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ENHANCING HIGH SCHOOL STUDENTS' LEARNING OUTCOMES IN REDOX REACTIONS THROUGH A GREEN CHEMISTRY-BASED MICROSCALE EXPERIMENTAL APPROACH

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Abstract. Redox reactions are often considered difficult concepts in chemistry learning because students frequently struggle to connect observable phenomena with electron transfer processes. This study aimed to examine the effectiveness of a green chemistry-based microscale experimental approach in improving high school students' learning outcomes in redox reactions. A quantitative pre-experimental one-group pretest–posttest design was employed involving 30 eleventh-grade science students at SMAN 22 Gowa selected through purposive sampling. Data were collected using a 20-item higher-order thinking skills (HOTS) test consisting of multiple-choice and short-answer questions. The data were analyzed using descriptive statistics, the Shapiro–Wilk test, the Wilcoxon signed-rank test, N-gain analysis, and effect size calculation. The results showed that students' mean scores increased from 52.33 on the pretest to 72.00 on the posttest with a significant difference ($p < 0.05$). The average N-gain score was 0.41 (medium category), while the effect size was 0.88 (large effect). These findings suggest that green chemistry-based microscale experiments can support safer, more efficient, and meaningful chemistry learning, particularly in schools with limited laboratory facilities.

Keywords: green chemistry; higher-order thinking skills; learning outcomes; microscale experiments; redox reactions

INTRODUCTION

Learning chemistry requires students to understand concepts through multiple levels of representation, namely macroscopic, submicroscopic, and symbolic representations. Meaningful chemistry learning occurs when students are able to connect observable phenomena with the underlying particle processes and symbolic expressions. However, many students still experience difficulties in relating these representations, resulting in fragmented conceptual understanding. One chemistry topic that is often considered challenging is redox reactions because students are required to understand electron transfer processes that cannot be directly observed (Garnett & Treagust, 1992).

These conceptual difficulties are commonly encountered in redox learning. Redox reactions are fundamental concepts in chemistry that underlie various natural and industrial processes. Understanding redox reactions requires students to interpret observable changes, represent them symbolically, and relate them to processes occurring at the submicroscopic level. In practice, many students tend to rely on procedural approaches, such as memorizing rules for determining oxidation numbers, without fully understanding the underlying concepts. As a result, students are often able to solve problems algorithmically but experience difficulty explaining the reasoning behind their answers (Sanger & Greenbowe, 1999). Similar findings

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have also been reported in the Indonesian context, where students' understanding of redox concepts remains relatively low and misconceptions are still frequently identified (Nugrohadi & Chasanah, 2023).

Laboratory activities play an important role in chemistry learning because they provide opportunities for students to observe chemical phenomena directly and construct understanding through hands-on experiences. Well-designed laboratory activities can improve student engagement and support deeper conceptual understanding (Gericke et al., 2022). Experimental activities also encourage students to become active participants in the learning process rather than passively receiving information from teachers.

Experimental and project-based learning activities are also reported to support students' science process skills, conceptual understanding, and participation during chemistry learning (Khodizah et al., 2025). In this context, the integration of experimental activities with contextual learning approaches can provide more meaningful learning experiences while supporting the development of higher-order thinking skills.

Despite these benefits, conventional laboratory activities often face several limitations. Laboratory procedures commonly require considerable time, relatively large quantities of chemicals, and complex equipment. These conditions may reduce learning efficiency and limit students' opportunities to actively engage in experimental activities. The use of large amounts of chemicals also increases safety risks and generates chemical waste that may negatively affect the environment. These limitations highlight the need for alternative laboratory approaches that support effective learning while promoting safer and more sustainable practices. In this context, green chemistry has gained increasing attention in chemistry education (Zuin et al., 2021).

Green chemistry encourages the use of chemical processes that reduce hazardous substances and minimize environmental impact. In educational settings, the integration of green chemistry principles can help students develop environmental awareness and responsible scientific attitudes (Karpudewan et al., 2021). Recent studies have also emphasized the importance of incorporating green chemistry principles into chemistry education to support sustainable learning practices (Morales et al., 2024). Green chemistry is closely related to sustainable education because it promotes environmentally responsible scientific practices while supporting safer and more efficient learning environments.

