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Microscale Gas Diffusion Experiments as a Catalyst for Conceptual Learning and Motivation in Senior High School Chemistry

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ABSTRACT

This study investigated the effectiveness of a microscale gas diffusion experiment as an instructional strategy for teaching Graham's Law to Grade 11 STEM learners. Employing a one-group pretest–posttest quasi-experimental design, the study involved 48 students from Valencia National High School. Learners' conceptual understanding was assessed using a 15-item researcher-developed Conceptual Understanding Test administered before and after the intervention, while motivation toward chemistry learning in the context of microscale experimentation was measured post-intervention using a 33-item, 4-point Likert scale questionnaire covering seven motivational dimensions. Descriptive statistics summarized mean percentage scores and motivation levels. Normality tests indicated non-normal distributions; therefore, the Wilcoxon Signed-Rank Test was used to evaluate differences in pretest and posttest scores, and Spearman's rank-order correlation assessed the relationship between conceptual understanding and motivation dimensions. Results indicated a notable increase in mean percentage scores from 60.87% (pretest) to 74.72% (posttest), with the Wilcoxon test confirming a statistically significant improvement ($Z = -3.81$, $p < .001$) and a large effect size ($r = 0.59$). Learners demonstrated high to very high motivation across the seven dimensions, with engagement and safety motivation showing a significant positive correlation with conceptual understanding ($\rho = 0.385$, $p = 0.007$), while other dimensions were not significantly related. These findings suggest that microscale gas diffusion experiments effectively enhance conceptual understanding of Graham's Law and foster learner motivation, with engagement and perceived safety emerging as key factors associated with improved learning outcomes.

Key Words: Microscale Chemistry, Gas Diffusion, Graham's Law, Conceptual Understanding, Motivation.

1. INTRODUCTION

Developing robust conceptual understanding remains a central objective of chemistry education, particularly for topics that require learners to coordinate mathematical relationships with particulate-level explanations of physical phenomena. Despite sustained instructional efforts, a substantial body of research demonstrates that students both enter and exit chemistry courses with persistent and deeply rooted misconceptions concerning gaseous systems and particle behavior. Common difficulties include misunderstandings related to diffusion and effusion processes, molecular motion, and the relationship between particle mass and diffusion rate (Azizoğlu & Geban, 2004; Benson et al., 1993; Kind, 2004; Nakhleh, 1992; Taber, 2002). These misconceptions are notably resistant to change and frequently persist even after formal instruction.

Prior research consistently indicates that such conceptual difficulties are exacerbated by instructional approaches that fail to explicitly confront learners' underlying mental models. In many classroom and laboratory contexts, chemistry instruction is characterized by limited hands-on conceptual engagement, excessive cognitive load, and an overreliance on highly procedural tasks, conditions that may inadvertently reinforce rather than remediate misconceptions (du Toit & du Toit, 2024; Koperová et al., 2025; Mundy et al., 2024). When instructional emphasis privileges algorithmic problem solving over conceptual sense-making, learners may successfully manipulate formulas without understanding the scientific rationale that underpins observed relationships (Niaz, 1994; Taber, 2013). Consequently, students may demonstrate acceptable performance on assessments while lacking the ability to integrate macroscopic observations, particulate explanations, and symbolic representations into a coherent and transferable conceptual framework (Abdullah et al., 2009; Naibert & Barbera, 2022). From a conceptual change perspective, such misconceptions are especially resistant because learners' existing explanatory frameworks often appear adequate for interpreting everyday experiences. Meaningful conceptual change therefore requires instructional experiences that generate dissatisfaction with naïve conceptions and support the construction of alternative explanations that are intelligible, plausible, and fruitful (Posner et al., 1982).

Laboratory learning has long been identified as a critical avenue for supporting conceptual development in chemistry, as it offers opportunities to connect observable macroscopic phenomena with abstract theoretical models and to engage learners in evidence-based explanation and argumentation (Hofstein & Lunetta, 2004; National Research Council, 2000, 2006). Contemporary research in laboratory education further emphasizes that practical work should be deliberately designed to promote inquiry, reasoning, and interpretation rather than mere procedural completion (Agustian, 2025; Jegstad, 2024). When laboratory tasks encourage learners to identify patterns, employ science process skills, and explicitly relate experimental outcomes to underlying concepts, improvements in conceptual understanding are more likely to occur (Feyzioğlu, 2009; Shana & Abulibdeh, 2020). This instructional focus is particularly relevant for diffusion-related concepts, which remain challenging even after instruction and often require carefully structured activities that foreground particulate reasoning (Odom & Barrow, 1995).

Graham's Law, commonly introduced through the inverse square-root relationship between diffusion or effusion rate and molar mass, exemplifies a conceptually demanding topic within gas laws instruction. Mastery of this principle requires learners to coordinate symbolic representations, particulate-level explanations, and observable diffusion phenomena (Flowers et al., 2019). Although classroom demonstrations—such as the diffusion of ammonia and hydrogen chloride gases forming ammonium chloride—can make differences in diffusion rates visible, such demonstrations alone are insufficient without guided interpretation and explicit conceptual scaffolding (University of Colorado Boulder, Department of Chemistry and Biochemistry, n.d.). Students' pre-existing misconceptions about gases frequently interfere with accurate interpretation of these phenomena, underscoring the necessity of instructional approaches that intentionally link observation to particle-based models (Azizoğlu & Geban, 2004; Benson et al., 1993).

Despite the pedagogical value of laboratory instruction, many secondary schools face practical constraints related to cost, time, equipment availability, safety considerations, and waste management. Microscale chemistry has emerged as a promising response to these challenges by employing reduced quantities of chemicals and simplified apparatus while maintaining the integrity of core chemical principles. Microscale laboratory activities can lower financial costs, minimize hazards, reduce waste, and shorten preparation and cleanup time, thereby aligning chemistry instruction with principles of sustainability and feasibility (Abdullah et al., 2009; Botella & Ibanez, 2020). Empirical studies suggest that microscale laboratory experiences can enhance students' conceptual understanding and engagement; however, reported effects on motivation and attitudes toward chemistry remain inconsistent across contexts, indicating the need for systematic and context-specific investigation.

