of 62.93 and a standard deviation of 10.615.

The post-test score comparison between the two groups demonstrates that students using the STEM based flipped classroom achieved higher outcomes than those in traditional settings. This aligns with Jeong et al. (2020), who found that flipped STEM learning enhanced motivation and performance in pre-service teachers, and with Divjak et al. (2022), who reported that tech-enabled flipped classrooms effectively promote student engagement and deep understanding in higher education.

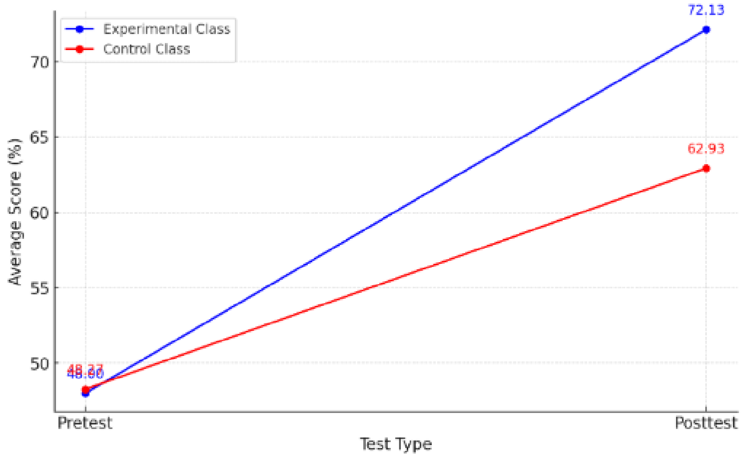

Figure 1. Diagram of descriptive statistics of learning outcomes

Figure above depicts the mean pre-test and post-test scores of the experimental and control groups. Although the data variability remains within acceptable limits, the observed improvement, particularly in the experimental group, is notably substantial from a visual standpoint.

Statistical Prerequisite Test

The Kolmogorov-Smirnov test results revealed that the pre-test and post-test scores for both the experimental and control groups followed a normal distribution, as indicated by significance values (sig.) exceeding 0.05. In addition, Levene's test confirmed that the variance across the groups was homogeneous (sig. > 0.05). These findings meet the necessary assumptions for employing parametric statistical tests in the subsequent data analysis. The confirmation of normality and variance homogeneity permits the use of parametric methods for further examination of the data (Clark et al., 2024).

Table 2. Normality test results

Group	Test type	Kolmogorov–Smirnov statistic	Significance value
Experiment class	Pre-test	0.155	0.063
	Post-test	0.147	0.097
Control class			
	Pre-test	0.152	0.076
	Post-test	0.145	0.111

The normality test results presented in the table above aim to determine whether the student learning outcomes data obtained from the pre-test and post-test in both the experimental and control groups are normally distributed. The normality test was conducted using the Kolmogorov-Smirnov method, in which the significance value (sig.) was compared with $\alpha = 0.05$ as the threshold. If the sig. value is greater than 0.05, the data are considered normally distributed. Conversely, if the sig. value is less than or equal to 0.05, the data are not normally distributed.

The results of the Kolmogorov–Smirnov normality test indicate that all groups met the assumption of normal distribution, as evidenced by significance values (sig.) greater than 0.05 for both the pre-test and post-test. Specifically, the experimental group obtained a sig. value of 0.063 in the pre-test and 0.097 in the post-test, while the control group scored 0.076 for the pre-test and 0.111 for the post-test. These findings confirm that the data for each group are normally distributed, thus fulfilling one of the key prerequisites for conducting subsequent parametric statistical analyses.

