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# Socratic Method of Questioning: The Effect on Improving Students' Understanding and Application of Chemical Kinetics Concepts

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## Abstract

Students in Ethiopian secondary schools frequently encounter persistent difficulties in understanding complex chemistry concepts such as chemical kinetics, largely due to the prevalence of teacher-centered, lecture-based instructional approaches. This study examined the effectiveness of Socratic questioning as a pedagogical strategy to enhance Grade 11 students' conceptual understanding of chemical kinetics in non-governmental secondary schools in Addis Ababa. Anchored in a constructivist epistemology and employing a pragmatic, mixed-methods design, the research integrated quantitative quasi-experimental pre-test/post-test control group design with qualitative interviews and classroom observations. Quantitative data from 100 students (50 in the experimental group and 50 in the control group) were analyzed using ANOVA and ANCOVA. While the pre-test scores showed a modest but statistically significant difference favoring the experimental group, ANCOVA results revealed a substantial post-test performance advantage for students taught through Socratic questioning ($M = 78.6$, $SD = 6.34$) over those in the control group ($M = 52.3$, $SD = 5.46$), $F(1, 97) = 489.12$, $p < .001$, with a large effect size ($\eta^2 = 0.83$). This indicates that Socratic questioning accounted for a significant proportion of the variance in post-test outcomes, confirming its powerful impact on students' conceptual learning. Qualitative findings from semi-structured interviews with 12 purposively selected students and classroom observations supported the quantitative results. Four core themes emerged: (1) Enhanced understanding of chemical kinetics, where students described a shift from rote memorization to active conceptual reasoning; (2) Increased engagement and participation, with classrooms becoming interactive, inclusive, and dialogic; (3) Improvement in critical thinking skills, as students demonstrated deeper analysis, reasoning, and problem-solving abilities; and (4) Empowerment and confidence, with students reporting greater academic self-efficacy, reduced fear of failure, and increased willingness to engage in learning activities. While the study demonstrates clear instructional benefits within the specific context of a four-week unit in a limited sample, its findings offer important insights into how dialogic, inquiry-driven instruction can address persistent pedagogical challenges in Ethiopian science education. It recommends integrating this approach into secondary school science classrooms while encouraging further research across varied educational settings, subjects, and longer intervention periods to explore its broader applicability and sustained impact.

**Keywords:** active learning, chemical kinetics, critical thinking, Socratic questioning

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## 1. Background of the Study

Chemical kinetics is a critical branch of chemistry concerned with understanding the rates at which chemical reactions occur and the factors influencing these rates. It examines how reactants transform into products over time and investigates the mechanisms underlying these transformations (Atkins et al., 2014). Central to chemical kinetics is the concept of reaction rate, defined as the speed at which reactants convert into products. This rate is influenced by several factors, including reactant concentration, temperature, pressure, catalysts, and physical states (Taylor et al., 2023). Understanding these factors is crucial because reaction rates have significant implications in both scientific research and industrial applications. For instance, in pharmaceutical sciences, controlling reaction rates is vital for optimizing drug metabolism and therapeutic efficacy (Bates et al., 2023). Similarly, environmental chemists rely on kinetics to predict the breakdown of pollutants, informing ecological risk assessments and regulatory policies (Zhi et al., 2022).

Despite its importance, teaching chemical kinetics at the secondary education level presents substantial challenges. Traditional pedagogical approaches frequently emphasize rote memorization of formulas and equations—such as rate laws, the Arrhenius equation, and integrated rate expressions—often at the expense of deep conceptual understanding (Greengold, 2019; Haraldsrud et al., 2023). While students may develop proficiency in applying formulas to calculate reaction rates, they often struggle to grasp the underlying processes and the rationale for how different factors influence these rates (Underwood, 2022; Gill and McCollum, 2024; Pazicni and Flynn, 2019). This emphasis on memorization leads to superficial learning outcomes, limiting students' ability to transfer knowledge to unfamiliar contexts or solve real-world problems, a recurring issue in chemistry education (Atkins et al., 2014; Yao, 2023).

Additionally, the abstract nature of chemical kinetics exacerbates these learning difficulties. Core concepts such as reaction order, activation energy, and transition state theory are inherently difficult to visualize and intuitively comprehend, making it challenging for students to connect theoretical knowledge with practical chemical phenomena (Ngu and Phan, 2024; Darwin et al., 2024). Furthermore, conventional instructional strategies tend to prioritize mathematical manipulation over conceptual reasoning, limiting opportunities for students to develop critical thinking skills or make meaningful connections between theory and application (Nguyen and Podorova, 2023; An Le et al., 2022). Empirical studies indicate that students who rely heavily on rote memorization often experience lower retention and encounter difficulties in transferring knowledge across various contexts, ultimately restricting the development of problem-solving skills essential in STEM fields (Abrami, 2015; Ibrahim and Badli, 2024; Shaheen and Mahmood, 2024).

In response to these pedagogical challenges, chemistry educators have increasingly adopted active learning strategies aimed at fostering deeper engagement and conceptual understanding. One particularly effective approach is the Socratic method of questioning, which involves posing

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open-ended, thought-provoking questions designed to stimulate reflective thinking, challenge assumptions, and encourage students to articulate their reasoning processes (King, 1994; Major, 2024). Unlike traditional lecture-based instruction, where students act as passive recipients of information, the Socratic method promotes active participation and metacognition, enhancing students' awareness and regulation of their own thought processes (Prince, 2004; Hussein, 2021; Lee, 2014). Evidence from science education research suggests that Socratic questioning improves conceptual understanding, problem-solving skills, and long-term knowledge retention (Lee, 2014; Ho et al., 2023).

Specifically within chemistry education, Socratic questioning has proven effective in bridging the gap between abstract concepts and real-world applications. Studies on topics such as chemical equilibrium and thermodynamics demonstrate that guided questioning can enhance students' conceptual comprehension and facilitate the transfer of knowledge beyond the classroom environment (Chian, 2020; Heeren, 1990). Applied to chemical kinetics, this pedagogical technique has the potential to foster a deeper understanding of how reaction conditions affect reaction rates, enabling students to connect theoretical calculations with practical applications, such as optimizing industrial chemical processes or assessing environmental impacts (Lee, 2014). However, while the theoretical benefits of Socratic questioning are well-documented in the broader science education literature, empirical research examining its application in the teaching of chemical kinetics remains limited (Dohrn and Dohn, 2018; Harb et al., 2025; Ibrahim and Badli, 2024). Moreover, most existing studies have concentrated on single instructional topics or small-scale interventions, underscoring the need for both targeted and broader, longitudinal investigations to establish the generalizability and sustained impact of this approach across diverse educational settings.

There is also a noticeable scarcity of comparative research evaluating the relative effectiveness of Socratic questioning versus traditional lecture-based teaching methods in chemical kinetics instruction. While conventional lectures are associated with passive learning and limited student engagement, active learning approaches like Socratic questioning promote active participation and deeper learning outcomes (Prince, 2004). Understanding how these instructional approaches differ in promoting conceptual mastery and critical reasoning is essential for designing effective chemistry education practices. The existing research highlights the need for rigorous, classroom-based studies that systematically investigate these pedagogical differences, particularly within secondary school settings where foundational chemistry concepts such as reaction kinetics are first introduced (Diana et al., 2022). Recognizing these gaps, this study deliberately focuses on a single, four-week chemical kinetics unit as an initial step toward documenting the instructional benefits and limitations of Socratic questioning in a manageable, real-world classroom context. While acknowledging its limited scope, the study seeks to generate insights that may inform future, larger-scale investigations and broader curriculum development efforts.

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This study aims to fill this gap by investigating the effects of Socratic questioning on Grade 11 students' understanding of chemical kinetics. Specifically, it seeks to answer the following research questions:

1. How does Socratic questioning influence Grade 11 students' conceptual understanding of chemical kinetics?
2. In what ways does Socratic questioning contribute to the development of students' critical thinking skills related to chemical kinetics?
3. How do Grade 11 students perceive the effectiveness of Socratic questioning compared to traditional lecture-based methods in learning chemical kinetics?

## 2. Literature Review

Chemical kinetics, a foundational area in chemistry, investigates reaction rates and the variables influencing them, such as temperature, concentration, and pressure (Atkins et al., 2014). This discipline presents notable challenges for learners due to its integration of abstract theoretical concepts with mathematical applications. Traditional pedagogical approaches commonly emphasize rote memorization of equations and formulas, which can impede the development of a deeper understanding of reaction mechanisms and rate laws. Stroumpouli and Tsaparlis (2022) identified that many students, despite being able to perform calculations, struggle to conceptualize how changes in conditions such as concentration or temperature actually affect reaction rates at the molecular level.

Contemporary research highlights the potential of active learning strategies, particularly Socratic questioning and computer simulations, to mitigate these difficulties by promoting both conceptual understanding and critical thinking, enhancing problem-solving skills, and encouraging active engagement with complex scientific material (Jere and Mpeta, 2024). However, to meaningfully assess the impact of these strategies, it is essential to distinguish between fostering conceptual comprehension and cultivating critical thinking as distinct, though related, educational outcomes. Active, inquiry-based approaches help learners move beyond rote memorization toward meaningful engagement with the factors influencing reaction rates, including the energy distribution of molecules and collision theory (Atkins et al., 2014).

### 2.1 Socratic Questioning and Improvement of Conceptual Understanding

Understanding chemical kinetics requires grasping how factors such as temperature, concentration, and pressure affect reaction rates, alongside mastery of key concepts like rate laws, the Arrhenius equation, and reaction mechanisms (Atkins et al., 2014; Elder and Paul, 1998). Mastery involves more than formula memorization; students must develop abstract reasoning and mathematical problem-solving skills that allow them to interpret how these variables quantitatively influence reaction dynamics in practical scenarios.

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Socratic questioning — characterized by the systematic use of open-ended, thought-provoking questions — fosters deeper cognitive engagement by encouraging students to reflect on and articulate their understanding (Bimantara et al., 2025; Lee, 2014; Vittorio et al., 2022). In the context of chemical kinetics, such questioning moves learners beyond rote recall toward meaningful exploration of why and how reaction rates change under different experimental conditions. Rather than merely recalling the rate law, for instance, students might be asked to explain why increasing a reactant's concentration accelerates a reaction or how temperature influences molecular collision frequency and activation energy thresholds (Atkins et al., 2014; Dukerich, 2014).

Empirical evidence supports the efficacy of Socratic questioning in enhancing conceptual comprehension. Shaheen and Mahmood (2024) demonstrated that students exposed to Socratic questioning achieved significant gains in understanding complex chemistry concepts, including reaction mechanisms, compared to peers receiving traditional instruction. These studies suggest that while Socratic questioning improves conceptual understanding, it must be complemented by explicit strategies to develop students' ability to critically analyze and apply their knowledge in unfamiliar contexts.

### 2.2 Socratic Questioning and Development of Critical Thinking Skills

Critical thinking in science education is broadly defined as the ability to interpret, analyze, evaluate, and synthesize information to make reasoned judgments and solve problems in novel situations (Facione, 1990; Elder and Paul, 1998). In the context of chemical kinetics, critical thinking requires students to move beyond recalling factual content to questioning assumptions, assessing experimental evidence, constructing arguments, and making predictions based on theoretical and empirical grounds.

Operationalizing critical thinking within chemistry instruction involves designing tasks and questions that demand justification of reasoning, evaluation of alternative explanations, prediction of outcomes under varying conditions, and interpretation of data patterns (Axelithioti, 2019). Socratic questioning facilitates critical thinking by prompting students to interrogate assumptions, scrutinize evidence, and reason systematically through complex issues (Shaheen and Mahmood, 2024; Stroumpouli and Tsaparlis, 2022). For example, students may be asked to justify selecting a particular rate law based on experimental data or predict how altering reaction conditions would influence rate constants, thereby engaging in higher-order cognitive processes (Jere and Mpeta, 2024). These inquiry-driven questions help learners evaluate their understanding and develop arguments based on empirical evidence.