Motivation constitutes a critical component of chemistry learning, as students must sustain effort, persist through conceptual difficulty, and actively engage in explanation and problem solving. Contemporary theoretical frameworks conceptualize motivation as a multidimensional construct encompassing self-efficacy beliefs (Bandura, 1977), autonomy and intrinsic motivation processes (Ryan & Deci, 2000), and expectancy–value beliefs regarding success and task importance (Wigfield & Eccles, 2000). Similarly, student engagement—understood as a behavioral, emotional, and cognitive phenomenon—has been strongly associated with learning outcomes and is influenced by the

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perceived relevance, safety, and structure of classroom activities (Fredricks et al., 2004). Practical laboratory experiences that are manageable, safe, and participatory—characteristics commonly attributed to microscale approaches—may therefore support not only conceptual understanding but also motivational and engagement-related outcomes.

Grounded in the literature on conceptual change, laboratory learning, gas misconceptions, microscale chemistry, and student motivation, the present study investigated the effectiveness of a microscale gas diffusion experiment as an instructional strategy for teaching Graham's Law to Grade 11 STEM learners. Specifically, the study examined changes in learners' conceptual understanding from pretest to posttest, assessed students' motivation toward learning chemistry within a microscale laboratory context, and explored the relationship between conceptual understanding and key motivational dimensions.

2. METHODOLOGY

This section delineates the research design, participants, procedures, data collection instruments, and analytical strategies employed to examine the effects of a microscale gas diffusion experiment on Grade 11 STEM learners' conceptual understanding of Graham's Law and their motivation toward learning chemistry. To enhance transparency, clarity, and replicability, essential methodological components—including participant characteristics, intervention timeline, assessment instruments, scoring procedures, and statistical analyses—are summarized in tabular form and cross-referenced throughout this section.

2.1 Research Design

The study adopted a quasi-experimental, one-group pretest–posttest design to evaluate changes in learners' conceptual understanding following exposure to a microscale gas diffusion instructional intervention. Within this design, the same cohort of participants completed a conceptual understanding assessment prior to the intervention (pretest) and an equivalent assessment after the instructional implementation (posttest). This approach enabled direct within-group comparison of learners' performance before and after engagement with the microscale laboratory activity embedded in instruction on Graham's Law.

Although the absence of a control group limits causal inference, the one-group pretest–posttest design was considered appropriate given contextual constraints in the school setting and the exploratory nature of the intervention. Moreover, the design allowed for sensitive detection of learning gains attributable to the instructional treatment by controlling for inter-individual variability in prior knowledge.

Learners' motivation toward learning chemistry in the context of microscale experimentation was assessed after completion of the intervention using a structured self-report questionnaire. The post-intervention administration of the motivation instrument was intentionally selected to ensure that participants' responses reflected their authentic experiences with the microscale gas diffusion activity, rather than anticipated perceptions or preconceived expectations. This timing aligns with established methodological practices in motivation research, where situational motivation is best captured following direct engagement with the learning task.

2.2 Participants

The participants comprised 48 Grade 11 students enrolled in the Science, Technology, Engineering, and Mathematics (STEM) strand at Valencia National High School and currently taking Chemistry as part of the senior high school curriculum. A purposive sampling strategy was employed through the selection of an intact Grade 11 STEM class that was accessible during the study implementation period. The use of an intact class minimized instructional disruption, preserved the natural classroom context, and ensured consistency of instructional exposure across all participants.

Eligibility criteria were applied to define the study sample and maintain data integrity. Inclusion criteria required that learners be officially enrolled in the selected Grade 11 STEM Chemistry class, present during all phases of the intervention, and able to complete both the pretest and posttest assessments. Learners who were absent during

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either assessment phase or who did not participate in the microscale laboratory activity were excluded from the final analysis. A summary of participant demographics, sampling procedures, and inclusion and exclusion criteria is presented in Table 1.

By clearly specifying the participant profile and selection criteria, the study establishes a well-defined target population, enhances internal consistency across study phases, and supports methodological comparability for future replications in similar secondary school STEM contexts.

Table 1. Participant profile and inclusion criteria

Item	Description
Target participants	Grade 11 STEM learners enrolled in Chemistry
Locale	Valencia National High School
Sampling size	n = 48
Sampling technique	Purposive (intact class)
Inclusion criteria	Enrolled as Grade 11 STEM; enrolled in Chemistry; present during pretest, intervention, and posttest; completed required consent/assent; completed instrumentswith usable responses.
Exclusion criteria	Not part of the selected class; absence during keyphases; incomplete responses preventing valid scoring

2.1 Research Instruments and Validation

The study utilized three primary research instruments: (a) a Learning Activity Sheet designed for microscale laboratory instruction, (b) a Conceptual Understanding Test on Graham's Law, and (c) a Motivation Toward Learning Chemistry Instrument. Collectively, these instruments were developed and validated to capture learners' cognitive and motivational responses to microscale instruction on gas diffusion and effusion.

Learning Activity Sheet.

The Learning Activity Sheet (LAS), entitled "When Gases Meet: Visualizing Diffusion and Molecular Mass," was specifically developed to support the instruction of Graham's Law through a microscale laboratory approach and was aligned with the learning competencies prescribed in the Grade 11 Chemistry curriculum. The LAS functioned as a structured scaffold that guided learners through the experimental process, from problem orientation and procedural execution to systematic observation and post-activity conceptual reflection.

The LAS comprised clearly articulated learning objectives, safety precautions, materials and apparatus lists, step-by-step experimental procedures, and higher-order guide questions intended to elicit particulate-level reasoning and conceptual explanation. To ensure linguistic accessibility without compromising conceptual rigor, readability analyses were conducted using the Flesch–Kincaid Grade Level and the SMOG Readability Test. Results yielded a mean Flesch–Kincaid Grade Level of 5.94 and a mean SMOG Grade Level of 6.33, indicating that the instructional material was appropriately readable for Grade 11 learners while supporting engagement with abstract gas concepts.

Conceptual Understanding Test on Graham's Law. Learners' conceptual understanding of gas diffusion, effusion, and Graham's Law was assessed using a researcher-developed, 15-item Conceptual Understanding Test administered as both a pretest and a posttest. The instrument was designed to measure learners' ability to interpret diffusion phenomena, relate observable outcomes to particulate explanations, and apply the inverse square-root relationship between diffusion rate and molar mass.