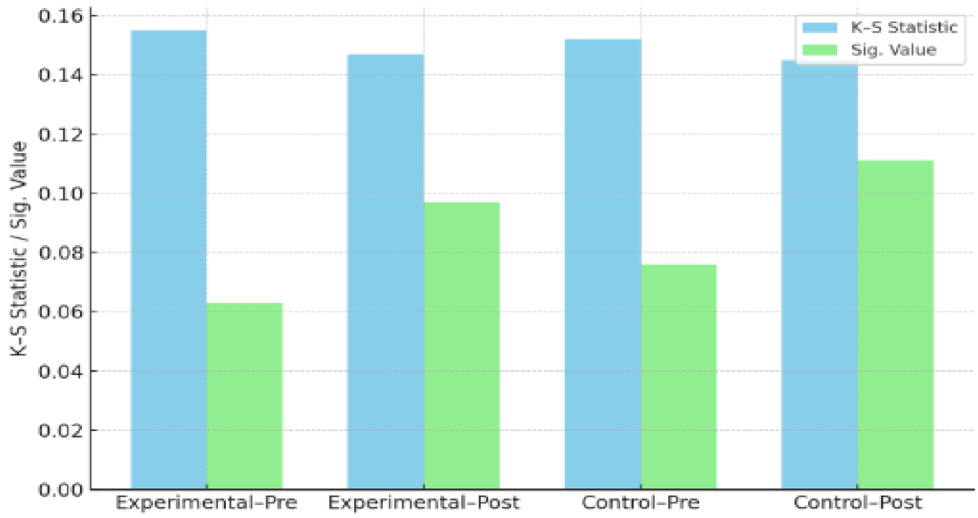

Figure 2. Kolmogorov–Smirnov test results for normality based on statistic and significance values across experimental and control groups.

Since all sig. values are greater than 0.05, it can be concluded that the pre-test and post-test data for both groups follow a normal distribution.

Table 3. Homogeneity test results

Test type	Levene statistic	degrees of freedom (df_1)	degrees of freedom (df_2)	Significance
Based on mean	0.387	3	116	0.762
Based on median	0.307	3	116	0.820
Based on median (adjusted df)	0.387	3	111.829	0.820
Based on trimmed mean	0.379	3	116	0.768

The results of the homogeneity test in the table above aim to determine whether the variance of student learning outcome data in the experimental and control groups is homogeneous. This test is conducted using levene's test for equality of variances by examining the significance value (sig.) in various calculation methods, such as the mean, median, median with adjusted degrees of freedom (df), and trimmed mean.

The homogeneity test was conducted to determine whether the variances between the experimental and control groups were statistically similar. The null hypothesis (H_0) states that the variances of the two groups are homogeneous, while the alternative hypothesis (H_1) posits that the variances are significantly different. Based on the decision criteria, if the significance value (sig.) is greater than 0.05, H_0 is accepted, indicating that the group variances are homogeneous. Conversely, if the sig. value is less than or equal to 0.05, H_0 is rejected. The results presented in the table show that all calculation methods yielded sig. values above 0.05: 0.762 based on the mean, 0.820 based on the median, 0.820 based on the median with adjusted degrees of freedom, and 0.768 based on the trimmed mean. These results confirm that the variance between the experimental and control groups is homogeneous, thereby satisfying another assumption required for parametric testing.

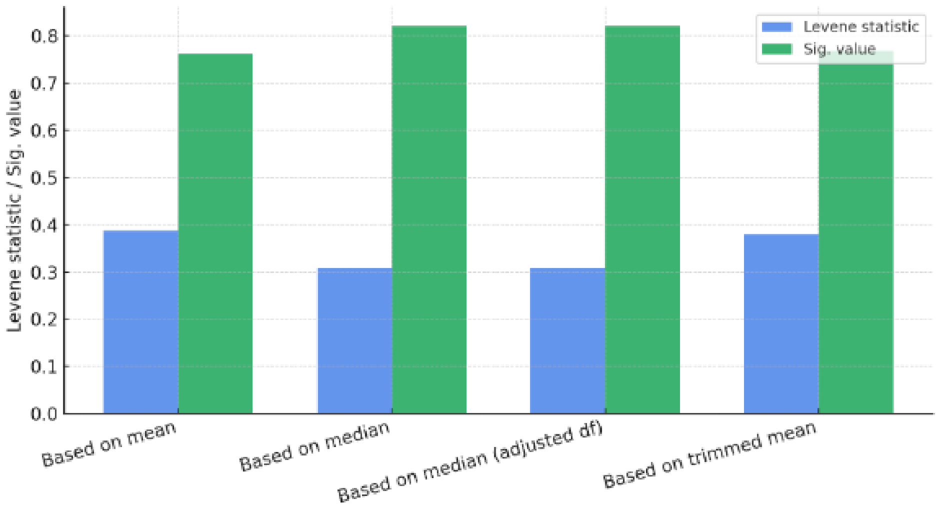

Figure 3. Results of Levene's test for homogeneity of variances based on different central tendency measures.

Because all sig. values > 0.05, it can be concluded that the variance of student learning outcomes in the experimental and control groups is homogeneous.

Table 4. Paired samples t-test results on student learning outcomes

Pair	Mean difference	Standart deviation	Standart error mean	95% confidence limit lower	t	Degrees of freedom	Sig. (2-tailed)
Experimental (pre–post)	-24.100	6.763	1.235	-26.618	-19.510	29	0.000
Control (pre–post)	-14.067	8.030	1.466	-17.063	-9.598	29	0.000

The results of the paired sample t-test in the table above are used to determine whether there is a significant difference between the pre-test and post-test scores in the experimental and control groups. This test aims to assess the effectiveness of the STEM-based flipped classro om learning model in improving student learning outcomes on the topic of buffer solutions.