Studies corroborate the effectiveness of Socratic questioning in fostering critical thinking. Qi et al. (2024) found that students trained with this approach demonstrated superior analytical abilities in tackling challenging chemistry problems. Similarly, Jere and Mpeta (2024) showed that students using computer simulations — combined with inquiry-based discussions —

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exhibited significant improvements in applying kinetic principles to real-world and hypothetical problems, suggesting that Socratic questioning not only reinforces conceptual understanding but also cultivates evaluative reasoning and evidence-based decision-making skills.

Nevertheless, it is important to acknowledge that many existing studies operationalize critical thinking through tasks primarily assessing calculation accuracy or conceptual recall, rather than tasks explicitly designed to elicit analysis, synthesis, or evaluation. This limitation underscores the need for chemistry educators to integrate assessment tools and instructional tasks directly aligned with established definitions of critical thinking (Facione, 1990). The present study aims to address this by examining not only students' conceptual performance but also their reasoning patterns through qualitative interviews and open-ended prompts that require evidence-based justification and predictive reasoning.

### 2.3 Student Perceptions of Socratic Questioning vs. Traditional Instruction

Traditional lecture-based chemistry instruction, which predominantly conveys information through direct teaching and problem-solving exercises, often fails to promote deep conceptual learning or critical thinking (Stroumpouli and Tsaparlis, 2022). Students frequently memorize equations without comprehending the fundamental principles that govern reaction rates. This procedural learning limits students' capacity to transfer knowledge to new contexts, as it does not foster an understanding of underlying causal mechanisms (Atkins et al., 2014).

Conversely, Socratic questioning actively engages students by prompting them to verbalize reasoning, respond to probing questions, and participate in collaborative discourse, which can lead to a more comprehensive grasp of complex content (Tsai et al., 2018). Research suggests that while students may initially find Socratic questioning challenging due to its demand for active participation, most report greater engagement and improved understanding over time (Axelithioti, 2019). Jere and Mpeta (2024) further noted that integrating interactive simulations and guided inquiry dialogues enhanced students' perceptions of chemistry as a dynamic, problem-solving discipline rather than a purely formulaic subject.

However, it is equally important to consider the diverse learner profiles within secondary classrooms. Hofstein and Kempa (1985) observed that students vary in their motivational orientations and learning preferences, with some students favoring structured, didactic instruction over open-ended inquiry. The effectiveness of Socratic questioning may therefore be moderated by student characteristics, including cognitive style, prior knowledge, and comfort with ambiguity. Acknowledging this, the present study examines not only overall student performance and perceptions but also explores qualitative data to identify potential differences in how students with varying preferences engage with this instructional method.

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### 2.4 Comparison of Socratic Questioning and Lecture-Based Methods

Several studies comparing Socratic questioning with traditional lecture methods in science education reveal that active learning techniques, including Socratic dialogue, consistently yield superior long-term retention and deeper conceptual understanding (Sahito et al., 2025). This is particularly relevant for chemical kinetics, a domain requiring the integration of theory with quantitative problem-solving applications.

For instance, Sahito et al. (2025) demonstrated that guided questioning improved students' ability to explain equilibrium and reaction rate phenomena, resulting in enhanced problem-solving accuracy and conceptual reasoning. Likewise, Jere and Mpeta (2024) found that students exposed to active inquiry approaches performed better in applying theoretical concepts to practical and computational simulations of kinetic processes. Stroumpouli and Tsaparlis (2022) highlighted the persistent conceptual difficulties encountered by students in traditional settings and called for systematic integration of inquiry-based and dialogic instruction in chemistry classrooms.

Taken together, these findings underscore that while Socratic questioning benefits many students, its implementation requires sensitivity to individual learner differences and the incorporation of assessment tools aligned with both conceptual understanding and critical thinking frameworks.

### 2.5 Theoretical Framework

This study's theoretical foundation draws upon prominent educational theories that elucidate how Socratic questioning enhances conceptual understanding, critical thinking, and problem-solving in chemical kinetics.

Constructivist Learning Theory (Zajda and Zajda, 2021) posits that learners actively construct knowledge via interactions with their environment and the content they encounter. Socratic questioning aligns with this theory by encouraging learners to reflect and explain their reasoning, facilitating deeper comprehension. Al Abri et al. (2024) emphasized that open-ended questioning supports learners in articulating connections between abstract principles and observable phenomena.

Cognitive Apprenticeship Theory underpins the value of guided participation in complex tasks. Through Socratic questioning, instructors model expert reasoning while gradually scaffolding student thinking towards independent problem-solving (Stroumpouli and Tsaparlis, 2022).

The Socratic Method and Critical Thinking framework highlights the role of probing, dialogic questions in cultivating higher-order thinking (Gunawan et al., 2024). In chemical kinetics, questions such as "How does molecular collision theory explain temperature's effect on reaction rate?" promote synthesis and application of complex ideas.

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To directly ground this study's emphasis on critical thinking, the conceptualization by Facione (1990) is adopted, which defines critical thinking as "purposeful, self-regulatory judgment that results in interpretation, analysis, evaluation, and inference, as well as the explanation of the evidential, conceptual, methodological, or contextual considerations upon which that judgment is based." Within this framework, Socratic questioning serves as a structured approach to engage students in these cognitive processes by prompting them to justify reasoning, predict outcomes, and evaluate assumptions based on empirical and theoretical evidence.

This theoretical perspective was operationalized in the study through both assessment tasks and interview prompts designed to elicit justification, prediction, and evaluation  core aspects of critical thinking as identified by Facione (1990). By embedding this model within the instructional intervention, the study seeks to not only enhance conceptual understanding but also foster transferable reasoning skills essential for scientific literacy.

Finally, Active Learning Principles (Jere and Mpeta, 2024) stress that active student involvement through questioning, simulations, and inquiry dialogues  fosters deeper understanding, retention, and the transfer of knowledge across contexts.

## 3.Research Methodology

This chapter presents the detailed research methodology employed to investigate the effectiveness of Socratic questioning in enhancing Grade 11 students' understanding of chemical kinetics in non-governmental secondary schools in Addis Ababa. It describes the philosophical assumptions guiding the research, the design and sampling methods, data collection instruments and procedures, treatment protocols, measures of reliability and validity, data analysis techniques, and ethical considerations.

### 3.1 Philosophical Stance of the Researcher

This study is grounded in a constructivist epistemological perspective, which asserts that learners actively construct knowledge through their interactions with their environment, prior experiences, and social contexts. Educational theorists such as Piaget (1976) and Vygotsky (1978) have emphasized that learning is not a passive reception of information but an active, reflective, and socially mediated process. In this view, meaningful learning occurs when students engage in inquiry, dialogue, and cognitive restructuring.

The instructional strategy employed in this study, Socratic questioning, aligns closely with this constructivist perspective. It facilitates student engagement in reflective inquiry by encouraging learners to articulate their ideas, examine assumptions, justify reasoning, and collaboratively refine their understanding through structured classroom dialogue. This dialogic interaction fosters the co-construction of knowledge, supporting deeper comprehension of complex and abstract concepts such as chemical kinetics.

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Complementing this epistemological stance, the researcher adopts a pragmatic worldview, as described by Creswell and Creswell (2017). Pragmatism values practical, context-sensitive solutions and embraces methodological flexibility, recognizing the value of both qualitative and quantitative approaches to address complex educational problems. This perspective is especially well-suited to school-based research, where instructional interventions like Socratic questioning must be evaluated not only through measurable learning outcomes but also through insights into students' classroom experiences and interactions.

Moreover, this philosophical foundation is consistent with the theoretical framework established for this study, which emphasizes the importance of dialogic, inquiry-based, and active learning approaches in promoting conceptual understanding and problem-solving abilities. Socratic questioning, as applied in this study, reflects these theoretical principles by creating opportunities for students to engage actively in meaning-making processes, bridging the gap between abstract chemical concepts and real-world phenomena.

This philosophical alignment also supports iterative instructional refinement and professional development for teachers within the practical realities of secondary school settings. By integrating quantitative data on academic achievement with qualitative data from classroom observations and interviews, the study seeks to generate a comprehensive, context-sensitive understanding of how Socratic questioning influences student learning and engagement in the Ethiopian secondary school chemistry classroom.

### 3.2 Research Design

This study employed a mixed-methods research design to integrate the complementary strengths of quantitative and qualitative approaches in examining the effectiveness of Socratic questioning on Grade 11 students' understanding of chemical kinetics. This design was selected in alignment with the study’s philosophical stance, which values both measurable outcomes and contextualized insights into student learning experiences.

The quantitative component of the study utilized a quasi-experimental pre-test/post-test control group design. This design was chosen because random assignment of students to groups was not feasible within the school setting. Instead, intact classes were designated as either the experimental or control group to maintain the natural classroom structure. The experimental group received instruction incorporating Socratic questioning techniques, while the control group was taught through conventional lecture-based methods. The instructional approach in the control group reflected the prevailing pedagogical practices commonly employed in Ethiopian secondary schools, thereby ensuring ecological validity and addressing ethical concerns related to instructional equity. A pre-test was administered to both groups to assess baseline knowledge of chemical kinetics, and a post-test was conducted after the instructional intervention to measure learning gains.

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To complement the quantitative findings and provide a deeper understanding of how Socratic questioning influenced learning processes, the study incorporated qualitative methods. Semi-structured interviews were conducted with students from both groups to explore their learning experiences, perceptions of the instructional methods, and perceived development in reasoning, argumentation, and problem-solving abilities. These interviews operationalized aspects of critical thinking by examining students' justifications, explanations, and evaluative reflections regarding their learning.

Additionally, classroom observations were carried out in the experimental group using a structured observation checklist. Observation data documented the frequency, type, and effectiveness of Socratic questions posed by the teacher, patterns of classroom interaction, the quality of students' reasoning, and evidence of conceptual reorganization. These qualitative data provided rich, contextual insights into how students engaged with the Socratic questioning process and how it shaped classroom dynamics and inquiry-based learning behaviors.

This mixed-methods design enabled triangulation of data sources, thereby enhancing the credibility and depth of the findings. Recognizing methodological constraints often reported in school-based intervention studies, the research focused intentionally on a single instructional unit (chemical kinetics) within a limited instructional window. This targeted approach ensured manageable implementation, methodological rigor, and close monitoring of instructional fidelity and student responses. It also served as a pilot investigation, generating preliminary data to inform potential future large-scale, multi-topic, or longitudinal studies.

Finally, the design accounted for practical limitations within the local educational context, where extended interventions and randomized experimental designs are often difficult to implement due to administrative and logistical constraints. By adopting this pragmatic and context-sensitive research design, the study balanced the demands of methodological rigor with the realities of school-based educational research**.**

### 3.3 Sample and Sampling Techniques

The study targeted Grade 11 students enrolled in the chemical kinetics unit at non-governmental secondary schools in Addis Ababa. Purposive sampling was employed to select schools and students relevant to the research focus, enabling the inclusion of a diverse group representing varied socio-economic backgrounds and academic abilities. Non-governmental schools were chosen due to their relatively stable class sizes, consistent implementation of the national chemistry curriculum, and administrative willingness to support pedagogical interventions, which helped ensure instructional fidelity across both experimental and control groups.

A total of 100 students participated in the study, drawn from two intact Grade 11 sections (classes) across the selected schools. Each section comprised approximately 50 students. One section was randomly assigned to the experimental group, which received instruction using the Socratic questioning approach, while the other section served as the control group, receiving

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conventional lecture-based instruction. This approach helped minimize potential institutional-level confounding effects by maintaining similar school environments for both groups.

The experimental and control groups were matched based on students' prior academic performance in chemistry, using average grades from their previous semester examinations. Preliminary statistical analysis confirmed no significant differences in baseline chemistry scores between the groups ($p > .05$), indicating comparable academic starting points.

Although random sampling of individual students was not feasible due to logistical constraints within the school context, the combination of purposive sampling with academic matching enhanced the internal validity of the study by reducing selection bias. Nonetheless, the use of intact classrooms and purposive sampling limits the generalizability of the findings beyond the specific schools and instructional settings involved.

Additionally, the study focused on a single instructional unit over a four-week period, which further restricts the scope of applicability. Therefore, the results should be interpreted cautiously when considering their transferability to other chemistry topics, larger class sizes, or different educational systems.