Test content was anchored in the senior high school chemistry curriculum and systematically aligned with instructional objectives through the use of a Table of Specifications to ensure balanced representation of content domains and cognitive levels. Readability analysis of the test items produced a mean Flesch–Kincaid Grade Level of

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5.06 and a mean SMOG Grade Level of 5.37, indicating that item wording was accessible to the target population and unlikely to confound conceptual understanding with linguistic difficulty.

Motivation Toward Learning Chemistry Instrument. Learners' motivation toward learning chemistry in the context of microscale experimentation was measured using a 33-item Motivation Toward Learning Chemistry Instrument administered after the instructional intervention. The instrument assessed motivational constructs across seven subscales, reflecting multidimensional theoretical perspectives on student motivation. Responses were recorded on a four-point Likert-type scale, and both overall motivation scores and subscale mean scores were computed for analysis.

Instrument Validation. Multiple validation procedures were undertaken prior to data collection to establish the adequacy of the research instruments. The Learning Activity Sheet and the Conceptual Understanding Test were subjected to readability analyses using the Flesch–Kincaid Grade Level and the SMOG Readability Test, and minor revisions were made to improve clarity and reduce unnecessary linguistic complexity where required. The Motivation Toward Learning Chemistry Instrument underwent face and content validation by a panel of subject-matter and research-methodology experts. The validation process yielded a Content Validity Index (CVI) of 3.99, indicating a very high level of expert agreement regarding the relevance, clarity, and alignment of the items with the intended motivational constructs.

2.3 Data Gathering Procedure

Data collection was conducted in three sequential stages: (1) pre-implementation, (2) implementation of the microscale gas diffusion experiment integrated into instruction on Graham's Law, and (3) post-implementation evaluation. This phased procedure ensured systematic documentation of baseline conceptual understanding, controlled delivery of the instructional intervention, and immediate assessment of learning and motivational outcomes.

During the pre-implementation stage, the Conceptual Understanding Test was administered as a pretest to establish learners' initial understanding of diffusion, effusion, and Graham's Law. Standardized administration procedures—including uniform instructions, consistent time allotment, and the use of respondent codes to ensure anonymity—were strictly followed to enhance comparability of results.

The implementation stage involved the integration of the microscale gas diffusion experiment into regular classroom instruction. Learners worked in small groups under the direct supervision of the teacher-researcher to promote safe handling of materials, procedural consistency, and collaborative engagement. The Learning Activity Sheet guided learners throughout the activity, emphasizing careful observation, interpretation of diffusion patterns, and explicit linkage between experimental evidence and particulate-level explanations.

In the post-implementation stage, the Conceptual Understanding Test was re-administered as a posttest to measure changes in learners' conceptual understanding following the intervention. The Motivation Toward Learning Chemistry Instrument was also administered to capture learners' motivational responses to the microscale laboratory experience. A summary of the major activities conducted at each stage of the data gathering process is presented in Table 2.

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Table 2. Summary of data-gathering procedure

Item	Description
Pre-implementation	Orientation on procedure and confidentiality; assignment of respondents' codes (R1-R48); administration of 15-item Conceptual Understanding Test as pretest under standardized direction.
Intervention	Conduct of the microscale gas diffusion experiment in small groups; completion of activity output/guide questions; teacher-researcher supervision emphasizing safe handling and accurate observation; processing discussion connecting observation to Graham's Law and practice items.
Post-implementation evaluation	Administration of the same 15-item Conceptual Understanding Test as posttest (Item order rearranged); administration of 33-item motivation questionnaire after the posttest; checking for completeness and coding of responses.

Measures and scoring. Three research instruments were employed to collect data for the present study, and the timing of their administration is summarized in Table 3. Instructional implementation was supported through a Learning Activity on Graham's Law designed for microscale laboratory experimentation. Learners' conceptual understanding of gas diffusion, effusion, and Graham's Law was assessed using a 15-item researcher-developed test administered both prior to the intervention (pretest) and immediately after its completion (posttest). In addition, learners' motivation toward learning chemistry in the context of microscale experimentation was measured using a 33-item questionnaire administered after the instructional intervention to capture motivational responses grounded in learners' actual laboratory experiences.

Table 3. Research instruments and administration schedule

Instrument	Items	Administration
Learning Activity on Graham's Law	NA	During intervention
Conceptual Understanding Test on Graham's Law	15	Pre-Test and Post-Test
Motivation Towards Learning Chemistry Instrument	33	Post-Intervention only

To establish alignment between the assessment items and the intended learning competencies, a Table of Specifications is presented in Table 4. This table delineates the distribution of test items across the targeted content domains, specifically those addressing diffusion processes, the influence of molecular mass on diffusion rate as articulated by Graham's Law, and their application to real-life contexts. Learners' conceptual understanding was initially recorded as raw scores ranging from 0 to 15 and subsequently transformed into Mean Percentage Scores (MPS) to facilitate standardized interpretation and comparison of achievement levels. The MPS was computed using the following formula:

$$\text{MPS} = \left(\frac{\text{score}}{15}\right) \times 100.$$

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Table 4. Table of specifications for the conceptual understanding test on Graham's Law

Learning competency	No. of items	Item numbers
Compare the diffusion of two gases	3	1, 2, 8
Explain the effect of molecular mass on diffusion rate	9	3, 4, 5, 6, 9, 10, 11, 13, 15
Appreciate applications of gas behavior principles in real-life situations	3	7, 12, 14
Total	**15**	

To facilitate systematic interpretation of learners' achievement levels, Table 5 presents the descriptive equivalents corresponding to the Mean Percentage Score (MPS) ranges employed in the analysis.

Table 5. Interpretation of Mean Percentage Score (MPS)

Mean Percentage Score (MPS) %	Description
96 - 100	Mastered
86 - 95	Closely Approximating Mastery
66 - 85	Moving Towards Mastery
35 – 65	Average Mastery
Below 35	Low Mastery

Reference: DepEd Order No. 73 s. 2012, and DepEd Order No. 8, s. 2015.

Learners' motivation was assessed using a four-point Likert-type scale, with descriptive interpretations applied to classify motivation levels based on the mean score ranges presented in Table 6. The forced-choice structure of the scale was intentionally employed to minimize neutral response tendencies and to elicit clearer indications of respondents' agreement or disagreement with each motivational statement.

