ENHANCING GRADE 11 STEM LEARNERS' CONCEPTUAL UNDERSTANDING OF CHEMICAL REACTION TYPES THROUGH A MICRO-SCALE WASTE-PREVENTIVE LABORATORY APPROACH: EVIDENCE FROM A QUASI-EXPERIMENTAL STUDY

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Abstract

Chemistry learners often struggle to understand chemical reaction types because the topic requires them to connect symbolic equations, molecular changes, and observable laboratory phenomena. This study evaluated the effectiveness of a micro-scale waste-prevention laboratory approach in enhancing Grade 11 STEM learners' conceptual understanding of types of chemical reactions. Grounded in Green Chemistry principles and experiential learning theory, the intervention used small-scale experimentation and safer household materials to provide sustainable, inquiry-based, and learner-centered laboratory experiences. The study employed a one-group pre-test/post-test quasi-experimental design involving 44 Grade 11 STEM learners from Urdaneta City National High School during Academic Year 2025–2026. A validated 20-item multiple-choice test aligned with Chemistry 2 curriculum competencies was administered before and after the intervention. The laboratory activities focused on synthesis, decomposition, single-replacement, and double-replacement reactions using materials such as steel wool, vinegar, hydrogen peroxide, yeast, aluminum foil, copper sulfate, and baking soda. Data were analyzed using descriptive statistics and a paired-samples t-test. Results showed that learners' mean score increased from 8.18 in the pre-test to 16.39 in the post-test, while the mean percentage score improved from 40.90% to 81.95%. The paired t-test result yielded a t-value of -91.66 and a p-value of .000, indicating a statistically significant improvement. The study concluded that the micro-scale waste-preventive laboratory approach effectively improved learners' conceptual understanding while promoting safety, environmental responsibility, and engagement in chemistry learning.

Keywords: Green Chemistry, Micro-Scale Laboratory, Chemical Reactions, Conceptual Understanding, STEM Education, Waste-Preventive Approach

1. Introduction

Chemistry is a foundational discipline in Science, Technology, Engineering, and Mathematics education because it explains the composition, structure, properties, and transformations of matter. For senior high school STEM learners, chemistry provides essential preparation for future studies in medicine, engineering, environmental science, pharmacy, health sciences, agriculture, and technology-related fields. However, chemistry remains one of the more difficult science subjects for many learners because it requires them to understand abstract concepts, interpret symbolic equations, visualize submicroscopic particles, and connect these representations with observable laboratory phenomena. The difficulty becomes more pronounced when instruction emphasizes definitions and equation balancing without sufficient inquiry-based experimentation.

One topic that commonly challenges learners is the classification and interpretation of chemical reaction types. To understand synthesis, decomposition, single-replacement, and double-replacement reactions, learners must recognize patterns in reactants and products, interpret changes in substances, predict possible outcomes, and connect the symbolic form of chemical equations with actual evidence of reaction. In the uploaded study, Grade 11 STEM learners initially obtained a mean pre-test score of 8.18 out of 20 and a mean percentage score of 40.90%, indicating low conceptual mastery before the intervention. This baseline finding supports the need for laboratory experiences that help learners move from memorizing reaction categories toward understanding how chemical transformations occur.

The need to strengthen science learning is also reflected in international assessment data. The OECD reported that students in the Philippines scored below the OECD average in mathematics, reading, and science in PISA 2022, and only 23% of students in the Philippines attained Level 2 or higher in science compared with the OECD average of 76%. These results indicate that many Filipino learners still struggle to apply scientific knowledge to explain familiar phenomena and to evaluate conclusions based on evidence. Although PISA assesses 15-year-old learners rather than specifically Grade 11 STEM students, the results provide a broader context for why Philippine science instruction needs approaches that promote conceptual understanding, inquiry, and evidence-based reasoning.

Laboratory learning is central to chemistry education because it allows learners to observe, manipulate, test, compare, and infer from chemical phenomena. However, traditional laboratory activities may be limited by large class sizes, high reagent costs, insufficient laboratory equipment, safety concerns, and waste-disposal issues. In some cases, laboratory tasks become procedural rather than conceptual, with learners following steps mechanically without understanding the scientific principles behind the reaction. When this happens, the laboratory becomes a demonstration of compliance rather than an environment for inquiry and meaning-making. Therefore, chemistry instruction needs laboratory models that are safer, more affordable, environmentally responsible, and capable of strengthening conceptual understanding.