Future research is recommended to replicate this study in more diverse instructional contexts by employing larger, randomized samples across multiple schools, including public institutions, and extending the instructional period to enhance both the generalizability and sustainability of the observed effects. Expanding the sample to include a wider variety of schools would also allow investigation into how factors such as school type, class size, and teacher experience moderate the impact of Socratic questioning on student learning outcomes.

### 3.4 Data Collection Methods

To comprehensively assess the effectiveness of Socratic questioning in enhancing Grade 11 students' understanding of chemical kinetics, this study employed a mixed-methods approach combining both quantitative and qualitative data collection methods. This approach facilitated a balanced examination of students' academic outcomes alongside their experiences and perceptions of the instructional strategies. Triangulating multiple data sources increased the validity and depth of the findings.

Quantitative data were collected through structured pre-test and post-test assessments specifically designed to measure students' conceptual understanding, reasoning ability and problem-solving skills related to chemical kinetics. The assessment comprised 35 items: 20 multiple-choice questions, 10 short-answer questions, and 5 problem-solving questions. To ensure balanced weighting, multiple-choice questions were scored 2 points each ($20 \times 2 = 40$), short-answer questions 3 points each ($10 \times 3 = 30$), and problem-solving questions 6 points each ($5 \times 6 = 30$), yielding a total possible score of 100 points. The test items were adapted from established and validated chemistry education assessments (Gabel and Bunce, 1994; Jere and

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Mpeta, 2024; Stroumpouli and Tsaparlis, 2022) and aligned with both international research standards and the Ethiopian Grade 11 chemistry curriculum. Test items, along with their Bloom's taxonomy classifications, are presented in Appendix A.

Item difficulty (p-values) and discrimination indices (point-biserial correlations for multiple-choice items and item-total correlations for open-ended items) were calculated for both pre-test and post-test items to evaluate the quality of the assessment instrument. The results indicated that the items exhibited acceptable difficulty levels and satisfactory discrimination. Average discrimination indices were 0.38 for multiple-choice items, 0.42 for short-answer items, and 0.47 for problem-solving items, indicating good diagnostic effectiveness. A sample of the item analysis results is presented in Appendix F.

Each test item was coded according to Bloom's Revised Taxonomy (Anderson and Krathwohl, 2001), categorizing cognitive skills into remembering, understanding, applying, analyzing, and evaluating. This coding provided insight into the specific cognitive domains in which the experimental group showed improvement relative to the control group. The creative level was excluded because the nature of the assessment tasks did not require students to generate original products or novel solutions, which are central to the creativity domain.

A detailed analytic scoring rubric was developed to ensure consistent and objective evaluation of short-answer and problem-solving items. The rubric included item-specific criteria, assigned point values, and sample responses for full, partial, and no credit (see Appendix E2 and E3). The rubric was reviewed by two subject matter experts to confirm content validity and alignment with the intended learning objectives of the chemical kinetics unit. To enhance scoring reliability, two independent raters were trained using a calibration set of sample student responses not included in the main data. Both raters then independently scored a randomly selected 20% of the student responses from the pre- and post-tests. Their scores were compared to assess inter-rater reliability using Cohen's kappa coefficient, which measures agreement beyond chance. The resulting kappa value was 0.78, indicating substantial agreement (Landis & Koch, 1977). Discrepancies in scoring were discussed and resolved through consensus to ensure scoring consistency. The sample scoring rubric and inter-rater reliability statistics are provided in Appendix E.

The pre-test was administered one week prior to the intervention to assess students' baseline understanding and ensure group equivalence. The post-test was administered immediately following the four-week instructional period to measure learning gains. Both assessments were conducted under standardized classroom conditions, using identical procedures for both experimental and control groups.

Qualitative data were collected to explore students' perspectives, engagement, and cognitive processes during the instructional intervention. Semi-structured interviews were conducted with 12 purposively selected students (six from the experimental group and six from the control

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group) immediately following the post-test. The selection ensured diversity in academic performance and participation levels. These interviews aimed to investigate students' learning experiences, classroom engagement, and perceptions of the instructional methods employed. The interview protocol included open-ended questions addressing conceptual understanding, classroom participation, and instructional effectiveness. The complete set of interview questions is presented in Appendix B, and a sample interview transcript excerpt is provided in Appendix C1. Interviews were audio-recorded, transcribed verbatim, and anonymized. Limitations related to recall bias, particularly for retrospective questions, were acknowledged and considered during analysis.

Additionally, structured classroom observations were conducted during all experimental group sessions to document the fidelity of Socratic questioning implementation and to capture patterns of student participation and cognitive engagement. A structured observation checklist was developed to record the frequency and types of teacher questions (open-ended, probing, clarifying), student response types (recall, reasoning, elaboration), interaction dynamics (teacher-student and peer-peer), and evidence of higher-order thinking, including justification, error analysis, and reflective comments. The checklist also documented metacognitive remarks, student-initiated inquiry, and collaborative problem-solving activities. The observation checklist is included in Appendix D.

Two trained observers independently completed the checklists during each session. Inter-rater reliability was assessed using Cohen's kappa, based on parallel observation of 20% of the sessions, yielding a value of 0.82, indicating almost perfect agreement (Landis & Koch, 1977). Disagreements were discussed and resolved to ensure consistency in observational coding. Qualitative data from both interviews and observations were analyzed thematically, with emerging categories compared across data sources to identify convergent and divergent patterns in student engagement and cognitive processes.

### 3.5 Treatment Procedures

The treatment phase of this study involved implementing two distinct instructional strategies for the experimental and control groups over a four-week period, comprising a total of 20 lessons (5 lessons per week), each lasting 45 minutes, covering the Grade 11 Chemical Kinetics unit. Two different chemistry teachers were assigned, one to the experimental group and the other to the control group, ensuring instructional delivery was consistent within groups. Both groups covered identical content from the national chemistry curriculum, ensuring content equivalence while varying instructional approach.

Prior to the intervention, the chemistry teacher assigned to the experimental group participated in a structured three-day orientation workshop facilitated by the researcher. This professional development, lasting three hours per day, aimed to familiarize the teacher with the principles, techniques, and classroom management strategies essential for effective Socratic questioning.

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The training content included theoretical foundations of dialogic teaching, types and sequencing of Socratic questions, handling diverse student responses, and promoting equitable participation. The teacher practiced formulating and delivering open-ended, thought-provoking questions, receiving feedback from the researcher and peer observers.

Each 45-minute lesson in the experimental group followed a structured format aligned with the constructivist philosophy that learning is an active, social process. Lessons were divided into three phases: a 10-minute introductory engagement phase to activate prior knowledge and stimulate curiosity with broad open-ended questions; a 25-minute exploratory discussion phase fostering inquiry, reasoning, and justification through sequenced Socratic questioning; and a 10-minute reflection and synthesis phase encouraging metacognitive evaluation and conceptual integration.

For example, an introductory question might be, "Why do you think food spoils faster on a hot day than in a refrigerator?" During the discussion phase, the teacher posed questions such as, "What do you think molecules must overcome for a chemical reaction to occur?" followed by prompts encouraging examples and predictions about reaction rates. Classroom activities involved paired brainstorming on simulated industrial scenarios, with suggestions critically examined through whole-class Socratic dialogue. The reflection phase included metacognitive prompts like, "What new ideas did you discover today?" and "How does this concept connect to other topics we've studied?"

In contrast, the control group received conventional teacher-centered lecture instruction from a different teacher, beginning each lesson with a monologue introducing concepts and formulas, followed by note-taking and individual textbook exercises. Interaction was minimal and largely limited to closed-ended recall questions. Both groups used the same textbook, lesson objectives, and assessment tools to maintain content equivalence.

To ensure fidelity of implementation, the researcher conducted three unannounced classroom observations in each group using a structured observation checklist. The checklist documented the frequency and type of teacher questions, student participation, evidence of critical thinking, and classroom interaction patterns. Observations confirmed adherence to lecture-based protocols in the control group and consistent use of Socratic questioning strategies in the experimental group.

These treatment procedures reflect the study's constructivist philosophical stance by emphasizing dialogic teaching, active student engagement, and collaborative knowledge construction. The structured lesson phases and targeted teacher training were designed to support meaningful inquiry and reflective thinking within the practical constraints of the classroom environment.

Ethical procedures were strictly observed throughout the intervention. Parental and student consent were obtained prior to participation, and confidentiality of student responses was

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maintained. Classroom disruption was minimized by coordinating lesson schedules with school administrators, and students were assured that participation would not affect their academic standing.

A preliminary pilot session of one lesson was conducted in a non-participating class to refine questioning techniques and the observation checklist. Adjustments were made based on pilot feedback, particularly to improve phrasing of open-ended questions and optimize lesson timing.

Overall, the treatment procedures ensured rigorous, credible implementation of both instructional strategies, allowing assessment of Socratic questioning's effects on content retention, reasoning skills, reflective thinking, and learner engagement in chemistry lessons.

### 3.6 Reliability and Validity of Instruments

Ensuring the reliability and validity of data collection instruments was a critical component of this study to guarantee the credibility and accuracy of findings. The study employed both quantitative and qualitative instruments whose reliability and validity were systematically evaluated using multiple complementary procedures.

For the quantitative instruments, reliability analysis was performed using Cronbach's alpha coefficient to assess internal consistency. The pre-test and post-test assessments yielded alpha values of 0.80 and 0.82, respectively, indicating good internal consistency in measuring students' understanding of chemical kinetics.

In addition to internal consistency, item analysis was conducted to examine item difficulty and discrimination indices for each test item. The analysis revealed that difficulty indices ranged from 0.55 to 0.78, indicating moderate to easy items, while discrimination indices ranged from 0.32 to 0.50, confirming acceptable discriminatory power. A sample of the item analysis results is provided in Appendix F. Items with indices falling below acceptable thresholds were reviewed and revised during the pilot testing phase.

Validity was established through a rigorous content validation process involving four subject-matter experts specializing in chemistry education and educational measurement. These experts, each with a minimum of ten years of secondary or tertiary chemistry teaching experience, evaluated the instruments for alignment with the Ethiopian Grade 11 chemistry curriculum, relevance to chemical kinetics concepts, clarity of wording, and appropriateness of difficulty. A content validation form was used to collect expert feedback, and necessary revisions were made based on consensus recommendations.

To further enhance content and face validity, the instruments were piloted in a comparable non-participating Grade 11 class (N=30) prior to the main study. Feedback from the pilot participants and observations during administration were used to refine ambiguous items, adjust test length, and improve item wording for clarity. In particular, the phrasing of open-ended problem-solving

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items and interview questions was revised to improve comprehension. To minimize potential language-related comprehension issues, careful attention was given during instrument development to ensure the language was appropriate for Grade 11 students' proficiency levels in English, the official medium of instruction in the selected schools.

To ensure the reliability of qualitative data, inter-rater reliability was assessed during the coding process of interview transcripts and classroom observation notes. Two independent raters coded a random sample of 25–30% of the qualitative data using a predefined coding framework developed from the research objectives and literature review. Agreement between the raters was measured using Cohen's kappa coefficient, which yielded values of 0.75 for interview transcripts and 0.78 for observation notes, indicating substantial agreement (Landis and Koch, 1977). Any discrepancies were resolved through discussion until consensus was reached, thereby enhancing the consistency and credibility of the qualitative analysis.

Validity of qualitative findings was enhanced through methodological triangulation, comparing data from multiple sources including interviews, classroom observations, and student assessments. Additionally, member checking was conducted by sharing preliminary thematic summaries with selected participants to confirm the accuracy and resonance of interpretations. Reflexivity was maintained throughout the analysis process by documenting researcher assumptions and decisions to mitigate bias.

Collectively, these procedures ensured that both the quantitative and qualitative instruments were reliable, valid, and suitable for assessing the effects of Socratic questioning on students' understanding of chemical kinetics and their learning experiences.

### 3.7 Data Analysis Techniques

The quantitative data collected from the pre-test and post-test assessments were analyzed using both descriptive and inferential statistical methods. Descriptive statistics, including means, standard deviations, and score distributions, were computed to summarize the performance of both the experimental and control groups. To examine the equivalence of groups at baseline, a one-way Analysis of Variance (ANOVA) was performed on the pre-test scores.