The integration of green chemistry into chemistry learning has increasingly been associated with sustainable education practices. Learning activities that combine environmental awareness with contextual and project-oriented approaches are considered capable of supporting students' conceptual understanding and active participation during chemistry learning (Sari et al., 2024). In this context, laboratory activities designed through simpler and environmentally responsible procedures may provide more meaningful learning experiences for students.

One approach that aligns with green chemistry principles is microscale experimentation. Microscale experiments use smaller quantities of chemicals and simpler apparatuses, allowing laboratory activities to be conducted more safely and efficiently. The reduced procedural complexity also enables students to focus more on conceptual understanding rather than technical laboratory procedures. In addition, microscale experiments are practical for schools with limited laboratory resources because they require fewer materials and simpler equipment.

Microscale experiments also provide students with opportunities to observe chemical changes more carefully and repeat experiments when necessary. Such

experiences can help students connect observable phenomena with abstract chemical processes, particularly in topics such as redox reactions that require understanding at the submicroscopic level (Allanas et al., 2024; Wijaya et al., 2024).

Initial observations conducted at SMAN 22 Gowa, Indonesia, indicated that many students experienced difficulties in connecting observable color changes with electron transfer processes in redox reactions. These difficulties were often influenced by limited laboratory time and restricted availability of materials, causing classroom instruction to rely more heavily on theoretical explanations than experimental activities. As a result, students tended to memorize concepts rather than develop meaningful conceptual understanding of redox processes.

Although microscale experiments and green chemistry have received considerable attention in chemistry education, most previous studies have primarily emphasized laboratory efficiency, environmental awareness, and students' motivation toward learning (Karpudewan et al., 2021; Morales et al., 2024). Research examining the implementation of green chemistry-based microscale experiments in redox learning, especially those related to students' conceptual understanding and higher-order thinking skills (HOTS), is still limited. Within the context of Indonesian secondary education, research focusing on this area has not been widely reported.

Accordingly, this study was conducted to investigate the effectiveness of a green chemistry-based microscale experimental approach in improving high school students' learning outcomes on redox reaction topics. The study also seeks to contribute empirical findings regarding the integration of green chemistry principles with microscale experimentation in supporting conceptual understanding and the development of HOTS in chemistry learning.

In this study, students' learning outcomes were assessed using HOTS-oriented indicators, including the ability to analyze redox processes, interpret experimental observations, evaluate electron transfer phenomena, and apply redox concepts to contextual chemical situations.

METHOD

This study employed a quantitative pre-experimental one-group pretest–posttest design to investigate the effectiveness of a green chemistry-based microscale experimental approach on students' learning outcomes in redox reactions. The study was conducted in April 2026 at SMAN 22 Gowa, Indonesia, involving 30 eleventh-grade science students selected through purposive sampling. The selected participants had not previously been exposed to microscale experimental activities in chemistry learning. To minimize potential confounding variables, the same teacher, instructional materials, and instructional duration were consistently maintained throughout the study.

A pre-experimental design was selected because the study was exploratory in nature and aimed to obtain preliminary empirical evidence regarding the implementation of green chemistry-based microscale experiments in authentic classroom settings. The implementation of a quasi-experimental design involving a control group was constrained by school scheduling policies and class allocation limitations during the research period. Nevertheless, the one-group pretest–posttest design allowed the researchers to examine students' conceptual improvement before and after the intervention under relatively consistent instructional conditions. The stages of the research procedure are illustrated in Figure 1.

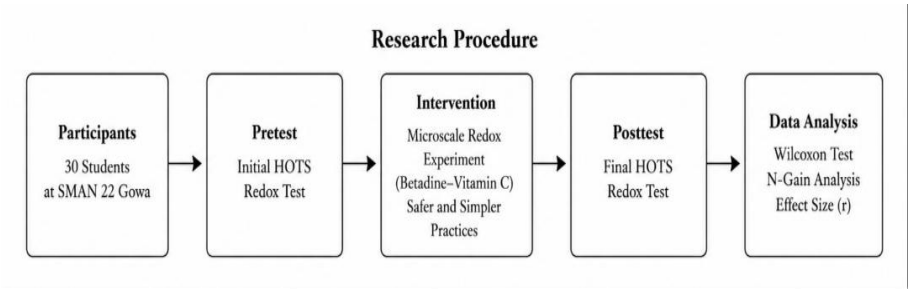

Figure 1. Research procedure of the green chemistry-based microscale experimental study