Table 6. Mean range interpretation of overall motivation dimension.

Scale Point	Mean Range	Interpretation	Motivation Level
4	3.26 - 4.00	Strongly Agree	Very High Motivation
4	2.52 - 3.25	Agree	High Motivation
2	1.76 - 2.50	Disagree	Low Motivation
1	1.00 - 1.75	Strongly Disagree	Very Low Motivation

Adapted from the Department of Education (DepEd, 2015).

The motivation questionnaire encompassed seven distinct dimensions, as summarized in Table 7. Reporting the distribution of items across these dimensions clarifies the operationalization of motivation and supports meaningful interpretation of dimension-specific mean scores in relation to learners' conceptual understanding outcomes. Motivation scores were computed as mean ratings for each dimension as well as an overall mean rating across all questionnaire items.

Table 7. Motivation dimensions toward learning chemistry, their meaning and item distribution

Dimension	No. of Items	What it Measures
Intrinsic Motivation	5	Interest and enjoyment in learning Chemistry and participating in the
Perceived Value	5	activity.
Self-Efficacy	5	Perceived usefulness and relevance of Graham's Law and the
Motivation		learning activity
	5	Confidence in learning Graham's Law and doing Chemistry tasks
Effort & Persistence	5	successfully.

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		Willingness to exert effort and continue learning despite difficulty.
Achievement Motivation	5	Desire to perform well and achieve success in Chemistry learning tasks.
Engagement & Safety Motivation	3	Active participation and motivation influenced by comfort and perceived safety in the learning activity.
Motivation Toward Microscale Chemistry		Willingness to engage in microscale activities and preference toward microscale laboratory learning

2.3.1 Preparation Phase

During the preparation phase, the study was systematically readied for implementation through the acquisition of administrative approval, adherence to established ethical research standards, and the finalization of all research instruments and instructional materials. A formal request to conduct the study was submitted to and approved by the school administration prior to data collection. All research instruments were refined and finalized, including the Learning Activity on Graham's Law, the Conceptual Understanding Test administered as both pretest and posttest, and the Motivation Toward Learning Chemistry Instrument administered following the intervention.

Careful attention was given to ensuring that the materials and procedures required for the microscale gas diffusion experiment were safe, feasible, and appropriate for completion within a regular class period. Prior to participation, learners were informed of the purpose of the study, the voluntary nature of their involvement, measures taken to ensure confidentiality, and other relevant ethical considerations. To maintain anonymity and enable accurate data tracking across study phases, respondent identification codes (R1–R48) were assigned.

The Conceptual Understanding Test on Graham's Law was subsequently administered as a pretest under controlled classroom conditions to establish learners' baseline understanding of diffusion, effusion, and the relationship between molecular mass and diffusion rate.

2.3.2 Implementation Phase

The implementation phase consisted of the systematic integration of a microscale gas diffusion experiment into classroom instruction on Graham's Law. The lesson commenced with a brief activation of prior knowledge through a guided review of previously learned gas concepts and an elicitation of learners' predictions regarding diffusion behavior. Learners were then organized into small groups, with each group assigned specific roles to ensure active participation and procedural accountability.

Following group formation, learners conducted the microscale gas diffusion experiment in accordance with the standardized instructions provided in the Learning Activity Sheet. The sheet served as a structured tool for documenting observations, interpreting diffusion patterns, and responding to guiding questions. Throughout the activity, the teacher-researcher facilitated learning by posing probing questions, addressing emerging misconceptions, reinforcing particulate-level explanations, and consistently emphasizing laboratory safety protocols.

Upon completion of the experimental procedure, learners' observations were collectively examined through a structured post-laboratory discussion that explicitly linked empirical evidence to the theoretical principles underlying Graham's Law. The lesson concluded with reinforcement activities designed to consolidate conceptual understanding and with follow-up tasks that required learners to apply both qualitative reasoning and quantitative problem-solving skills related to diffusion rate and molecular mass.

2.3.3 Evaluation Phase

The primary objective of the evaluation phase was to systematically assess learners' cognitive and motivational outcomes following the instructional intervention. The Conceptual Understanding Test on Graham's Law was administered as a posttest under standardized conditions, with respondents identified solely by their assigned

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codes to ensure anonymity and data integrity. Upon completion of the microscale gas diffusion experiment, learners' motivation was measured using the Motivation Toward Learning Chemistry Instrument, capturing self-reported engagement and interest in relation to the laboratory experience. All completed tests and questionnaires were verified for completeness, scored in accordance with pre-established rubrics, and encoded exclusively using respondent identifiers. The resulting dataset was subsequently validated for accuracy and integrity prior to the application of statistical analyses, as described in the Data Analysis section.

2.4 DATA ANALYSIS

All learner responses were systematically scored, encoded, and analyzed using the assigned respondent codes (R1–R48) to maintain participant anonymity and ensure traceability across study phases. Descriptive statistics—including means, standard deviations, frequencies, and percentage distributions—were calculated to summarize (a) learners' pretest and posttest performance, reported as raw scores and Mean Percentage Scores (MPS), and (b) post-intervention motivation, presented as both overall mean scores and dimension-specific mean ratings. These summaries provided an initial overview of changes in conceptual understanding and motivational outcomes resulting from the microscale laboratory intervention.

The assumption of normality for test score distributions was evaluated using the Kolmogorov–Smirnov test with Lilliefors correction and the Shapiro–Wilk test at a significance level of α = 0.05. Due to violation of normality assumptions, the nonparametric Wilcoxon Signed-Rank Test (two-tailed, α = 0.05) was employed to determine whether pretest and posttest scores differed significantly. The magnitude of observed changes in conceptual understanding was quantified using effect size. This metric provided an index of the practical significance of the intervention beyond mere statistical significance.

To examine potential associations between learners' conceptual understanding and their motivation following the intervention, Spearman's rank-order correlation coefficient (\rho) was computed between posttest scores (or gain scores, when appropriate) and overall as well as dimension-specific motivation mean scores, at a significance level of α = 0.05. A summary of all statistical treatments employed, along with their corresponding analytic purposes, is presented in Table 8, providing a clear mapping of each research question to the applied method.

Table 8. Statistical tests used in the study.