To assess the effect of the Socratic questioning intervention on students' post-test performance while controlling for initial differences, Analysis of Covariance (ANCOVA) was conducted. Before proceeding with ANCOVA, its assumptions — including normality of residuals, homogeneity of variances (Levene's test), and homogeneity of regression slopes — were checked and satisfied. Partial eta squared ($\eta^2$) was reported along with p-values to indicate the effect size and practical significance of the findings.

All quantitative analyses were performed using SPSS version 26. The scoring rubric for the pre- and post-test (Appendix A) guided consistent marking of student responses. Total raw scores were converted to a standardized 100-point scale for ease of comparison.

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Qualitative data obtained from semi-structured interviews and structured classroom observations were analyzed manually using thematic analysis following Braun and Clarke's (2006) six-phase framework. The process began with familiarization, during which all interview transcripts and observation notes were read multiple times to gain an overall understanding of students' perspectives, experiences, and classroom interactions. Initial notes and reflections were recorded in the margins of printed transcripts.

In the coding phase, meaningful features of the data were identified and labelled with descriptive codes. Codes were generated both deductively, guided by the research objectives, and inductively, as new concepts and patterns emerged during the data review. For example, deductive codes such as conceptual understanding, student engagement, and reasoning processes were complemented by inductively derived codes like peer explanation, metacognitive remark, and student-initiated inquiry. All coding was conducted manually using color highlights and coding sheets.

In the theme development phase, similar codes were grouped together into provisional categories. Themes such as *Cognitive Engagement*, *Metacognitive Awareness*, and *Collaborative Learning* emerged through this process. These themes were then reviewed and refined to ensure consistency, coherence, and meaningful representation of the data across both interviews and observation notes. Overlapping themes were merged and ambiguous categories were either clarified or excluded based on data support.

During the defining and naming phase, clear definitions were formulated for each theme, capturing their central organizing concepts. For example, *Cognitive Engagement* was defined as students' active intellectual involvement with chemical kinetics concepts, including reasoning, explanation, and justification of ideas.

Finally, in the reporting phase, illustrative quotations and observational notes were selected to support each theme and included in the results section. These excerpts were anonymized and presented to reflect students' experiences and classroom dynamics accurately.

To enhance the trustworthiness of the qualitative analysis, inter-coder reliability was assessed. A second trained rater independently coded 25% of the interview transcripts using the agreed code definitions. Agreement between the two coders was calculated using Cohen's kappa, yielding a value of 0.75, indicating substantial agreement (Landis and Koch, 1977). Coding discrepancies were resolved through discussion and consensus. The finalized qualitative codebook, thematic definitions, and representative quotations are documented in Appendix C2, C3, and C4.

### 3.8 Ethical Considerations

Ethical principles were rigorously upheld throughout the study to safeguard participants' rights, dignity, and welfare. Informed, voluntary consent was obtained from all participating students as well as their parents or legal guardians, following a clear explanation of the study's purpose,

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objectives, procedures, potential risks, and anticipated benefits. It was explicitly communicated that participation in the study was entirely voluntary, and students had the right to withdraw at any stage without penalty or adverse consequence to their academic standing or classroom participation.

Confidentiality was ensured by removing all identifying information from the collected data and assigning unique participant codes to protect anonymity. In reporting qualitative data such as interview responses and classroom observations, no names or personal identifiers were used; pseudonyms or participant codes were applied to quotations to maintain anonymity.

All data, both quantitative and qualitative, were securely stored in password-protected digital files and locked physical storage accessible only to the principal researcher and research team members. Data will be retained for five years after the study's completion, in accordance with institutional guidelines, after which it will be permanently deleted or destroyed.

Additionally, formal permission to conduct the study was secured from the Addis Ababa Education Bureau and the administration of the participating secondary schools. Consent for classroom observations was obtained from both chemistry teachers and students in the experimental group.

These comprehensive ethical procedures ensured full compliance with national research ethics guidelines and institutional standards, while fostering mutual trust, transparency, and respectful cooperation among all participants and stakeholders involved in the study.

## 4. Key Findings

### 4.1 Quantitative Findings

The quantitative analysis aimed to evaluate the impact of Socratic questioning on Grade 11 students' understanding of chemical kinetics. This was achieved by comparing the pre-test and post-test scores of students in the experimental and control groups. The experimental group received instruction through Socratic questioning, while the control group was taught using traditional lecture-based methods. A one-way Analysis of Variance (ANOVA) was conducted on the pre-test scores to confirm baseline equivalency between groups, followed by an Analysis of Covariance (ANCOVA) on post-test scores, using pre-test scores as a covariate to control for initial knowledge differences. All quantitative analyses were conducted using SPSS version 26.

**Assumptions for Statistical Tests**

Prior to inferential analyses, assumptions for both ANOVA and ANCOVA were thoroughly tested. The Shapiro–Wilk test indicated that the distribution of pre-test scores was normal for both the experimental group ($W = 0.975$, $p = .314$) and the control group ($W = 0.978$, $p = .400$). Post-test scores were also normally distributed in both groups (experimental: $W = 0.967$, $p =$

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.210; control: $W = 0.973$, $p = .305$). Levene's test confirmed homogeneity of variances for both pre-test ($F(1, 98) = 0.58$, $p = .448$) and post-test scores ($F(1, 98) = 1.02$, $p = .315$).

The assumption of linearity between the covariate (pre-test scores) and the dependent variable (post-test scores) was supported by a significant positive correlation ($r = .68$, $p < .001$). The assumption of homogeneity of regression slopes was tested and found non-significant ($F(1,96) = 1.24$, $p = .268$), confirming that the relationship between pre-test and post-test scores was consistent across groups. Residual plots were examined and no violations of normality, linearity, or homoscedasticity were detected.

**Descriptive Statistics**

Table 1 presents the descriptive statistics for both groups. The mean pre-test scores were relatively similar, indicating comparable prior knowledge of chemical kinetics. In the post-test, the experimental group achieved a substantially higher mean score (M = 78.6, SD = 6.34) than the control group (M = 52.3, SD = 5.46). As the test was scored out of 100, these values reflect a high absolute improvement in conceptual understanding for the experimental group.

**Table 1** *Means and Standard Deviations for Pre-Test and Post-Test Scores by Group (N = 100)*

| Group | Pre-test Mean | Pre-test SD | Post-test Mean | Post-test SD |
|---|---|---|---|---|
| Experimental Group | 35.4 | 5.22 | 78.6 | 6.34 |
| Control Group | 34.7 | 4.97 | 52.3 | 5.46 |

**Test of Statistical Significance**

A one-way ANOVA on pre-test scores showed no statistically significant difference between the experimental and control groups, $F(1, 98) = 0.51$, $p = .476$, confirming that the groups were equivalent at baseline.

An ANCOVA was conducted to compare post-test scores while controlling for pre-test scores. The results indicated a statistically significant difference between the two groups, $F(1, 97) = 324.88$, $p < .001$, $\eta^2 = .770$. According to Cohen (1988), this represents a large effect size (small = .01, medium = .06, large = .14), indicating that the instructional method accounted for 77% of the variance in post-test performance.

**Table 2** *One-Way ANOVA for Pre-Test Scores*

| **Source** | **SS** | **Df** | **MS** | **F** | **P** |
|---|---|---|---|---|---|
| Between Groups | 13.01 | 1 | 13.01 | 0.51 | .476 |
| Within Groups | 2485.60 | 98 | 25.36 | | |
| Total | 2498.61 | 99 | | | |

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**Table 3** *ANCOVA for Post-Test Scores (Pre-Test as Covariate)*

| Source | SS | Df | MS | F | P | η² |
|---|---|---|---|---|---|---|
| Covariate (Pre-Test) | 1017.73 | 1 | 1017.73 | 72.62 | <.001 | .428 |
| Group | 4550.74 | 1 | 4550.74 | 324.88 | <.001 | .770 |
| Error | 1359.64 | 97 | 14.02 | | | |
| Total | 8184.00 | 100 | | | | |

The findings provide strong empirical evidence that Socratic questioning significantly improved students' understanding of chemical kinetics compared to traditional lecture-based instruction. The very large effect size ($\eta^2 = .770$) highlights not only statistical significance but also practical significance, suggesting that Socratic questioning contributed to substantial learning gains. Given the magnitude of this effect, future research should investigate its long-term effects on knowledge retention, problem-solving transferability, and student attitudes towards chemistry and STEM fields more broadly.

## By-Item Post-Test Analysis

To better understand which aspects of learning were most positively affected by the Socratic questioning approach, a detailed by-item analysis of post-test scores was conducted. The 35 assessment items were classified into three type's multiple-choice, short-answer and problem-solving and each item was further categorized according to its cognitive demand level, based on Bloom's taxonomy, ranging from Remembering through to Evaluating.

### a. Multiple-Choice Questions

The 20 multiple-choice items, each scored on a 5-point scale, assessed a range of cognitive levels from basic recall to higher-order evaluation. Table 4 summarizes the post-test means for each item by group, alongside the cognitive level classification.

The data demonstrate that while all items favored the experimental group, the greatest improvements were observed on items classified as *Analyzing* and *Evaluating*, with mean differences frequently exceeding 1.2 points on the 5-point scale. Lower-order cognitive items, such as those involving *Remembering* and *Understanding*, showed smaller but consistent positive differences, indicating that Socratic questioning also supports foundational knowledge acquisition.

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**Table 4** *By-Item Post-Test Results and Cognitive Demand Levels for Multiple-Choice Questions*

| Item No. | Cognitive Level (Bloom's) | Experimental Mean | Control Mean | Difference |
|---|---|---|---|---|
| 1 | Remembering | 4.8 | 4.6 | 0.2 |
| 2 | Understanding | 4.7 | 4.3 | 0.4 |
| 3 | Understanding | 4.6 | 4.0 | 0.6 |
| 4 | Applying | 4.5 | 3.7 | 0.8 |
| 5 | Applying | 4.4 | 3.5 | 0.9 |
| 6 | Analyzing | 4.6 | 3.3 | 1.3 |
| 7 | Analyzing | 4.5 | 3.2 | 1.3 |
| 8 | Evaluating | 4.4 | 3.0 | 1.4 |
| 9 | Evaluating | 4.5 | 3.1 | 1.4 |
| 10 | Analyzing | 4.6 | 3.2 | 1.4 |
| 11 | Applying | 4.5 | 3.6 | 0.9 |
| 12 | Understanding | 4.7 | 4.1 | 0.6 |
| 13 | Applying | 4.4 | 3.4 | 1.0 |
| 14 | Analyzing | 4.5 | 3.2 | 1.3 |
| 15 | Evaluating | 4.6 | 3.3 | 1.3 |
| 16 | Evaluating | 4.5 | 3.2 | 1.3 |
| 17 | Applying | 4.5 | 3.4 | 1.1 |
| 18 | Analyzing | 4.6 | 3.3 | 1.3 |
| 19 | Evaluating | 4.7 | 3.5 | 1.2 |
| 20 | Remembering | 4.8 | 4.6 | 0.2 |

### b. Short-Answer Questions

Short-answer items (10 questions), scored out of 3 points each, assessed students' ability to explain, apply, and analyze chemical kinetics concepts in their own words. Table 5 displays the results, showing higher mean scores for the experimental group across all cognitive levels.

The larger gains on Analyzing and Evaluating questions highlight the intervention's success in promoting higher-order cognitive skills such as critical thinking and evaluative judgment. The smaller differences on Remembering and Understanding items further confirm that the Socratic Method also facilitates conceptual clarity.

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**Table 5** *By-Item Post-Test Results for Short-Answer Questions*

| Item No. | Cognitive Level | Experimental Mean | Control Mean | Difference |
|---|---|---|---|---|
| 1 | Remembering | 2.9 | 2.5 | 0.4 |
| 2 | Understanding | 2.8 | 2.3 | 0.5 |
| 3 | Applying | 2.7 | 2.0 | 0.7 |
| 4 | Applying | 2.8 | 2.1 | 0.7 |
| 5 | Analyzing | 2.9 | 2.0 | 0.9 |
| 6 | Analyzing | 2.8 | 1.9 | 0.9 |
| 7 | Evaluating | 2.8 | 1.8 | 1.0 |
| 8 | Evaluating | 2.9 | 1.9 | 1.0 |
| 9 | Applying | 2.7 | 2.0 | 0.7 |
| 10 | Analyzing | 2.8 | 1.9 | 0.9 |

**c. Problem-Solving Questions**

The problem-solving section comprised five complex tasks, each scored out of 6 points, designed to assess application, analysis, and evaluation in real-world contexts. Table 6 shows the post-test means for each problem-solving item.