The research procedure consisted of three stages: pretest, intervention, and posttest. At the beginning of the study, students completed a HOTS-oriented pretest to identify their initial understanding of redox concepts. The intervention was conducted over three instructional sessions using green chemistry-based microscale experiments. The learning activities employed small-scale apparatuses and minimal quantities of chemicals to support safer and more efficient laboratory practices. During the intervention, students observed chemical phenomena, carried out experimental activities, and participated in group discussions to interpret experimental results. One of the implemented activities involved a redox experiment using betadine solution and vitamin C as safer alternative materials. At the end of the intervention, a HOTS-oriented posttest was administered to evaluate students' learning outcomes.

Data were collected using a 20-item higher-order thinking skills (HOTS) test consisting of multiple-choice and short-answer questions. The instrument was developed based on redox learning indicators and higher-order cognitive processes. The assessed HOTS indicators included students' ability to analyze redox processes, interpret experimental observations, evaluate electron transfer phenomena, and apply redox concepts to contextual chemical situations. Content validity was evaluated by two experts in chemistry education to ensure the alignment of the test items with the learning objectives and conceptual content. Revisions to the instrument were made based on the experts' suggestions prior to its administration.

The data were analyzed using IBM SPSS Statistics. Descriptive statistics were used to examine students' pretest and posttest scores, followed by the Shapiro–Wilk test to determine data normality. Because the data were not normally distributed ($p < 0.05$), the Wilcoxon signed-rank test was used to examine differences between pretest and posttest scores. In addition, N-gain and effect size (r) analyses were conducted to determine the magnitude of students' learning improvement. The interpretation of N-gain values followed Hake's criteria, namely high ($g \geq 0.70$), medium ($0.30 \leq g < 0.70$), and low ($g < 0.30$).

Prior to data collection, permission to conduct the study was obtained from the school. Student participation was voluntary, and all collected data were treated confidentially and used solely for research purposes.

RESULTS AND DISCUSSION

The effectiveness of the green chemistry-based microscale experimental approach in improving students' learning outcomes on redox reactions was examined through descriptive and inferential statistical analyses. The findings are discussed together with their educational implications to explain how the learning activities contributed to students' conceptual understanding.

Descriptive Statistics

Table 1. Descriptive statistics of pretest and posttest scores

Statistical Indicator	Pretest	Posttest
Number of Students (N)	30	30
Minimum Score	35.00	60.00
Maximum Score	70.00	85.00
Mean Score	52.33	72.00
Standard Deviation	8.48	7.94

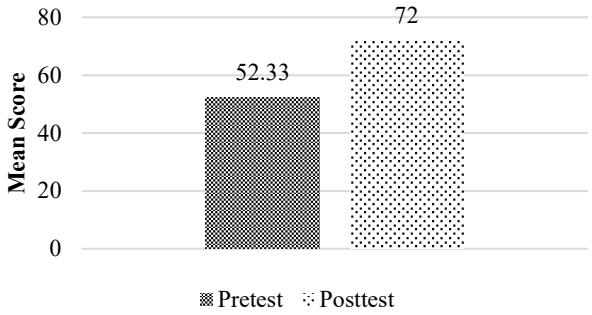

Figure 2. Comparison of pretest and posttest mean scores

Table 1 and Figure 2 show an increase in students' mean scores from 52.33 on the pretest to 72.00 on the posttest. This result may indicate that students demonstrated better understanding of redox concepts after participating in the learning activities. The relatively low pretest scores suggest that students initially experienced difficulties in understanding redox concepts, particularly in relating observable phenomena to electron transfer processes at the submicroscopic level.