Mean Percentage Score (MPS) %	Description
Describe conceptual understanding	Mean, SD, frequency, MPS
(pretest/posttest)	Kolmogorov–Smirnov (Lilliefors), Shapiro-Wilk
Check distribution assumption	Wilcoxon Signed-Rank Test (two-tailed)
Test pretest vs posttest difference	Effect size r =Z/N
Quantify magnitude of improvement	Mean, SD (overall and by dimension)
Describe motivation after intervention	Spearman correlation (ρ)
Relate motivation to conceptual understanding	

2.5 Ethical Considerations

Ethical protocols were rigorously observed throughout the study. Participation was entirely voluntary, and learners retained the right to withdraw from the study at any point without penalty. Informed consent was obtained from parents or legal guardians, and learners' confidentiality and anonymity were strictly maintained through the use of respondent codes. All collected data were securely stored and accessed exclusively by the researcher. The study was conducted in a manner that ensured no physical, emotional, or psychological harm was inflicted on any participant, in full compliance with established ethical guidelines for research involving human subjects.

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3. RESULTS AND DISCUSSIONS

3.1. Learners' Conceptual Understanding of Graham's Law

This subsection delineates the learners' conceptual comprehension of Graham's Law prior to and following engagement with the microscale gas diffusion experiment. Learner performance is initially quantified through Mean Percentage Scores (MPS), providing a clear depiction of the overall trend from pretest to posttest. Subsequently, a non-parametric statistical analysis is employed to ascertain whether the observed enhancements in understanding are both statistically significant and pedagogically substantive.

3.1.1. Mean Percentage Scores Before and After the Microscale Gas Diffusion Experiment

Figure 1 presents the Mean Percentage Scores (MPS) of the learners in the pretest and posttest administered before and after the microscale gas diffusion experiment.

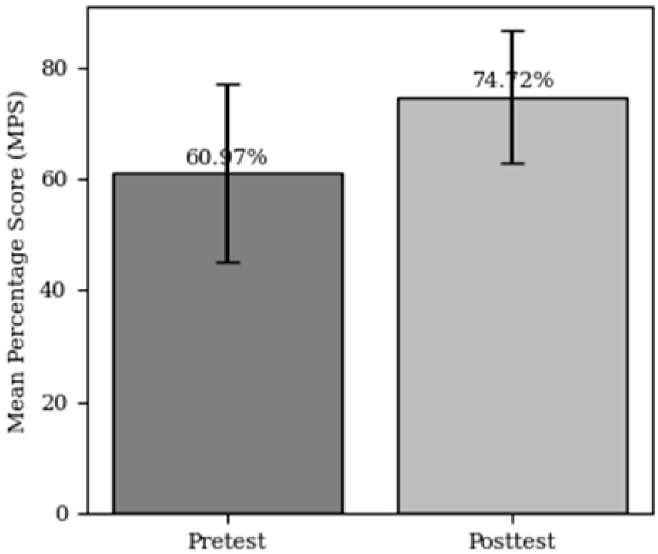

Figure 1 . Mean Percentage Scores of learners' conceptual understanding of Graham's Law before and after the microscale gas diffusion experiment.

Note. Error bars represent ±1 standard deviation. *N* = 48.

As illustrated in Figure 1, the pretest Mean Percentage Score (MPS) of 60.87% indicates that students initially demonstrated a moderate level of conceptual understanding of Graham's Law. Following the instructional intervention involving the microscale gas diffusion experiment, the posttest MPS increased to 74.72%, reflecting an improvement of approximately 13.85 percentage points. This upward shift suggests that students developed a more thorough grasp of the concept after engaging in the hands-on activity. Although the error bars reflect variability in individual performance, the general trend indicates a positive effect of the intervention on learning outcomes.

These findings underscore the efficacy of microscale gas diffusion experiments as an instructional strategy to enhance conceptual understanding in chemistry. The observed increase in MPS aligns with evidence that inquiry-based, hands-on laboratory activities facilitate comprehension of abstract concepts while promoting student engagement. Incorporating microscale experiments into chemistry instruction not only enriches the classroom experience but also produces measurable gains in academic performance. The improvement from pretest to posttest corroborates prior research demonstrating that active, inquiry-driven laboratory interventions significantly enhance

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conceptual understanding (Agustian, 2024; Mundy & Nokeri, 2024). Specifically, students participating in meaningful laboratory activities consistently achieve higher learning outcomes than those exposed to traditional teaching methods (Mundy & Nokeri, 2024). Furthermore, engaging learners in experimental tasks mitigates cognitive challenges and fosters a deeper understanding of abstract chemical phenomena (Mundy et al., 2024). Collectively, these data support the conclusion that microscale gas diffusion experiments represent a highly effective pedagogical approach for promoting mastery of Graham's Law.

3.1.2. Determination of the significant difference between the students' pretest and posttest performance on the conceptual understanding test on Graham's Law

Prior to conducting inferential statistical analyses, the pretest and posttest scores were examined for normality. Data distribution was assessed using the Kolmogorov–Smirnov test with Lilliefors significance correction and the Shapiro–Wilk test. Results from the Shapiro–Wilk test indicated that both pretest and posttest scores deviated from a normal distribution. Consistently, the Kolmogorov–Smirnov tests for both sets of scores were significant ($p = 0.000$), confirming a violation of the normality assumption at the 0.05 significance level. Consequently, parametric tests were deemed inappropriate. To evaluate whether the observed differences between pretest and posttest scores were statistically significant, the non-parametric Wilcoxon Signed-Rank Test for two related samples was employed. The results of this analysis are presented in Table 9.

Table 9. Wilcoxon Signed-Rank Test Results for Pretest and Posttest Scores

Comparison	N	Z	p-value	Effect Size (*r*)
Posttest – Pretest	48	-3.81	< 0.001	0.59 (large)

Note. Wilcoxon signed-rank test (two-tailed).

The Wilcoxon Signed-Rank Test revealed a statistically significant difference between students' pretest and posttest scores, $Z = -3.81$, $p < .001$, leading to the rejection of the null hypothesis that there is no difference in performance. Moreover, the large effect size ($r = .59$) indicates that the microscale gas diffusion experiment had a substantial impact on students' conceptual understanding of Graham's Law, as evidenced by the predominance of positive ranks ($n = 32$) relative to negative ranks ($n = 10$).