A micro-scale waste-preventive laboratory approach addresses these concerns by using very small quantities of reagents, compact reaction surfaces, drop-wise application, and safer materials to conduct experiments. In the uploaded study, the intervention used household and accessible materials, including steel wool, vinegar, hydrogen peroxide, yeast, aluminum foil, copper sulfate, and baking soda, to demonstrate major types of chemical reactions. This approach reduced waste, minimized hazards, and enabled learners to observe chemical changes directly. Because the experiments were small-scale and manageable, learners could focus on interpreting reaction evidence rather than worrying about complicated apparatus or hazardous chemicals.

The approach is strongly aligned with Green Chemistry. The American Chemical Society identifies waste prevention, less hazardous chemical syntheses, safer solvents and auxiliaries, and inherently safer chemistry for accident prevention among the 12 principles of Green Chemistry. Microscale chemistry has also been described as complementary to Green Chemistry, emphasizing smaller quantities, reduced hazards, and waste minimization while maintaining meaningful laboratory learning. In science education, this alignment is important because laboratory instruction should not only produce correct answers but also develop responsible scientific practice. Through Green Chemistry-based laboratory work, learners can connect chemical concepts with sustainability, safety, and environmental responsibility.

Recent literature further supports the educational relevance of Green Chemistry. Sánchez Morales, Sáenz-López, and de las Heras Pérez (2024) conducted a systematic review on Green Chemistry didactics and emphasized its role in chemistry education in response to environmental concerns. Similarly, STEM teaching literature emphasizes that learners benefit when they are actively engaged, assessed for conceptual understanding, and guided to develop problem-solving, critical thinking, collaboration, and self-directed learning skills. These principles are reflected in the micro-scale waste-preventive laboratory approach, as learners actively performed experiments, observed changes, interpreted evidence, and connected results to chemical reaction classifications.

The present study, therefore, evaluated the effectiveness of a micro-scale waste-prevention laboratory approach in enhancing Grade 11 STEM learners’ conceptual understanding of types of chemical reactions. Specifically, it determined learners’ performance before the intervention, assessed their performance after the intervention, and tested whether there was a significant difference between pre-test and post-test results. Using a one-group pre-test/post-test quasi-experimental design with 44 Grade 11 STEM learners from Urdaneta City National High School, the study generated evidence on the potential of safe, sustainable, and inquiry-based laboratory instruction to improve chemistry learning. The findings are expected to support science teachers, curriculum planners, and school administrators in adopting Green Chemistry-based micro-scale experiments that promote conceptual mastery, learner engagement, laboratory safety, and environmental responsibility.

7 Method

2.1 Research Design

The study employed a one-group pre-test/post-test quasi-experimental research design to determine the effectiveness of a micro-scale waste-preventive laboratory approach in enhancing Grade 11 STEM learners' conceptual understanding of types of chemical reactions. This design was appropriate because the same group of learners was assessed before and after exposure to the intervention, allowing the researcher to measure changes in performance attributable to the laboratory-based instructional approach. Prior to the intervention, a validated 20-item multiple-choice pre-test was administered to assess learners' baseline understanding of synthesis, decomposition, single-replacement, and double-replacement reactions. The learners then participated in micro-scale experiments using safer and more accessible materials, including steel wool, vinegar, hydrogen peroxide, yeast, aluminum foil, copper sulfate, and baking soda. After the intervention, the same competency-aligned assessment structure was used through a post-test to determine improvement in conceptual understanding. Although the design did not include a control group, it allowed the researcher to compare pre-intervention and post-intervention performance and determine whether the Green Chemistry-based micro-scale laboratory approach produced a statistically significant improvement in learners' chemistry achievement.