Specifically for the experimental group, the paired samples t-test revealed that the mean difference between pre-test and post-test scores was -23.100, indicating a substantial increase of 23.100 points following the intervention. The resulting t-value of -18.763 with a significance level (Sig. 2-tailed) of 0.000 suggests that the difference is statistically significant ($p < 0.05$). Thus, the null hypothesis (H_0), which states there is no difference in student performance before and after the implementation of the STEM based flipped classroom model, is rejected. This confirms that the applied learning model significantly improved students' academic performance.

When comparing both groups, it was evident that although both experienced an increase in learning outcomes after the learning process, the experimental group (STEM based flipped classroom) showed a greater improvement than the control group. These results indicate that the implementation of a STEM based flipped classroom is more effective in enhancing student learning outcomes compared to conventional learning methods.

The results of the paired samples t-test indicated a statistically significant difference between the pre-test and post-test scores in both the experimental and control groups. Nevertheless, the improvement observed in the experimental group was notably greater. This outcome supports the notion that integrating a STEM oriented flipped classroom model can more effectively enhance student learning outcomes compared to traditional teaching methods. Similar findings have been reported in previous research, which emphasize that the flipped classroom, especially when combined with STEM principles, contributes to better academic performance and deeper understanding of the material (Lo & Hew, 2020; Alshahrani et al., 2022).

Table 5. Independent samples t-test results

Variance assumption	t	Degrees of freedom	Sig. (2-tailed)	Mean difference	Standart error difference	95% confidence limit lower	95% confidence limit upper
Equal variances assumed	2.964	58	0.004	8.167	2.755	2.651	13.681
Equal variances not assumed	2.964	57.994	0.004	8.167	2.755	2.651	13.681

The independent sample t-test in the table above is used to compare the learning outcomes between the experimental group using the STEM based flipped classroom and the control group using conventional learning methods. This test aims to determine whether there is a significant difference between the two groups after the learning process.

Based on the results of the independent sample t-test, there is a statistically significant difference in student learning outcomes between the experimental group, which used the flipped classroom based on STEM, and the control group, which used conventional learning methods. This is indicated by a t-value of 2.964 with df = 58 and a significance value of Sig. (2-tailed) = 0.004. Since the significance value is smaller than 0.05, H_0 is rejected, indicating a meaningful difference between the two groups. Furthermore, the mean difference in learning outcomes between the experimental and control groups is 8.167 points, with a 95% confidence interval (95% confidence limit) ranging from 2.652 to 13.681. This suggests that the observed difference is unlikely to be due to chance and can be generalized to the population.

In addition, the homogeneity of variance was tested using Levene's test, which produced an F value of 0.078 and a significance (p) level of 0.781. Since this value exceeds the threshold of 0.05, it can be concluded that the variance between the experimental and control groups is statistically equal. Consequently, the results of the subsequent independent sample t-test are interpreted under the assumption that the variances of both groups are homogeneous.

The results of the independent samples t-test revealed a statistically significant difference in learning outcomes between the experimental and control groups following the treatment, with a p-value below 0.05. This finding highlights the efficacy of the STEM based flipped classroom approach in improving students' academic performance (Maspul, 2023).

Table 6. Descriptive statistics of N-gain scores for experimental and control group

No	Statistic	Experimental class	Control class
1		45.704	28.297
2	Mean	3.02553	3.05943
3	Standard error	39.5425	22.1401
	95% confidence limit lower bound		
4	95% confidence limit upper bound	51.8658	34.4541
	5% trimmed mean		
5	Median	44.9587	28.2665
6	Variance	44.925	28.625
7	Standard Deviation	272.615	269.866
8	Minimum	16.510	16.757
9	Maximum	14.50	9.00
10	Range	100.00	65.00
11		85.50	56.00

Based on the results of the descriptive analysis of the N-gain percentage scores in the experimental and control classes, the mean score for the experimental class was 45.73 with a standard deviation of 16.57. Meanwhile, the mean score for the control class was recorded at 28.39 with a standard deviation of 16.76. These findings indicate that the improvement in students' learning outcomes in the experimental class, which implemented the STEM based flipped classroom model, was higher than that of the control class, which received conventional instruction.

The score range in the experimental class was also wider, at 85.42, compared to 69.17 in the control class. The maximum score in the experimental class reached 100, while in the control class it was only 65. This indicates that there were students in the experimental class who achieved the highest possible improvement in learning outcomes.