These findings are consistent with prior research demonstrating that hands-on and microscale laboratory experiences enhance conceptual understanding in chemistry. For instance, Du Toit and du Toit (2024) reported that small-scale laboratory kits improve learners' comprehension by fostering active, minds-on engagement, enhancing visualization, and facilitating concept formation, particularly in resource-limited contexts. Kolil et al. (2020) similarly found that both physical and technology-assisted experimental activities strengthen students' confidence and conceptual understanding when learners actively observe and interpret chemical phenomena. Tantayanon et al. (2024) emphasized that small-scale chemistry activities present manageable yet cognitively challenging tasks, enabling safe, meaningful engagement that translates into significant pretest-posttest gains. In addition, Easa and Blonder (2024) highlighted that structured laboratory kits enhance both achievement and self-efficacy, leading to improved posttest performance. Toma (2021) further corroborated that microscale kits offer a safe, affordable, and efficient means of involving students actively in experimental chemistry, promoting accurate observation, interpretation, and deeper conceptual understanding.

Collectively, the significant gains and large effect size observed in the present study provide strong empirical evidence that incorporating microscale gas diffusion experiments into chemistry instruction effectively promotes learners' understanding of abstract concepts such as Graham's Law. These results align with the broader literature advocating inquiry-based, hands-on, and microscale laboratory interventions as impactful strategies for enhancing conceptual learning and student engagement in secondary chemistry education.

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3.2. Learners' level of motivation toward learning Chemistry after the implementation of the microscale gas diffusion experiment.

Figure 2 presents the descriptive statistics, including mean scores and standard deviations, used to assess learners' motivation toward learning chemistry following the implementation of the microscale gas diffusion experiment. Learner motivation was examined across multiple dimensions, including intrinsic motivation, perceived value, self-efficacy, effort and persistence, achievement motivation, engagement and safety, as well as motivation specifically toward microscale chemistry activities.

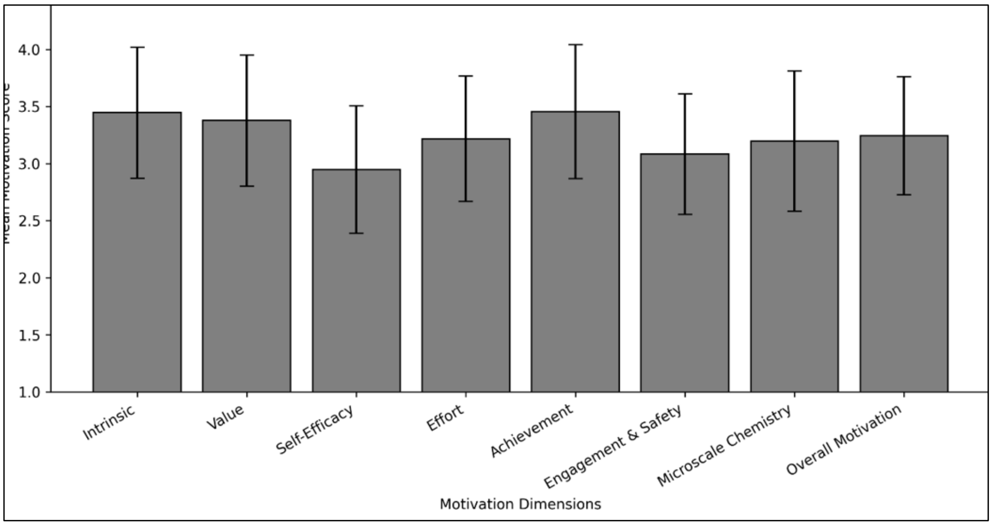

Figure 2. Mean Motivation Scores of Learners Across Seven Motivational Dimensions After the Implementation of the Microscale Gas Diffusion Experiment

Figure 2 presents the descriptive statistics of learners' motivation following the implementation of the microscale gas diffusion experiment. Overall, learners exhibited very high motivation (M = 3.30, SD = 0.30) toward chemistry learning through the microscale intervention. Among the motivation dimensions, intrinsic motivation (M = 3.51, SD = 0.37), achievement motivation (M = 3.52, SD = 0.39), perceived value (M = 3.44, SD = 0.39), and effort and persistence (M = 3.28, SD = 0.37) were particularly elevated, suggesting that students recognized the relevance of the activity, engaged actively, and demonstrated sustained effort in learning. Self-efficacy (M = 3.00, SD = 0.43), engagement and safety (M = 3.14, SD = 0.36), and motivation toward microscale chemistry (M = 3.25, SD = 0.48) fell within the high motivation range, indicating areas for further enhancement while still reflecting positive responses overall. The relatively low standard deviations across all dimensions suggest a consistent motivational impact across learners.

These results align with prior research highlighting the motivational benefits of hands-on, inquiry-based, and contextually relevant laboratory activities in chemistry education. Active engagement with chemical phenomena has been shown to increase perceived task value, intrinsic motivation, effort, and goal attainment (Kaneza et al., 2024; Jegstad, 2024). Such findings are consistent with Expectancy-Value Theory, which posits that tasks perceived as desirable, relevant, and achievable enhance motivation (Eccles & Wigfield, 2002), and with Social Cognitive Theory, which emphasizes that learners' belief in their capabilities strengthens motivation and self-regulation (Bandura, 1986).

The very high intrinsic and achievement motivation scores indicate that the microscale experiment promotes active participation and ownership of learning. Microscale and individualized experiments allow learners to engage deeply with procedural tasks, reinforcing achievement-oriented behaviors (Abdullah et al., 2009; Oliveira & Bonito, 2023). Similarly, perceived value and effort and persistence scores suggest that learners recognized the usefulness of

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the experiment and were willing to sustain effort throughout the tasks, reflecting the benefits of safe, independent, and hands-on experimentation (Botella & Ibáñez, 2020; Naibert & Barbera, 2022).

Despite the overall high motivation, self-efficacy remained the lowest dimension, consistent with literature noting that laboratory confidence develops gradually due to procedural complexity, anxiety, or fear of errors (Kolil et al., 2020; Nzomo et al., 2023). Engagement and safety motivation were high, indicating that the microscale experiment provided a secure environment conducive to active participation (Toma, 2021; du Toit & du Toit, 2024). Motivation toward microscale chemistry was also high, suggesting that students generally held positive attitudes toward microscale experimentation, though sustained interest may require continued scaffolding and contextualized instruction (Tantayanon et al., 2024).