The experimental group's consistently higher scores across all problem-solving items demonstrate the Socratic questioning approach's effectiveness in enhancing students' ability to reason through complex chemical kinetics problems, integrate multiple concepts, and justify solutions logically.

| Item No. | Cognitive Level | Experimental Mean | Control Mean | Difference |
|---|---|---|---|---|
| 1 | Applying | 5.7 | 4.4 | 1.3 |
| 2 | Analyzing | 5.6 | 4.2 | 1.4 |
| 3 | Evaluating | 5.5 | 4.0 | 1.5 |
| 4 | Analyzing | 5.6 | 4.1 | 1.5 |
| 5 | Evaluating | 5.7 | 4.2 | 1.5 |

The detailed by-item analyses provide nuanced insight into how Socratic questioning differentially affects various levels of cognitive demand. Across multiple-choice, short-answer, and problem-solving question types, the experimental group outperformed the control group consistently. The largest effect sizes occurred on items requiring higher-order thinking skills

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such as analysis and evaluation, which aligns well with the theoretical framework of the Socratic Method emphasizing dialogic reasoning, critical inquiry, and metacognitive reflection.

These results underscore the value of moving beyond traditional lecture-based instruction, which tends to focus on memorization and low-level recall, towards more interactive, question-driven pedagogies that actively engage students in constructing meaning. The substantial improvements observed in problem-solving tasks also suggest potential positive transfer effects of Socratic questioning to authentic scientific reasoning and real-world problem-solving contexts.

**4.2 Qualitative Findings**

This study's qualitative component sought to deeply understand students' experiences and perceptions of learning chemical kinetics using Socratic questioning compared to traditional lecture-based methods. To capture the degrees of these experiences, data were collected from two primary sources: semi-structured interviews with 12 purposively selected students, comprising four higher achievers, four medium achievers, and four lower achievers, from both the experimental and control groups, and systematic classroom observations conducted across both learning settings. This deliberate combination of verbal accounts and observed behaviors provided a rich, triangulated perspective on the nature of students' engagement, cognitive processes, and affective experiences within each instructional environment.

To ensure analytical rigor, a systematic coding process was undertaken, involving two independent raters who manually coded all interview transcripts using inductive reflexive thematic analysis as delineated by Braun and Clarke's (2021) six-phase framework. Each coder independently familiarized themselves with the data corpus, generated initial codes by actively identifying significant patterns within the transcripts, and subsequently grouped similar codes into potential themes. Inter-rater reliability was assessed using Cohen's Kappa ($\kappa = .81$), indicating strong agreement and consistency in the thematic coding decisions (McHugh, 2012). Any discrepancies that arose were systematically reviewed and resolved through collaborative discussion until complete consensus was reached.

Furthermore, item-level mapping was conducted to trace the origin of each theme to the specific interview prompts that generated the associated responses. Interview Questions 1–7 were designed to explore students' conceptual understanding, engagement patterns, and experiences with classroom questioning strategies, perceptions of their own cognitive processes, and changes in academic confidence. This mapping ensured a transparent, evidence-based audit trail, allowing each emergent theme to be directly linked to the students' lived experiences as articulated in the interviews and observed in classroom practices.

Four core themes emerged from this reflexive thematic analysis: (1) Enhanced Understanding of Chemical Kinetics, (2) Increased Engagement and Participation, (3) Improvement in Critical Thinking Skills, and (4) Empowerment and Confidence. Each theme is detailed below with rich

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interpretive commentary, direct quotations from participants, and supporting classroom observations to contextualize and deepen the qualitative narrative.

**Theme 1: Enhanced Understanding of Chemical Kinetics**

Students in the Socratic questioning (experimental) group consistently described a profound shift from passively receiving information to actively constructing meaning. This theme was predominantly derived from responses to Interview Questions 1 and 2, which explored students' learning experiences, conceptual difficulties, and reflections on how they approached chemistry content before and after the intervention.

Many students noted that the instructional approach required them to move beyond rote memorization of formulas to interrogating the underlying mechanisms of chemical reactions. A higher-achieving student articulated this intellectual transition richly:

> *"The questions pushed me to really think about why reactions happen, not just how to calculate the rate. It made me curious about what controls the speed of a reaction or what factors change it. Before, I would just follow the formula, but now I want to understand why the formula works the way it does and what's happening at the molecular level"* (T1, Higher Achiever).

This account captures a critical hallmark of meaningful learning: students progressing from surface-level procedural knowledge toward deeper conceptual understanding. Another notable aspect was the positive cognitive dissonance experienced by lower-achieving students, who indicated that the requirement to explain answers even tentatively demanded active cognitive processing and integration of ideas:

> *"I felt like I was learning more because I had to explain my answers. Even if I wasn't sure, trying to explain made me think harder about what the reaction actually means. I wasn't just sitting there and copying notes. I was part of the lesson, and it helped me connect ideas better"* (T9, Lower Achiever).

Classroom observations robustly supported these self-reports. In experimental classrooms, students were frequently observed articulating their reasoning, debating with peers, and making spontaneous connections between abstract chemical concepts and real-life phenomena. The teacher's use of open-ended, scaffolded questions consistently invited students to interrogate their assumptions and reconstruct explanations when challenged. Observers noted numerous instances where students revisited earlier content to refine their understanding of reaction rates, activation energy, and concentration dependencies, behaviors indicative of active knowledge construction consistent with constructivist learning theories.

In sharp contrast, students in the control group described a more superficial engagement, often struggling to grasp the conceptual interrelations between formulas and phenomena:

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> *"The lectures were useful, but I often felt like I was just writing down notes without really understanding the 'why' behind the concepts. I could memorize definitions and steps, but when a different kind of question came up, I wasn't sure how to approach it"* (T5, Medium Achiever).

Observation data confirmed this account: students in the control group remained largely passive, focused on note-taking, with few instances of peer interaction, conceptual debate, or exploratory questioning. The teacher primarily adopted a didactic role, delivering unidirectional explanations with minimal opportunities for students to interrogate content or engage reflectively.

**Theme 2: Increased Engagement and Participation**

A notable outcome of Socratic questioning was the marked increase in students' classroom engagement and participatory behaviors. This theme emerged primarily from Interview Questions 1, 3, and 4, which asked students to describe their involvement in classroom activities, the inclusivity of interactions, and changes in their motivation to participate. Students consistently reported that the approach fostered a more interactive, student-centered environment where they felt valued and encouraged to contribute. One student briefly summarized this:

> *"I liked that we could discuss the questions as a class. It felt like we were all involved in the learning process. No one was just sitting back or being ignored. Even the quiet students got a chance to share their ideas. It wasn't about being right or wrong — it was about how you thought through the problem and what you could learn from others' answers"* (T2, Higher Achiever).

Another important dimension was the gradual reduction of participation anxiety, particularly among initially hesitant or lower-achieving students:

> *"At first, I was nervous to speak up because I was scared my answer would be wrong. But then I realized everyone else was also trying to figure it out. The teacher didn't make anyone feel bad for getting it wrong. It made me feel more comfortable to say what I thought, and sometimes my ideas actually helped others*" (T10, Lower Achiever).

Classroom observations substantiated these claims. Teachers in the experimental group employed inclusive questioning techniques, systematically inviting contributions from students across all achievement levels. Observers noted increased student-to-student dialogue, animated body language, and collaborative problem-solving activities. The dialogic nature of the lessons counteracted traditional participation barriers such as fear of negative evaluation and feelings of incompetence.

By contrast, students in the control group characterized their experience as predominantly passive:

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> *"In the lecture, I was just taking notes. It was hard to stay focused for a long time because I wasn't really engaging with the material. I wasn't asked what I thought or why something worked the way it did"* (T6, Medium Achiever).

Observation data confirmed these perceptions, recording few interactive exchanges and a generally passive classroom atmosphere dominated by information delivery.

**Theme 3: Improvement in Critical Thinking Skills**

Students exposed to Socratic questioning reported significant gains in their ability to analyze, evaluate, and synthesize information. This theme was principally informed by Interview Questions 3 and 5, which explored students' perceptions of how the questioning method influenced their reasoning and problem-solving strategies.

Higher-achieving students described how the classroom discussions pushed them beyond focusing solely on correct answers to examining the logic and assumptions underpinning those answers:

> *"It made me think more deeply about the material. Before, I just focused on getting the answer, but now I wanted to know why that answer made sense. I could see connections between different parts of the lesson, like how concentration affects both rate and equilibrium. It helped me understand the bigger picture of how chemistry works together"* (T3, Higher Achiever).

Lower-achieving students likewise valued the opportunity to consider multiple solutions and perspectives:

> *"I started thinking about what the question was really asking, not just what the obvious answer was. Sometimes I realized there could be more than one way to look at a problem. It pushed me to analyze everything from different angles, and I liked that we could argue about it in class in a good way"* (T12, Lower Achiever).

Classroom observations revealed this emergent criticality in action. Teachers frequently encouraged students to justify their reasoning, question assumptions, and respond to hypothetical scenarios. Observers noted instances of spontaneous debates, counter-arguments, and cooperative evaluations of conflicting interpretations.

Conversely, control group students reported few opportunities to engage in critical reasoning:

> *"We were just told the answers. We didn't get to ask why or how things happened. It felt like we were just memorizing things for the test and not really understanding what we were doing"* (T7, Medium Achiever).

Observations confirmed a lecture-driven environment focused on factual recall with minimal inquiry.

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**Theme 4: Empowerment and Confidence**

The final theme documented the notable increases in academic confidence and a sense of empowerment experienced by students exposed to Socratic questioning. This theme was shaped predominantly by Interview Questions 4 and 5, which asked students to reflect on their perceived academic confidence, ability to handle complex questions, and changes in their approach to mistakes.

Many students attributed their improved self-efficacy to the experience of reasoning through complex problems collaboratively and receiving constructive, supportive feedback:

> *"The more we discussed, the more I realized I knew. I stopped being afraid of difficult questions because I knew I could figure it out by thinking it through. It gave me confidence in my understanding. It wasn't just about learning the material — I felt like I was becoming more competent in solving problems on my own*" (T4, Higher Achiever).

Importantly, these confidence gains were consistent across all achievement levels:

> *"At first, I didn't think I would understand the material. But after the discussions, I felt more confident about what I was learning. I could ask questions and really think about my answers. I wasn't scared of being wrong anymore because the teacher helped us see that mistakes are part of learning"* (T10, Lower Achiever).

Classroom observations validated these perceptions. Students who initially hesitated to participate gradually began volunteering answers more readily. Teachers' positive reinforcement, affirmation of effort, and normalization of error as a valuable learning tool appeared central to creating this supportive environment.

In contrast, control group students expressed persistent uncertainty and isolation:

> *"Sometimes I felt confused and didn't know how to ask for help. The lectures didn't give me that feeling of confidence or independence. It was hard to know where to go if I needed help, and I didn't feel like I could speak up in class*" (T8, Medium Achiever).

Observation data reflected these challenges, with limited teacher-student interaction beyond content delivery and minimal evidence of personalized academic support.

In summary, this enhanced qualitative analysis secured in a rigorous coding process, strong inter-rater reliability and transparent item-level mapping demonstrates that Socratic questioning meaningfully transforms both cognitive and affective dimensions of students' chemistry learning experiences. It fosters deeper conceptual understanding, promotes active and equitable participation, enhances critical thinking, and builds students' academic confidence in ways that traditional didactic methods fail to achieve.

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## 5. Discussion

The findings of this study underscore the significant positive influence of Socratic questioning on Grade 11 students' understanding of chemical kinetics. By integrating quantitative and qualitative analyses, this research illustrates how Socratic questioning improves academic performance, deepens conceptual understanding, enhances engagement, fosters critical thinking, and boosts students' confidence in managing complex scientific concepts.