The increase in posttest scores may be associated with the characteristics of the microscale experimental activities. Through direct observation and hands-on experiences, students were given opportunities to connect visible chemical phenomena with underlying redox processes. The use of simpler experimental procedures also allowed students to focus more on conceptual understanding rather than procedural complexity during laboratory activities. Similar findings were reported by Allanas et al., (2024), who found that microscale experiments can help students understand abstract chemistry concepts more meaningfully.

One example of the implemented microscale activity involved the reaction between betadine solution and vitamin C as a safer alternative to conventional oxidizing agents such as potassium permanganate and potassium dichromate. During the experiment, students observed the gradual discoloration of iodine solution as vitamin C reduced iodine in the redox process. This activity enabled students to relate observable color changes to electron transfer processes occurring at the submicroscopic level. In addition, the use of safer and more familiar materials reduced procedural difficulties during laboratory activities and allowed students to focus more directly on conceptual understanding rather than memorizing oxidation number rules. The activity also reflected green chemistry principles through the reduction of hazardous chemical use and laboratory waste generation. These learning experiences may have contributed to the improvement in students' conceptual understanding and learning outcomes in redox reactions.

The standard deviation decreased slightly from 8.48 to 7.94 after the intervention. Although the difference was relatively small, this finding may indicate

that students' learning outcomes became more consistent following the learning activities. The use of simpler procedures and safer laboratory practices may have provided more equal opportunities for students with different levels of prior understanding to participate actively during the experiments. Similar observations have also been reported by Freese et al. (2024), who emphasized that supportive laboratory environments can encourage greater student participation in chemistry learning.

Normality Test

Table 2. Normality test results (Shapiro-Wilk)

Data	N	Statistic (W)	Sig. (p-value)	Interpretation
Pretest	30	0.954	0.221	Normally distributed
Posttest	30	0.925	0.037	Not normally distributed
Difference (Post–Pre)	30	0.907	0.012	Not normally distributed

The Shapiro–Wilk test results presented in Table 2 show that the pretest scores were normally distributed ($p = 0.221$), while the posttest and difference scores were not normally distributed ($p < 0.05$). The concentration of posttest scores in the higher score range may have reduced score variability after the intervention. Therefore, a non-parametric statistical test was considered more appropriate for further analysis.

Based on these findings, the Wilcoxon signed-rank test was used to examine differences between pretest and posttest scores.

Wilcoxon Signed-Rank Test

Table 3. Wilcoxon Signed-rank test results

Component	Value
Total N	30
Test Statistic	465,000
Standard Error	48.133
Z (Standardized Test Statistic)	-4.830
Asymp. Sig. (2-tailed)	0.000

The Wilcoxon Signed-Rank test results presented in Table 3 indicate a significant difference between pretest and posttest scores ($p < 0.001$). All students showed improvement after the intervention, as indicated by the absence of negative ranks and ties. This finding suggests that the green chemistry-based microscale experimental approach contributed positively to students' understanding of redox concepts.

The improvement in learning outcomes may be related to the nature of the laboratory activities. Microscale experiments allowed students to observe chemical changes directly through relatively simple procedures and the use of smaller quantities of chemicals. These conditions likely helped students focus more on conceptual reasoning during laboratory activities. Previous studies have similarly reported that laboratory-based learning can improve students' understanding and motivation through active participation in experimental activities (Ali et al., 2023).

The relatively consistent improvement across students may also indicate that the learning activities were sufficiently structured to support conceptual learning. Laboratory activities that are systematically organized can help students connect experimental observations with scientific concepts more effectively (Varadarajan & Ladage, 2022). Nevertheless, because this study employed a pre-experimental design without a control group, the observed improvement should be interpreted

carefully, as external factors outside the intervention may also have influenced the results.