The data distribution in both classes is relatively normal, as indicated by the skewness and kurtosis values falling within the range of ±2. In the experimental class, the skewness value of 0.997 suggests a slightly left skewed distribution, while the kurtosis value of 2.953 indicates a moderately leptokurtic distribution (with a sharper peak than a normal distribution). In contrast, the control class exhibits a skewness of 0.014 and a kurtosis of -0.833, which suggests that the distribution of data in this class is relatively symmetrical and slightly platykurtic.

The 95% confidence interval for the mean N-gain indicates that the experimental group's mean falls within the range of 39.54 to 51.92, whereas the control group's mean lies between 22.13 and 34.64. This difference in confidence intervals further emphasizes that the STEM based flipped classroom learning model has a more substantial positive impact on improving students' learning outcomes compared to the conventional learning model.

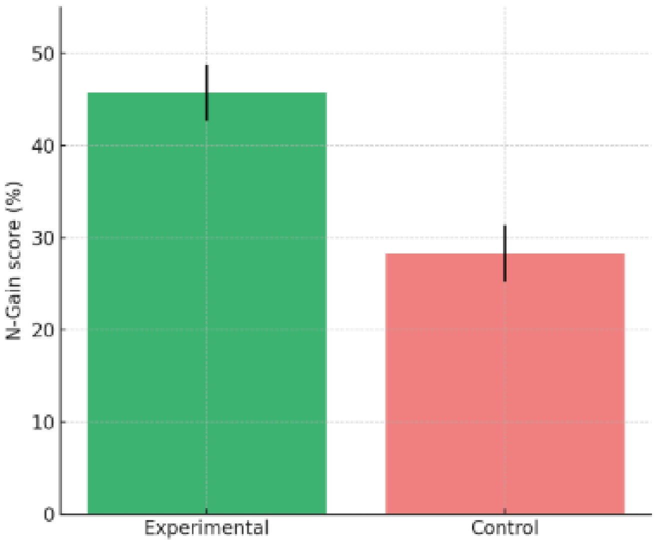

Figure 4. Comparison of mean N-gain scores between the experimental and control classes with standard error bars.

The experimental class demonstrated an average N-gain of 45.73%, in contrast to 28.39% observed in the control class. This suggests that the conceptual understanding improved more substantially in the experimental group than in the control group. The greater N-gain achieved by the experimental class highlights the efficacy of the flipped classroom method in enhancing students' comprehensive understanding (Clark et al., 2024). These findings further support that the STEM based flipped classroom learning model is more effective in improving student learning outcomes compared to the conventional method. The greater increase in scores in the experimental group suggests that this approach provides a more interactive learning experience, enabling students to gain a deeper understanding of the buffer solution material. Supported by this statistical evidence, innovative technology based learning models and self directed learning have been proven to enhance learning effectiveness and facilitate better comprehension among students. The application of the flipped classroom model integrated with STEM principles markedly improves students' academic performance relative to traditional instructional approaches (Ardiansyah et al., 2024).

These findings are consistent with previous studies that have confirmed the effectiveness of the flipped classroom model, especially when integrated with STEM principles, in enhancing both learning outcomes and metacognitive abilities. For instance, Shen et al. (2025) developed a flipped classroom framework that incorporates metacognitive, motivational, and self regulated learning elements, which significantly improved students' academic engagement and reflection abilities. Similarly, Clark et al. (2024) emphasized that repeated metacognitive reflection within a flipped STEM course increased students' ability to plan, monitor, and evaluate their understanding, aligning with the improvements observed in this study. Moreover, Hartandi & Mawardi (2023) demonstrated that the integration of guided inquiry with flipped classroom learning on the buffer solution topic led to higher conceptual understanding and student participation compared to conventional instruction. The significant improvement in N-gain scores in this study also echoes findings by Musva & Abdullah (2023), who applied a problem based flipped classroom model in teaching buffer solutions and reported superior post-test performance and increased student autonomy.

Conclusion

This study aims to examine the effectiveness of implementing a STEM based flipped classroom model in enhancing students' metacognitive skills and learning outcomes in the buffer solution topic. The results indicate that this model significantly improves students' metacognitive abilities and deep conceptual understanding compared to conventional methods. By utilizing a student centered learning approach combined with experimental exploration, students become more independent, reflective, and capable of connecting theoretical knowledge with real world applications. These findings affirm that the learning model is effective in developing HOTS and preparing students to face global challenges, thus recommending its implementation and further development across various disciplines to improve the quality of education in the digital era.

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