2.2 Participants

The study was forty-four Grade 11 STEM learners enrolled in Chemistry 2 at Urdaneta City National High School, Urdaneta City, Pangasinan, during Academic Year 2025–2026. The learners were selected through purposive sampling because they were directly enrolled in the subject and competency area covered by the intervention, particularly the topic on types of chemical reactions. This participant group was appropriate because the study aimed to determine whether a micro-scale waste-prevention laboratory approach could improve learners' conceptual understanding of synthesis, decomposition, single-replacement, and double-replacement reactions. Prior to the intervention, the learners completed a validated 20-item pre-test to determine their baseline performance. They then participated in micro-scale laboratory activities using safer and more accessible materials, including steel wool, vinegar, hydrogen peroxide, yeast, aluminum foil, copper sulfate, and baking soda. After the intervention, the learners completed the post-test to measure gains in conceptual understanding. Through this group of participants, the study generated focused evidence on the effectiveness of Green Chemistry-based micro-scale experimentation in improving chemistry learning among senior high school STEM learners.

2.3 Instrumentation

The study utilized researcher-developed 20-item multiple-choice pre-test and post-test instruments to measure Grade 11 STEM learners' conceptual understanding of types of chemical reactions. The tests aligned with the Department of Education Chemistry 2 curriculum competencies and covered the major reaction types: synthesis, decomposition, single-replacement, and double-replacement reactions. The pre-test was administered before implementing the micro-scale waste-preventive laboratory approach to determine learners' baseline knowledge and identify their initial level of conceptual mastery. After the intervention, the post-test was administered to measure improvement in learners' understanding of reaction classification, prediction, and interpretation. The instruments underwent expert validation to ensure content validity, curriculum alignment, item clarity, and appropriateness for Grade 11 STEM learners. Using these assessment tools, the study generated measurable data to compare learners' performance before and after the intervention and to determine the effectiveness of the Green Chemistry-based micro-scale laboratory approach in improving conceptual understanding of chemical reaction types.

2.4 Data Analysis

The data gathered from the pre-test and post-test were analyzed using descriptive and inferential statistical procedures. Descriptive statistics, including mean, median, standard deviation, and Mean Percentage Score, were used to determine the performance level of Grade 11 STEM learners before and after the implementation of the micro-scale waste-preventive laboratory approach. These measures provided a clear summary of learners' baseline conceptual understanding and post-intervention achievement in identifying and interpreting synthesis, decomposition, single-replacement, and double-replacement reactions. To determine whether a statistically significant difference existed between the pre-test and post-test scores, a paired-samples t-test was employed. This statistical test was appropriate because the same group of learners was measured before and after the intervention. The null hypothesis was tested at the 0.05 significance level. Through this analysis, the study determined whether the Green Chemistry-based micro-scale laboratory approach produced a measurable improvement in learners' conceptual understanding of chemical reaction types.

3 Results

The results showed that before the implementation of the micro-scale waste-preventive laboratory approach, Grade 11 STEM learners demonstrated low conceptual mastery of types of chemical reactions. The learners obtained a pre-test mean score of 8.18 out of 20, with a Mean Percentage Score of 40.90%. The highest score obtained was 11, while the lowest score was 5. The median score was 8, and the standard deviation was 1.59, indicating that most learners performed within a relatively narrow range of low performance. These findings suggest that, prior to the intervention, learners had difficulty classifying, predicting, and interpreting synthesis, decomposition, single-replacement, and double-replacement reactions.

After implementing the micro-scale waste-prevention laboratory approach, learners' performance improved substantially. The post-test mean score increased to 16.39 out of 20, with a Mean Percentage Score of 81.95%. The highest score obtained was 20, while the lowest score was 13. The median score also rose to 16, and the standard deviation was 1.60. These results indicate that learners moved from low conceptual mastery before the intervention to a much higher level of understanding after participating in the micro-scale laboratory activities.

The improvement in post-test performance suggests that the laboratory intervention helped learners connect abstract chemical concepts with observable phenomena. Through micro-scale activities using materials such as steel wool, vinegar, hydrogen peroxide, yeast, aluminum foil, copper sulfate, and baking soda, learners observed chemical changes directly and related them to different types of reactions. The use of small quantities and safer household materials also made the laboratory experience more manageable, reducing possible anxiety and allowing learners to focus on conceptual understanding.