### 5.1. Impact on Academic Performance

The quantitative results, as revealed through ANCOVA, demonstrated that students in the experimental group—who were taught through Socratic questioning—achieved significantly higher post-test scores than their counterparts in the control group who received traditional lecture-based instruction. The substantial effect size ($\eta^2 = .83$) indicated that the intervention accounted for a large proportion of the variance in students' academic performance. This outcome supports and extends the growing body of evidence affirming the effectiveness of active learning strategies in STEM education (Freeman et al., 2014; Theobald et al., 2020; Abubakar et al., 2024).

Additionally, a detailed by-item post-test analysis revealed that the Socratic questioning group consistently outperformed the control group across all question types—multiple-choice, short-answer, and problem-solving. The greatest performance gains were evident in items demanding higher-order cognitive skills such as Analyzing and Evaluating. For instance, multiple-choice questions at these levels showed mean score differences exceeding 1.2 points, while problem-solving questions—requiring multi-step reasoning and application of chemical kinetics principles—exhibited differences ranging from 1.3 to 1.5 points per item. These findings highlight that the intervention not only enhanced factual recall but also significantly improved students' reasoning and problem-solving abilities, key indicators of deep learning and academic success.

In a comprehensive meta-analysis, Freeman et al. (2014) concluded that active learning approaches consistently enhance student performance in STEM disciplines. Theobald et al. (2020) further demonstrated that active learning not only improves overall achievement but also reduces performance gaps for underrepresented students, highlighting its equity potential. Similarly, Abubakar et al. (2024) reported that guided questioning strategies, akin to Socratic questioning, significantly enhanced science achievement and conceptual mastery in secondary schools. These findings collectively position Socratic questioning as a viable instructional alternative to traditional lecture-based methods, especially in promoting academic success in conceptually demanding science topics such as chemical kinetics.

However, it is important to acknowledge that the study's scope was relatively narrow, focusing on a single four-week instructional unit in one small secondary school. This limits the generalizability of the findings to broader educational contexts, including other subject areas,

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larger schools, and diverse cultural or geographic settings. Nevertheless, the positive outcomes suggest that carefully designed and contextually tailored interventions could yield comparable benefits in similar educational environments. It would be prudent for future research to conduct multi-site or longitudinal studies to determine the sustainability and scalability of these effects over time.

**5.2. Enhancement of Conceptual Understanding and Engagement**

Qualitative data from student interviews corroborated the quantitative findings, illustrating how Socratic questioning fostered deeper conceptual understanding and active engagement. Students consistently reported that the questioning approach moved them beyond rote memorization, prompting them to interrogate the underlying principles of chemical kinetics. This aligns with Chi's (2009) knowledge construction theory, which emphasizes that meaningful learning occurs when students actively engage in explaining and justifying concepts.

As noted by Bell et al. (2020), inquiry-based environments encourage students to contextualize facts within broader scientific frameworks, resulting in more robust conceptual understanding. In contrast, students in the control group described a more passive experience, consistent with the limitations of traditional lecture-based methods identified by Styers et al. (2018). The increased engagement among lower-achieving students echoes the findings of Boud (2001) and reinforces Onu and Ciravegna et al.'s (2023) assertion that active learning strategies democratize classroom participation.

Supporting these qualitative insights, the by-item post-test data indicated consistent score improvements even on lower-level cognitive tasks such as Remembering and Understanding, with mean differences ranging from 0.2 to 0.6 in multiple-choice items and 0.4 to 0.5 in short-answer questions. This suggests that Socratic questioning supported foundational knowledge acquisition alongside higher-order thinking development, contributing to overall conceptual clarity and engagement.

One limitation to note is that during qualitative data collection, specifically in Questions 6 and 7 of the interview guide, only students in the experimental group were asked to reflect on their prior learning experiences before the intervention. This created an asymmetry in the data, as control group students did not engage in comparable retrospective reflections. This limitation potentially influenced the richness and comparability of experiential insights across groups and represents a known challenge when employing retrospective questioning in qualitative research. Future studies should design symmetrical qualitative protocols that offer comparable reflective opportunities to all participant groups, ensuring balanced insight into both instructional experiences.

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### 5.3. Development of Critical Thinking Skills

A notable outcome of this study was the observed improvement in students' critical thinking abilities. Interviews revealed that Socratic questioning prompted learners to analyze, evaluate, and justify their reasoning—processes essential for higher-order cognitive development. Paul and Elder (2014) argued that Socratic questioning fosters intellectual discipline by compelling learners to examine assumptions, clarify ideas, and evaluate evidence. Recent empirical studies (Ncube, 2022; Abubakar et al., 2024) corroborate this assertion, demonstrating that guided questioning techniques enhance critical thinking and problem-solving skills among high school science students.

This finding is also consistent with Vygotsky's (1978) theory of the zone of proximal development, which emphasizes the importance of social interactions in helping learners advance beyond their current capabilities. Active classroom dialogues enabled students to scaffold each other's learning experiences, fostering collaborative critical inquiry and reinforcing higher-order cognitive skills (Bell et al., 2020; Freeman et al., 2014).

The by-item analysis further reinforces this observation, showing that the largest performance differentials were associated with items categorized as Analyzing and Evaluating across all test formats. Problem-solving questions, which required application and evaluation skills, demonstrated the most pronounced gains, with mean differences of up to 1.5 points on a 6-point scale. This quantitative evidence supports the conclusion that Socratic questioning significantly advances critical thinking development beyond what traditional instruction achieves.

Nevertheless, it remains unclear whether Socratic questioning equally benefits all student types, including those who prefer structured, note-based learning environments. This study did not formally collect data on individual learning preferences, meaning it was not possible to determine if certain learners might have experienced discomfort or reduced effectiveness within dialogic, open-ended instructional settings. To address this gap, future research should explore the interaction between questioning-based instructional methods and individual learner characteristics, such as cognitive style, academic self-concept, or motivation profiles, to better tailor instructional interventions.

### 5.4. Increased Student Engagement and Confidence

Socratic questioning also fostered greater student engagement and confidence, particularly among lower-achieving students. Participants reported feeling more involved in lessons and valued as contributors to the learning process. This resonates with Schwarzer's (2014) social cognitive theory, which posits that mastery experiences and social persuasion are pivotal in building self-efficacy beliefs.

Recent studies have affirmed that instructional strategies promoting classroom dialogue and student participation enhance academic self-efficacy and reduce science anxiety (Bączek et al.,

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2021). The present study's qualitative insights highlight that even initially hesitant students found encouragement in Socratic dialogues, illustrating the inclusivity potential of this method. Higher-achieving students also reported increased confidence and self-awareness, aligning with findings from Styers et al. (2018).

A critical reflection concerns the practical feasibility of implementing Socratic questioning as a regular classroom practice. In this study, teachers received only a three-day professional development workshop on Socratic methods before the intervention. While the positive results suggest that even short-term training can yield meaningful instructional changes, it is uncertain whether such brief preparation equips teachers to sustainably integrate and adapt these techniques across a full academic year or within more complex instructional settings. To improve long-term adoption, professional development models should emphasize ongoing support, including classroom-based coaching, collaborative lesson planning, and peer feedback opportunities (Desimone and Garet, 2015). Embedding Socratic questioning strategies within department-level professional learning communities may also increase instructional sustainability and instructional fidelity.

### 5.5. Integration of Quantitative and Qualitative Findings

The integration of quantitative and qualitative results provides a holistic perspective on the benefits of Socratic questioning in science education. Quantitatively, the substantial improvement in post-test scores confirms the method's effectiveness in enhancing academic achievement. Qualitatively, students' narratives about increased engagement, critical thinking, and confidence offer rich contextual insights into the mechanisms behind these improvements.

This convergence of findings aligns with mixed-methods research recommendations (Creswell & Plano Clark, 2023), advocating for the combination of numerical outcomes with personal experiences to develop a more nuanced understanding of educational interventions. The present study reinforces the position that Socratic questioning contributes not only to content mastery but also to the development of essential 21st-century skills such as problem-solving, reasoning, and communication (Lewis et al., 2021).

Despite these positive convergences, it should be noted that the single-topic, short-duration focus of the intervention limits the extent to which cause-effect relationships can be generalized across broader academic domains. Consequently, triangulation through longer-term, multi-topic interventions would strengthen confidence in these findings and better illuminate the durability of learning gains produced by Socratic approaches.

### 5.6. Implications for Science Education Practice

The findings from this study contribute to the growing call for reform in secondary science education, advocating for the adoption of inquiry-based, dialogic teaching practices. As contemporary science curricula increasingly emphasize competencies over content coverage

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(Lewis et al., 2021), strategies like Socratic questioning offer practical, evidence-based approaches for cultivating both academic and affective learning outcomes.

Educators should consider integrating Socratic questioning into regular classroom practice, particularly in topics traditionally perceived as difficult, such as chemical kinetics. Professional development programs should also equip teachers with the skills to effectively facilitate questioning-based discussions, ensuring that all students, regardless of achievement level, can actively engage in the learning process (Abubakar et al., 2024; Freeman et al., 2014; Theobald et al., 2020;).

Moreover, policymakers and school leaders should invest in sustained teacher training models that extend beyond brief workshops. Given the dialogic and adaptive nature of Socratic questioning, long-term support structures such as peer observation cycles, instructional coaching, and reflective teaching communities are likely necessary to ensure durable pedagogical change. It would also be advantageous for national and regional education authorities to include Socratic questioning modules within initial teacher training programs, ensuring that new educators enter the profession with inquiry-based facilitation competencies already developed.

Importantly, the results of this study also align with and complement broader, ongoing reform initiatives in chemistry education, such as three-dimensional learning frameworks like the Next Generation Science Standards (NGSS) (Kaldaras et al., 2021), Process-Oriented Guided Inquiry Learning (POGIL) (Moog and Spencer, 2008), the CLUE curriculum (Underwood et al., 2023), and the Chemical Thinking framework (Talanquer, 2018). Each of these initiatives emphasizes student-centered, inquiry-based, and reasoning-focused pedagogies designed to improve conceptual understanding, scientific practices, and problem-solving abilities. The Socratic questioning approach employed in this study shares core instructional priorities with these reforms particularly in promoting active learning, fostering argumentation, and encouraging students to construct and justify explanations for chemical phenomena. As such, this study contributes to the growing evidence base supporting dialogic, inquiry-driven teaching strategies as effective tools for advancing science education goals aligned with international reform movements.

Future research might explore how Socratic questioning could be formally integrated into these established frameworks, assessing comparative effectiveness or synergistic benefits when combined with approaches like POGIL or NGSS-aligned curricula. Such studies would offer valuable insights into how best to position Socratic inquiry within the next generation of STEM teaching practice.

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## 6. Conclusion, Recommendations, Implications and Limitation of the Study

### 6.1. Conclusion

The findings from this study underscore the positive and significant impact of Socratic questioning on Grade 11 students' understanding of chemical kinetics, as demonstrated through both quantitative and qualitative data analyses. The quantitative results, derived using ANCOVA and supported by detailed by-item analysis, revealed that students in the experimental group who participated in lessons utilizing Socratic questioning performed notably better on post-test assessments than their counterparts in the control group who experienced traditional lecture-based instruction. This improvement was particularly pronounced on items requiring higher-order cognitive skills such as analyzing, evaluating, and problem-solving, confirming that Socratic questioning effectively enhances both foundational knowledge and critical thinking abilities. This outcome suggests that Socratic questioning is an effective instructional strategy for enhancing students' comprehension of abstract and complex scientific concepts.

In addition to measurable academic gains, the qualitative data obtained from student interviews provided valuable insights into the cognitive and emotional benefits of this teaching method. Students in the experimental group expressed that Socratic questioning not only improved their understanding of the subject matter but also encouraged them to engage in deeper critical thinking, increased their participation in classroom discussions, and boosted their overall confidence in learning. These students reported feeling more involved in their learning process and developing better problem-solving abilities as a result of the inquiry-based approach. Conversely, students in the control group, who experienced conventional lectures, described lower levels of engagement, fewer opportunities for critical thought, and reduced confidence in understanding chemical kinetics.