Collectively, these findings corroborate existing literature demonstrating that hands-on, inquiry-based, and microscale laboratory interventions enhance intrinsic motivation, perceived value, effort, engagement, and achievement motivation in chemistry education (du Toit & du Toit, 2024; Kaneza et al., 2024; Mundy & Nokeri, 2024; Nzomo et al., 2023). Self-efficacy, while positively influenced, remains a target for further instructional support to maximize motivational outcomes.

3.3. Relationships between students' conceptual understanding of Graham's Law and their motivation toward learning Chemistry

A Spearman's rank-order correlation analysis was conducted to examine the relationships between students' conceptual understanding of Graham's Law and various dimensions of motivation toward learning chemistry, including intrinsic motivation, perceived value, self-efficacy, effort and persistence, achievement motivation, engagement and safety, and motivation toward microscale chemistry. The results of this analysis are presented in Table 10, illustrating the extent to which each motivational dimension is associated with learners' post-intervention conceptual performance following the microscale gas diffusion experiment.

Table 10. Spearman's Rank-order Correlation between students' conceptual understanding of Graham's law and motivation dimensions

Motivation Dimension	ρ (Spearman)	p-value
Intrinsic	0.203	0.165
Perceived Value	0.015	0.920
Self-Efficacy	0.098	0,507
Effort & Persistence	0.076	0.607
Achievement	0.101	0.492
Engagement & Safety	0.385	0.007
Motivation Towards Microscale Chemistry	0.112	0.450
Overall Motivation	**0.149**	**0.311**

Note. ρ = Spearman's rank-order correlation coefficient. p < .05 indicates statistical significance. n = 48.

As presented in Table 10, among the motivational dimensions assessed, only engagement and safety motivation demonstrated a statistically significant relationship with students' conceptual understanding of Graham's Law ($\rho = 0.385$, $p = 0.007$). This finding indicates a weak-to-moderate positive correlation, suggesting that students who reported higher levels of engagement and perceived safety during the microscale experiment tended to achieve superior conceptual understanding.

In contrast, no statistically significant relationships were observed between conceptual understanding and intrinsic motivation, perceived value, self-efficacy, effort and persistence, achievement motivation, motivation toward

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microscale chemistry, or overall motivation ($p > 0.05$). The correlation coefficients for these dimensions were weak, indicating that general motivational factors were not strongly associated with conceptual understanding within the context of this intervention.

Figure 3 further illustrates this relationship, showing that higher engagement and safety scores correspond with higher conceptual understanding scores. The scatter plot visually reinforces the positive association reported in Table 11, highlighting the particular importance of creating engaging and safe learning environments in facilitating students' mastery of Graham's Law.

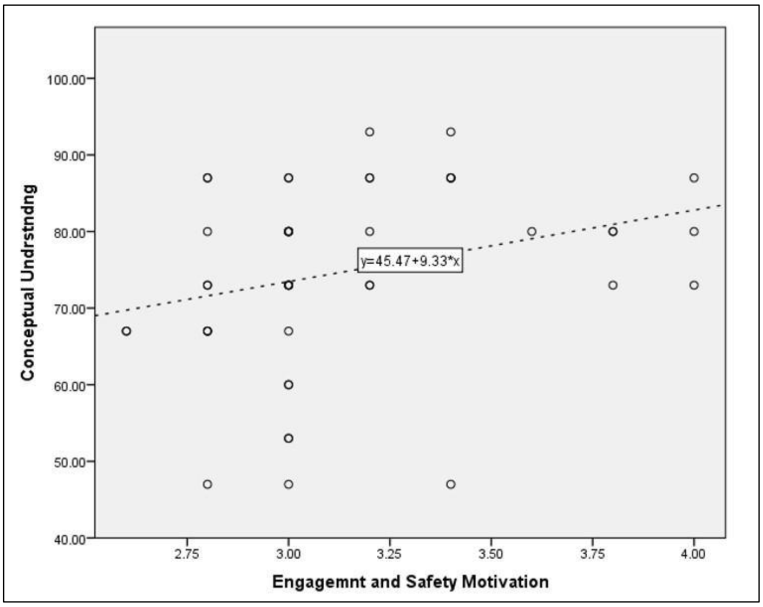

Figure 3. Scatter plot illustrating the relationship between students' engagement and safety motivation and their conceptual understanding of graham's law

Figure 3 illustrates a positive relationship between students' engagement and safety motivation and their conceptual understanding of Graham's Law. As engagement and perceived safety increase, students tend to achieve higher levels of conceptual understanding, visually corroborating the significant Spearman correlation reported. No similar trends were observed for the other motivational dimensions, consistent with the non-significant correlations.

These findings suggest that chemistry instruction, particularly for abstract concepts such as gas laws, should prioritize strategies that enhance student engagement and perceived safety. Microscale laboratory experiments appear particularly effective in achieving these goals by minimizing hazards and encouraging active participation, thereby facilitating deeper conceptual understanding. The intervention also positively influenced broader motivational constructs, notably intrinsic and achievement-oriented motivation, aligning with prior research indicating that active, student-centered laboratory experiences promote positive affective outcomes, including heightened interest, engagement, and motivation to learn scientific concepts (Naibert & Barbera, 2022).

However, relatively lower scores for self-efficacy and perceived value indicate areas for further development. These results highlight the importance of sustained exposure to microscale experiments combined with targeted instructional scaffolding to strengthen learners' confidence and maintain motivation in chemistry learning. Overall, the intervention effectively enhanced specific motivational dimensions, supporting the broader evidence that inquiry-based, hands-on laboratory activities stimulate both cognitive and affective gains in secondary chemistry education.