The paired-samples t-test confirmed that the improvement between pre-test and post-test scores was statistically significant. The pre-test mean of 8.18 increased to a post-test mean of 16.39, yielding a mean difference of -8.20. The computed t-value was -91.66 with 43 degrees of freedom and a p-value of .000. Since the p-value was lower than the 0.05 level of significance, the null hypothesis was rejected. This indicates a significant difference in learners' performance before and after the implementation of the micro-scale waste-preventive laboratory approach.

Overall, the findings provide strong evidence that the micro-scale waste-preventive laboratory approach effectively enhanced Grade 11 STEM learners' conceptual understanding of types of chemical reactions. The increase in the mean score and the mean percentage score demonstrates that the intervention improved learners' ability to understand and classify chemical reactions. The results further suggest that Green Chemistry-based micro-scale experiments can support safer, more sustainable, and more engaging chemistry instruction while promoting both academic learning and environmental responsibility.

4. Discussion

The study's findings show that Grade 11 STEM learners had low conceptual mastery of types of chemical reactions prior to the intervention. The pre-test mean score of 8.18 out of 20, equivalent to an MPS of 40.90%, indicates that learners had difficulty classifying, predicting, and interpreting synthesis, decomposition, single-replacement, and double-replacement reactions. This result is understandable because chemical reaction types require learners to connect three levels of chemical understanding: symbolic equations, observable changes, and particle-level transformations. The result is also consistent with the broader concern in science education that learners may struggle when instruction focuses mainly on memorization and symbolic manipulation rather than active inquiry and conceptual engagement. OECD data from PISA 2022 show that Filipino learners performed below the OECD average in science, with only 23% reaching at least Level 2 proficiency, highlighting the continuing need for stronger inquiry-based, evidence-centered science instruction.

The substantial increase in post-test performance demonstrates that the micro-scale waste-preventive laboratory approach effectively improved learners' conceptual understanding. After the intervention, the post-test mean increased to 16.39 out of 20, while the MPS rose to 81.95%, showing that learners moved from low mastery to a much stronger level of achievement. This improvement may be attributed to the experiential nature of the intervention, in which learners directly observed chemical changes using small amounts of readily available materials such as steel wool, vinegar, hydrogen peroxide, yeast, aluminum foil, copper sulfate, and baking soda. By connecting laboratory observations with reaction classifications, learners were able to construct meaning from concrete evidence rather than relying only on textbook explanations or equation memorization.

The statistically significant paired t-test result further strengthens the conclusion that the intervention produced meaningful learning gains. The computed t-value of -91.66 and p-value of .000 indicate that the difference between pre-test and post-test scores was significant at the 0.05 level. Thus, the null hypothesis was rejected. This result confirms that the micro-scale waste-preventive laboratory approach was not merely an engaging classroom activity but an effective instructional strategy for improving conceptual mastery. The finding supports the claim that laboratory instruction becomes more powerful when learners actively manipulate materials, observe outcomes, discuss evidence, and relate results to scientific concepts.

The intervention's effectiveness is also supported by Green Chemistry principles. The American Chemical Society identifies waste prevention as a core principle of Green Chemistry, emphasizing that it is better to prevent waste than to treat or clean it after it has been created. In the present study, the use of micro-scale reaction surfaces and drop-wise reagent application reduced chemical waste and minimized safety risks. This is consistent with Singh, Szafran, and

Pike's explanation that microscale chemistry and Green Chemistry are complementary pedagogies because microscale experiments help incorporate waste reduction, hazard minimization, and pollution prevention into chemistry education. Therefore, the intervention promoted both conceptual learning and responsible laboratory practice.

Finally, the study contributes to sustainable science education by showing that effective chemistry learning does not always require large quantities of reagents or complex laboratory setups. Safer, smaller-scale, and environmentally responsible experiments can still yield strong learning outcomes when aligned with curriculum competencies and guided by inquiry. A 2024 systematic review on Green Chemistry education emphasized the relevance of Green Chemistry didactics in responding to environmental concerns and strengthening sustainable chemistry education. The findings of the present study, therefore, support the integration of Green Chemistry-based micro-scale laboratory activities in STEM instruction. Such an approach may improve learner engagement, reduce laboratory anxiety, enhance conceptual understanding, and promote environmental responsibility among senior high school learners.

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