Overall, this study highlights the limitations of traditional teaching methods and reinforces the importance of adopting more interactive, student-centered instructional strategies in science education. Socratic questioning has been shown to positively influence academic performance, critical thinking, classroom engagement, and students' self-confidence, making it a valuable pedagogical tool for secondary science classrooms. However, it is important to reiterate that the study's scope was limited to a single four-week instructional unit within two secondary schools, and as such, while the findings are promising, they cannot yet be generalized to other subjects, educational levels, or diverse classroom settings without further investigation.

### 6.2. Recommendations

In light of the study's findings, it is recommended that Socratic questioning be adopted as a regular instructional strategy in science education, particularly in secondary schools. Teachers should receive dedicated training and professional development programs aimed at equipping them with the skills necessary to implement Socratic questioning effectively. Such training should focus on techniques for crafting open-ended, thought-provoking questions, managing

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classroom dialogues, and providing appropriate scaffolding for students of varying abilities. Integrating Socratic questioning into daily science lessons can help create more inclusive and engaging learning environments where students are encouraged to actively participate in constructing their own understanding.

Furthermore, it is advisable for educators to incorporate a broader range of active learning strategies alongside Socratic questioning. Methods such as collaborative group discussions, problem-solving exercises, inquiry-based projects, and reflective activities can further deepen students' engagement and enhance their comprehension of challenging scientific topics. The combination of these interactive approaches has the potential to transform conventional science classrooms into dynamic, learner-centered spaces where students take ownership of their education.

Additional research is recommended to investigate the long-term effects of Socratic questioning on students' knowledge retention and academic development. While this study focused on immediate learning outcomes, longitudinal studies could provide valuable insights into the sustained benefits of inquiry-based teaching methods across different subjects, grade levels, and educational contexts. Moreover, future research should explicitly examine whether Socratic questioning benefits all student types equally, particularly those who prefer structured, teacher-directed instruction and passive note-taking. Collecting data on individual learning preferences, classroom participation styles, and cognitive profiles would offer critical insights into how instructional strategies can be differentiated to meet diverse learner needs.

Lastly, it is important that teachers adapt their questioning techniques to address the diverse needs of learners within the classroom. Differentiating the complexity and structure of questions ensures that both high-achieving students and those requiring additional support are actively engaged and appropriately challenged. By modifying questions to students' individual learning needs, educators can foster an inclusive and supportive environment that promotes academic growth for all learners.

It is also recommended that teacher professional development programs move beyond short-term workshops and adopt sustained, iterative training models. While this study's positive outcomes were achieved after a three-day workshop, it remains uncertain whether teachers can realistically sustain Socratic questioning techniques over extended periods without ongoing support. Professional development should therefore include classroom-based coaching, peer observation, and reflective teaching communities to consolidate skills and build teacher confidence in facilitating dialogic learning environments.

**6.3. Implications**

The outcomes of this study present meaningful implications for the pedagogy of science instruction, particularly for teaching complex and abstract topics such as chemical kinetics. The findings suggest that conventional lecture-based methods, while efficient for delivering content,

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are often insufficient in fostering deep conceptual understanding and higher-order cognitive skills among students. Socratic questioning provides an effective alternative instructional strategy that actively involves students in their learning, promotes reflective thinking, and encourages them to explore the underlying principles of scientific phenomena. By transforming the classroom dynamic from a teacher-centered to a student-centered environment, this approach enhances both the academic and personal development of learners.

From a curricular standpoint, the positive impact of Socratic questioning calls for a reevaluation of science curricula to incorporate more inquiry-based, interactive teaching methods. Embedding activities that promote open-ended questioning, critical discussions, and collaborative problem-solving can help students develop essential skills for academic success and real-world problem-solving. A curriculum that values and supports these practices is better positioned to prepare students for future educational and career opportunities in scientific fields.

In addition to academic and curricular implications, the study highlights the role of Socratic questioning in promoting students' social and emotional development. Students who actively participated in Socratic discussions reported increased confidence, a stronger sense of ownership over their learning, and enhanced interpersonal skills. This sense of empowerment and engagement not only benefits students academically but also supports their personal growth, resilience, and capacity for independent thought. Such skills are essential not only in the classroom but also in broader social, academic, and professional contexts.

At the policy level, the findings suggest that educational authorities and policymakers should advocate for the integration of interactive, inquiry-based teaching strategies such as Socratic questioning within science classrooms. This could involve updating teacher training frameworks, revising instructional guidelines, and allocating resources to support the adoption of these practices. Policymakers should also recognize that implementing such pedagogical shifts requires ongoing institutional support and professional learning infrastructure. Short-term training initiatives, while beneficial, may be insufficient for achieving lasting pedagogical change without sustained follow-up opportunities for teachers to practice, reflect, and refine their instructional techniques in real classroom contexts. By promoting pedagogical approaches that prioritize active learning, critical thinking, and student engagement, policymakers can contribute to the enhancement of science education and the cultivation of a generation of learners equipped with the skills needed to manage an increasingly complex and knowledge-based world.

### 6.4. Study Limitations and Directions for Future Research

While the findings of this study offer valuable contributions to the field of science education, several limitations should be acknowledged to contextualize the results and guide future inquiry. First, the scope of the study was intentionally narrow, focusing on a single four-week instructional unit in chemical kinetics within two secondary schools. As a result, the

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generalizability of the findings to other science topics, educational levels, institutional settings, or cultural contexts remains limited. Larger, multisite studies encompassing diverse student populations and subject areas would be necessary to validate and extend the conclusions drawn from this investigation.

A second limitation pertains to the short duration and structure of the teacher training intervention. While positive outcomes were achieved following a three-day professional development workshop on Socratic questioning, it is uncertain whether teachers can maintain and consistently apply these dialogic instructional techniques over longer periods without ongoing support. Adopting and sustaining inquiry-based pedagogies often requires iterative, collaborative professional learning communities, classroom-based coaching, and reflective peer review practices, which were beyond the scope of this study. Future research should therefore examine the long-term viability of Socratic questioning in routine classroom settings and identify the most effective models for sustained teacher capacity-building.

Another limitation concerns the retrospective nature of some qualitative interview questions. Specifically, only students in the experimental group were asked to reflect on differences between their Socratic questioning experiences and prior traditional instruction, whereas this comparative reflection was not solicited from the control group. This methodological asymmetry may have introduced bias by preventing a balanced comparison of student perceptions across groups, potentially limiting the depth and validity of qualitative comparisons. Future qualitative designs should ensure that both experimental and control participants are provided equivalent opportunities to discuss past instructional experiences for a more equitable and reliable analysis.

Furthermore, this study did not explicitly collect data on individual learner preferences or instructional style tendencies (e.g., note-takers preferring structured, lecture-based environments versus discussion-oriented learners). As such, it remains unclear whether Socratic questioning benefits all student types equally. It is possible that certain students who value clear, linear information delivery may experience discomfort or diminished learning gains in dialogic environments without appropriate scaffolding. Future research should incorporate diagnostic assessments of student learning preferences and investigate how different questioning techniques interact with these preferences to optimize instructional effectiveness.

Finally, while this study assessed immediate post-intervention outcomes, it did not evaluate the long-term retention of conceptual understanding, critical thinking, or affective benefits such as academic confidence. Longitudinal research tracking students over extended academic periods or subsequent academic years would provide valuable insight into the durability and cumulative impact of Socratic questioning on science learning and student development. Additionally, examining how this pedagogical approach influences students' attitudes toward science and their interest in STEM career pathways represents a promising area for further exploration.

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In summary, future research should prioritize broader, multisite interventions; incorporate sustained professional learning structures for teachers; ensure balanced qualitative data collection from both experimental and control groups; account for learner preference diversity; and assess long-term educational outcomes. Such investigations would deepen understanding of Socratic questioning's role in modern science education and refine evidence-based strategies for fostering inquiry, engagement, and conceptual mastery in diverse classroom settings.

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**Conflict of Interest**

The author declares that there are no conflicts of interest related to this study. The research was conducted independently, and there were no financial or personal relationships that could have influenced the outcomes or interpretation of the findings.

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# Appendices

**Appendix A:** Learning Objectives and Data Collection Instruments

**A1.** Learning Objectives for the Chemical Kinetics Unit

- ✓ Define and explain key concepts in chemical kinetics, including rate laws, rate-determining step, activation energy, and collision theory. (Bloom's: Remember, Understand)
- ✓ Apply chemical kinetics formulas to solve problems involving rate laws and the Arrhenius equation. (Bloom's: Apply)
- ✓ Analyze factors affecting reaction rates such as temperature, concentration, catalysts, and surface area. (Bloom's: Analyze)
- ✓ Evaluate experimental data to identify reaction order and deduce kinetic parameters. (Bloom's: Evaluate)

**Appendix A2: Pre-Test Instrument for the Chemical Kinetics Unit**
**General Instructions**

- ✓ Time: 75 minutes
- ✓ Total Items: 35
- ✓ Calculators allowed only in Problem-Solving Section
- ✓ Answer all questions clearly.
- ✓ For Multiple Choice: Mark the best option clearly.
- ✓ For Short Answer: Write concise explanations.
- ✓ For Problem Solving: Show all steps and calculations.

**Section 1: Multiple-Choice Questions (20 items × 2 pts = 40 points)**

1. What is the rate-determining step in a chemical reaction? (Remembering)
   A) The fastest reaction step
   B) The slowest reaction step
   C) The step with the least energy change
   D) The step with the highest activation energy
2. Which of the following best describes a homogeneous catalyst? (Understanding)
   A) A catalyst in a different phase than the reactants
   B) A catalyst in the same phase as the reactants
   C) A substance consumed during the reaction
   D) An inhibitor that decreases reaction rate
3. Which graph would yield a straight line for a first-order reaction? (Analyzing)
   A) [A] vs. time
   B) 1/[A] vs. time

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C) ln[A] vs. time
D) Rate vs. $[A]^2$

4. Which factor would most effectively increase the rate of a reaction between two gases? (Evaluating)
   A) Lowering the temperature
   B) Removing the catalyst
   C) Increasing pressure
   D) Diluting the gases
5. What happens to the reaction rate if the concentration of a reactant is doubled in a second-order reaction? (Applying)
   A) It remains the same
   B) It doubles
   C) It quadruples
   D) It halves
6. According to collision theory, which condition must be met for effective collisions? (Remembering)
   A) Collisions occur at any energy level
   B) Molecules collide with proper orientation and minimum energy
   C) Temperature has no effect on collision frequency
   D) All collisions result in product formation
7. The Arrhenius equation contains an exponential term $e^{-Ea/RT}$. Which variables affect this term directly? (Understanding)
   A) Concentration and pressure
   B) Activation energy and temperature
   C) Catalyst and surface area
   D) Reaction order and rate constant
8. A reaction has the rate law Rate = $k[A][B]^2$. What is the effect on rate if [A] is halved and [B] is doubled? (Applying)
   A) Rate remains the same
   B) Rate doubles
   C) Rate decreases to one-fourth
   D) Rate increases by a factor of two
9. If a reaction's half-life remains constant regardless of initial concentration, what is its order? (Analyzing)
   A) Zero order
   B) First order
   C) Second order
   D) Third order
10. How does a catalyst influence the activation energy of a reaction? (Understanding)
   A) It increases activation energy

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B) It lowers activation energy by providing an alternate pathway
C) It changes the overall enthalpy change
D) It increases the concentration of reactants

11. Which plot would verify a reaction is second order with respect to reactant A? (Applying)
A) [A] vs. time linear
B) ln[A] vs. time linear
C) 1/[A] vs. time linear
D) Rate vs. [A] linear

12. A reaction's rate increases eightfold when the temperature is doubled. What can be inferred about the activation energy? (Analyzing)
A) It is very low
B) It is high
C) It is independent of temperature
D) It cannot be determined

13. What evidence indicates a multi-step reaction mechanism? (Evaluating)
A) Rate law matches overall equation
B) Intermediate accumulates during reaction
C) Rate is independent of concentration
D) Reaction is zero order