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3.4. Evaluation on the effectiveness of the microscale gas diffusion experiment as an instructional strategy in teaching Graham's Law in senior high school Chemistry

The effectiveness of the microscale gas diffusion experiment as an instructional strategy for teaching Graham's Law was evaluated by comparing learners' pretest and posttest Mean Percentage Scores (MPS). As illustrated in Figure 3.1.1.1, the mean score increased from 60.97% in the pretest to 74.72% in the posttest, indicating a notable improvement in conceptual understanding following the intervention. The Wilcoxon Signed-Ranks Test (Table 3.1.2.1) confirmed a statistically significant difference between pretest and posttest scores, $Z = -3.809$, $p < 0.001$, with a large effect size ($r = 0.55$), demonstrating substantial educational impact. These findings suggest that the microscale gas diffusion experiment is an effective pedagogical approach for teaching Graham's Law in senior high school chemistry.

In addition to cognitive gains, the intervention also enhanced students' motivation. As shown in Figure 3.2.1, overall motivation was notably high ($M = 3.30$, $SD = 0.30$), with learners exhibiting very high intrinsic motivation, perceived value, effort, persistence, and achievement motivation. High scores were also observed in self-efficacy, engagement and safety, and motivation toward microscale chemistry, indicating that the experiment provided a safe and supportive learning environment that encouraged active participation. Notably, engagement and safety motivation were significantly positively correlated with conceptual understanding ($\rho = 0.385$, $p = 0.007$), highlighting the critical role of an engaging, low-risk laboratory setting in fostering both motivation and learning outcomes. Other motivational dimensions, including intrinsic motivation, perceived value, and self-efficacy, showed no significant correlations with conceptual understanding, suggesting that general motivational constructs may not directly predict learning gains in this context.

The observed improvement in conceptual understanding aligns with prior research indicating that microscale, inquiry-based, and contextualized laboratory activities enhance learning more effectively than traditional instruction by reducing procedural complexity while maintaining conceptual rigor (Abdullah et al., 2009; Botella & Ibáñez, 2020). Hands-on microscale experiments support constructivist learning by enabling students to actively observe chemical phenomena, link evidence to theory, and engage with abstract concepts in meaningful ways, resulting in deeper understanding and superior learning outcomes (Oliveira & Bonito, 2023). High levels of engagement and perceived safety are consistent with studies demonstrating that microscale laboratory environments promote intrinsic motivation, perceived value, sustained effort, and focused attention by making chemistry learning relevant and student-centered (Mundy & Nokeri, 2024; Toma, 2021). Furthermore, research indicates that engagement and safety are positively associated with conceptual understanding, reinforcing the efficacy of the microscale gas diffusion experiment as a pedagogical tool for teaching Graham's Law (Kolil et al., 2020; Naibert & Barbera, 2022; Nzomo et al., 2023).

Overall, the findings provide robust evidence that integrating microscale gas diffusion experiments into chemistry instruction enhances both cognitive and affective learning outcomes. The intervention not only significantly improved students' understanding of Graham's Law but also fostered motivation, particularly in dimensions of engagement, safety, intrinsic motivation, and achievement orientation. These results support the continued use of microscale, inquiry-based laboratory strategies as effective and safe pedagogical approaches for teaching abstract chemistry concepts in secondary education.

4. CONCLUSION AND RECOMMENDATION

The microscale gas diffusion experiment is an effective instructional strategy for improving Grade 11 STEM learners' conceptual understanding of Graham's Law. The increase in Mean Percentage Score from pretest to posttest, supported by statistical evidence from the Wilcoxon Signed-Rank Test and a large effect size, indicates that learners significantly improved their understanding after the intervention.

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Learners who participated in the microscale gas diffusion experiment demonstrated high to very high motivation toward learning chemistry. The motivational results suggest that microscale experimentation can support learner interest, perceived value of learning tasks, persistence, and achievement motivation. Although self-efficacy and engagement and safety motivation were slightly lower than other dimensions, they still fell within the high motivation range, indicating an overall positive learning experience.

The engagement and safety motivation appears to be an important factor linked to learners' conceptual understanding within a microscale laboratory context. The significant positive relationship between engagement and safety motivation and conceptual understanding implies that learners' involvement and comfort during laboratory activities may contribute to better learning outcomes. This emphasizes that beyond providing an effective activity, teachers should also ensure that learners feel safe, guided, and engaged during laboratory-based instruction.

Finally, since most motivation dimensions were not significantly correlated with conceptual understanding, it may be inferred that improved test performance is not solely dependent on general motivation levels but may be more directly influenced by the instructional design, clarity of learning tasks, and the learning environment provided during microscale experimentation.

Based on the findings and conclusions, teachers are encouraged to integrate microscale laboratory activities, such as the microscale gas diffusion experiment, as a regular instructional strategy when teaching abstract gas behavior concepts, including diffusion, effusion, and Graham's Law. Lessons should be designed to allow learners to observe, analyze, and explain chemical phenomena through hands-on, guided inquiry, which can enhance conceptual understanding. Clear instructions, structured guide questions, and reflective discussions are recommended to help learners connect their observations to underlying scientific principles.

To strengthen factors shown to influence conceptual understanding, teachers should deliberately promote engagement and safety during laboratory implementation. Strategies may include providing simplified and well-demonstrated procedures, preparing materials in advance, reinforcing safety reminders consistently, and offering supervision and constructive feedback. A safe and supportive laboratory environment can increase learner participation and foster stronger conceptual understanding.

Administrators are advised to support the integration of microscale chemistry by ensuring the availability of materials and providing professional development opportunities for teachers. Microscale approaches reduce chemical use, minimize hazards, and lower costs, making them practical and sustainable for school laboratories. Training programs should focus on microscale laboratory management, safe practices, and strategies for linking microscale observations to conceptual learning objectives.

Future studies are recommended to replicate this research using a true experimental design with control groups to strengthen causal inferences regarding the effects of microscale experimentation. Researchers may also increase sample sizes, extend the duration of interventions, and include delayed posttests to examine long-term retention of conceptual understanding. Given the significant correlation between engagement and safety motivation and learning outcomes, future work could explore additional factors, such as classroom climate, laboratory anxiety, indicators of hands-on engagement, and teacher facilitation styles.

Additionally, researchers should continue validating and refining motivation instruments for broader contexts and consider qualitative data, such as interviews or reflective journals, to capture learners' deeper experiences during microscale laboratory activities. Ongoing readability checks, item analyses, and reliability testing are also recommended to ensure that assessments and questionnaires remain suitable for Grade 11 learners and accurately measure both conceptual understanding and motivation.

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