N-Gain Analysis

Table 4. N-Gain analysis

Category	N-Gain Range	Frequency (N)	Percentage (%)
High	$g \geq 0.70$	0	0%
Medium	$0.30 \leq g < 0.70$	27	90%
Low	$g < 0.30$	3	10%
Total	—	30	100%
Mean N-Gain	—	—	0.41 (Medium)

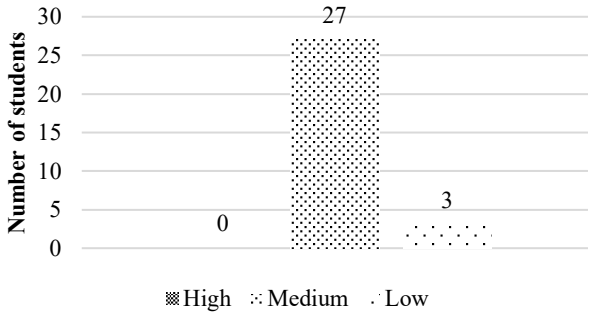

Figure 3. Distribution of students' *N-Gain* categories

The N-gain analysis presented in Table 4 shows that the average N-gain score was 0.41, which falls into the medium category. Most students were classified in the medium improvement category, while a smaller proportion remained in the low category. These findings indicate that the intervention contributed to a moderate improvement in students' understanding of redox concepts.

The improvement may be associated with the implementation of microscale experimental activities that emphasized simple and observable redox processes. The smaller-scale experiments allowed students to observe chemical phenomena more carefully and participate more actively during laboratory activities. Previous studies have also reported that microscale experiments can support conceptual understanding and student engagement in chemistry learning (Allanas et al., 2024).

The integration of green chemistry principles may also have contributed to the creation of a safer and more supportive learning environment. Learning activities emphasizing safety and sustainability can encourage student participation and support more meaningful learning experiences (Sari & Atun, 2023). However, the absence of students in the high N-gain category indicates that further development of instructional strategies and assessment design is still needed to support higher levels of conceptual understanding and HOTS performance.

Effect Size Analysis

Table 5. Effect size (r)

Parameter	Value	Interpretation
Z Value	4.830	-
N	30	-
Effect Size (r)	0.88	Large Effect

The effect size analysis presented in Table 5 yielded an effect size value of 0.88, which is categorized as a large effect. This result suggests that the learning activities contributed meaningfully to students' learning outcomes and were associated with improvement in students' understanding of redox concepts.

One possible explanation for this finding relates to the learning environment created during the laboratory activities. The use of smaller quantities of chemicals and simpler procedures may have helped students participate more confidently and actively during experimental work. Previous studies have similarly reported that microscale experiments can support students' conceptual understanding and learning outcomes in chemistry education (Wijaya et al., 2024).

The integration of green chemistry principles further strengthened the educational value of the learning activities by promoting safer and more environmentally responsible laboratory practices. Such learning experiences not only support conceptual understanding but also help students develop awareness of sustainable scientific practices (Sari & Atun, 2023).

The improvement in students' learning outcomes also reflects the development of higher-order thinking skills (HOTS). During the microscale experimental activities, students were encouraged to analyze reaction processes, interpret experimental observations, evaluate changes occurring during redox reactions, and relate macroscopic observations to symbolic and submicroscopic representations. These activities are closely associated with higher cognitive processes, particularly analysis and evaluation. The simplified and contextualized experimental procedures likely helped students focus more on conceptual reasoning rather than memorizing oxidation number rules.

Despite these positive findings, several limitations should be acknowledged. The use of a pre-experimental design without a control group limits the ability to attribute the improvement solely to the intervention. In addition, the study involved only one class, which may limit the generalizability of the findings. Nevertheless, the results indicate that green chemistry-based microscale experiments have potential as an alternative approach for supporting chemistry learning, particularly in schools with limited laboratory facilities.

CONCLUSION

The implementation of a green chemistry-based microscale experimental approach contributed positively to high school students' learning outcomes in redox reactions. This result was reflected in the increase in students' mean scores, the medium N-gain value (0.41), and the large effect size (0.88). Through simpler and safer laboratory activities, students were provided with opportunities to observe chemical phenomena directly and relate them to redox concepts more meaningfully.

The use of microscale experiments also offers practical advantages for schools with limited laboratory facilities because the activities require smaller quantities of chemicals and simpler equipment. In this study, the use of betadine solution and vitamin C as safer experimental materials demonstrated that redox concepts can be explored through more accessible and environmentally responsible laboratory practices.

Despite these findings, this study was limited by the use of a pre-experimental design without a control group and the relatively small sample size. Therefore, further studies involving broader participant groups and more rigorous research designs are recommended to examine the implementation of this approach in other chemistry topics and educational settings.

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