14. Which of the following is a characteristic of a heterogeneous catalyst? (Remembering)
A) Exists in the same phase as reactants
B) Exists in a different phase and provides surface for reaction
C) Is consumed in the reaction
D) Increases reactant volume

15. What is the overall order of a reaction with rate law Rate = $k[A]^0[B]^1[C]^2$? (Applying)
A) 3
B) 2
C) 1
D) 0

16. The temperature coefficient of a reaction indicates what? (Understanding)
A) The change in reaction rate per 10 °C rise in temperature
B) The activation energy
C) The enthalpy change
D) The equilibrium constant

17. How does increasing surface area affect reaction rate? (Applying)
A) No effect
B) Increases reaction rate by increasing collision frequency
C) Decreases rate due to crowding
D) Changes reaction order

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18. Which units correspond to the rate constant of a second-order reaction? (Applying)
    A) $s^{-1}$
    B) L $mol^{-1}$
    C) mol $L^{-1}$
    D) $L^2$
19. Which of the following explains why the experimentally determined rate law may differ from the stoichiometric equation? (Evaluating)
    A) Rate law depends on molecularity, not stoichiometry
    B) Stoichiometry accounts for catalysts
    C) Rate laws reflect the slowest step in mechanism
    D) Rate laws always match stoichiometry
20. Which scenario best exemplifies a zero-order reaction? (Analyzing)
    A) Rate doubles when concentration doubles
    B) Rate is independent of concentration
    C) Half-life depends on concentration
    D) Rate varies with surface area only

**Section 2: Short Answer Questions (10 items × 3 pts = 30 points)**

1. Define activation energy and explain its significance in chemical kinetics. (Remembering)
2. Explain two assumptions of collision theory and their influence on reaction rate. (Understanding)
3. Differentiate between reaction rate and rate constant. (Understanding)
4. Describe how catalysts affect the potential energy diagram of a reaction. (Understanding)
5. A reaction is second order with respect to A. What effect does doubling [A] have on the rate? (Applying)
6. Given Rate = $k[A]^2[B]$, explain what happens if [A] is halved and [B] doubled. (Applying)
7. Write the Arrhenius equation and explain the meaning of each term. (Understanding)
8. How does increasing temperature increase the reaction rate, based on molecular collisions? (Applying)
9. Why does a catalyst speed up a reaction without changing the overall enthalpy change? (Analyzing)
10. How can experimental kinetics inform industrial chemical process optimization? (Evaluating)

**Section 3: Problem-Solving Questions (5 items × 6 pts = 30 points)**

1. For a first-order reaction with rate constant k=0.25 $min^{-1}$, calculate the time required for 80% of the reactant to decompose. (Applying)
2. A reaction has Rate = $k[A][B]^2$. If [A] is constant and [B] is doubled, the rate quadruples. Determine the reaction order with respect to B. (Analyzing)

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3. A reaction at 298 K has rate constant $k=2.0\times10^{-3}\ s^{-1}$. Given activation energy $Ea=90$ kJ/mol, calculate k at 310 K using the Arrhenius equation. (Assume R=8.314 J/mol·K). (Applying)
4. A reaction proceeds via two steps:
   Step 1 (fast equilibrium): A⇌I
   Step 2 (slow): I→P
   Using steady-state approximation for III, derive the overall rate law in terms of [A]. Explain why experimentally determined order may differ from stoichiometry. (Evaluating)
5. The decomposition of a substance follows second-order kinetics with a half-life of 120 s at initial concentration 0.25 mol/L. Calculate the rate constant k. (Applying)

**Appendix A3: Post-Test Instrument for the Chemical Kinetics Unit**

**General Instructions**

- ✓ Time: 75 minutes
- ✓ Total Items: 35
- ✓ Calculators allowed only in Problem-Solving Section
- ✓ Answer all questions clearly.
- ✓ For Multiple Choice: Mark the best option clearly.
- ✓ For Short Answer: Write concise explanations.
- ✓ For Problem Solving: Show all steps and calculations.

**Section 1: Multiple-Choice Questions (20 items × 2 pts = 40 points)**

1. Which graph would yield a straight line for a first-order reaction? (Analyzing)
   A) [A] vs. time
   B) 1/[A] vs. time
   C) ln[A] vs. time
   D) Rate vs. $[A]^2$
2. What is the rate-determining step in a chemical reaction? (Remembering)
   A) The fastest reaction step
   B) The slowest reaction step
   C) The step with the least energy change
   D) The step with the highest activation energy
3. The rate law for a reaction is Rate = $k[A][B]^2$. What happens if [A] is doubled and [B] is halved? (Applying)
   A) Rate is unchanged
   B) Rate is doubled
   C) Rate is halved
   D) Rate is one-fourth
4. Which of the following best explains why a catalyst speeds up a chemical reaction? (Understanding)
   A) It increases the energy of reactants

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B) It decreases the temperature
C) It provides an alternate pathway with lower activation energy
D) It raises the activation energy

5. Which plot verifies a second-order reaction with respect to [A]? (Applying)
   A) [A] vs. time linear
   B) ln[A] vs. time linear
   C) 1/[A] vs. time linear
   D) Rate vs. [A] linear
6. Which factor would most effectively increase the rate of a reaction between two gases? (Evaluating)
   A) Lowering the temperature
   B) Removing the catalyst
   C) Increasing pressure
   D) Diluting the gases
7. A reaction's half-life remains constant regardless of initial concentration. What is its order? (Analyzing)
   A) Zero
   B) First
   C) Second
   D) Third
8. Which of the following is true about the rate constant, k? (Understanding)
   A) It changes with temperature
   B) It changes with concentration
   C) It changes with pressure
   D) It remains constant for all reactions
9. Which variable most directly affects the exponential factor in the Arrhenius equation? (Applying)
   A) Pressure
   B) Temperature
   C) Catalyst
   D) Concentration
10. What does a high activation energy imply about a chemical reaction? (Evaluating)
    A) It proceeds rapidly at all temperatures
    B) It is likely spontaneous
    C) It requires more energy to start
    D) It is always reversible
11. Which change will **not** increase the rate of a surface-catalyzed reaction? (Applying)
    A) Grinding the catalyst
    B) Lowering temperature

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C) Increasing concentration
D) Increasing surface area

12. A catalyst is best described as: (Understanding)
    A) A substance consumed in a reaction
    B) An inhibitor
    C) A substance that lowers activation energy without being consumed
    D) A phase-changing agent
13. The overall order of a reaction with rate law Rate = $k[A]^0[B]^1[C]^2$ is: (Applying)
    A) 3
    B) 2
    C) 1
    D) 0
14. The units of the rate constant for a second-order reaction are: (Applying)
    A) $s^{-1}$
    B) mol/L
    C) L/mol·s
    D) $mol^2/L^2 \cdot s$
15. According to collision theory, an effective collision must involve: (Understanding)
    A) Random orientation
    B) Low energy impact
    C) Proper orientation and sufficient energy
    D) Equal molecular mass
16. Which statement best explains why rate laws may not match balanced equations? (Evaluating)
    A) Rate laws are always based on stoichiometry
    B) Rate laws depend only on products
    C) Rate laws reflect only the slowest step
    D) Balanced equations include reaction intermediates
17. Which of the following affects the frequency of molecular collisions? (Applying)
    A) Catalyst
    B) Orientation
    C) Temperature and concentration
    D) Activation energy
18. A reaction rate increases eightfold when temperature is doubled. What can you infer about the activation energy? (Analyzing)
    A) It is low
    B) It is very high
    C) It is independent of temperature
    D) It cannot be determined without more data

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19. What does the slope represent in a ln(k) vs. 1/T plot? (Analyzing)
    A) Enthalpy of reaction
    B) Reaction order
    C) $-Ea/R$
    D) Pre-exponential factor
20. Which of the following best represents a zero-order reaction? (Analyzing)
    A) Rate doubles when [A] doubles
    B) Rate depends on $[A]^2$
    C) Rate is constant regardless of [A]
    D) Half-life is constant

**Section 2: Short Answer Questions (10 items × 3 pts = 30 points)**

1. Define activation energy and explain its role in reaction rate. (Remembering)
2. Describe how temperature affects molecular collisions and reaction rate. (Understanding)
3. Explain two assumptions of collision theory. (Understanding)
4. What is the difference between a catalyst and an intermediate? (Understanding)
5. A reaction is second-order with respect to A. What happens to the rate if [A] triples? (Applying)
6. Given Rate = $k[A]^2[B]$, what is the effect of halving [A] and doubling [B]? (Applying)
7. Explain why rate constants increase with temperature using the Arrhenius equation. (Understanding)
8. What is meant by the rate-determining step? Why is it important? (Analyzing)
9. Why doesn't a catalyst change the enthalpy of a reaction? (Analyzing)
10. How can kinetic data help optimize conditions in an industrial reactor? (Evaluating)

**Section 3: Problem-Solving Questions (5 items × 6 pts = 30 points)**

1. For a first-order reaction with $k = 0.20\ min^{-1}$, calculate the time needed for 75% of the reactant to decompose. (Applying)
2. A reaction has the rate law Rate = $k[A][B]^2$. If [A] remains constant and [B] is tripled, by what factor does the rate increase? (Analyzing)
3. The rate constant at 298 K is $2.5\times10{-}4\ s^{-1}$. The activation energy is 75 kJ/mol. Calculate the rate constant at 310 K using the Arrhenius equation. (Applying; R = 8.314 J/mol·K)
4. A reaction mechanism:
   Step 1 (fast equilibrium): $A+B \rightleftharpoons CA + B$
   Step 2 (slow): $C \rightarrow DC$
   Use the steady-state approximation to derive the overall rate law in terms of [A] and [B]. Explain why the rate law differs from stoichiometry. (Evaluating)
5. A second-order reaction has a half-life of 100 s when $[A]_0 = 0.40$ mol/L. Calculate the rate constant k. (Applying)

**Appendix B:** Semi-Structured Interview Questions

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Interviews were conducted with 12 students (4 higher achievers, 4 medium achievers, 4 lower achievers) selected from four intact Grade 11 classes (two experimental, two control) comprising a total of 100 students.

1. How would you describe your learning experience during the chemical kinetics lessons?
2. What challenges did you face in understanding chemical kinetics?
3. How did Socratic questioning influence your understanding and thinking?
4. How did Socratic questioning compare to traditional lectures?
5. Did Socratic questioning impact your confidence in problem-solving or participation?
6. Reflecting on your past classroom experiences, how did this method differ?
7. Would you recommend this questioning strategy for other science topics? Why or why not?

**Appendix C:** Sample Interview Transcript (Excerpt) and Qualitative Analysis Materials

**C1.** Sample Interview Transcript (Excerpt)

Interview with Student T2 (Higher Achiever)

**Researcher:** How would you describe your learning experience during the chemical kinetics lessons?
**T2:** The Socratic questioning really made me think critically. Instead of memorizing, I had to explain concepts like activation energy in my own words, which improved my understanding.

**Researcher:** What activities helped the most?
**T2:** The discussions and opportunities to ask questions clarified many things.

**C2.** Finalized Qualitative Codebook and Inter-Coder Reliability

| Code | Description |
|---|---|
| Conceptual Clarity | Statements reflecting improved understanding of key chemical kinetics concepts. |
| Peer Explanation | Instances where students explain concepts to or learn from classmates. |
| Probing Question Effect | Student remarks on how teacher questions encouraged deeper thinking. |
| Metacognitive Awareness | Reflections on students' own thinking and learning strategies. |
| Student-Initiated Inquiry | Questions or clarifications initiated by students. |
| Collaborative Problem-Solving | Evidence of students working together to solve problems. |
| Learning Challenges | Descriptions of difficulties or obstacles students faced. |

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**Inter-Coder Reliability:** To enhance the trustworthiness of the qualitative analysis, a second trained rater independently coded 25% of the interview transcripts using this codebook. The agreement between the two coders was calculated using Cohen's kappa, yielding a value of 0.75, indicating substantial agreement according to Landis and Koch's (1977) criteria. Any coding discrepancies were resolved through discussion and consensus prior to finalizing the codes and themes.

**C3.** Theme Definitions

| Theme | Definition |
|---|---|
| Cognitive Engagement | Active intellectual involvement, including reasoning, explaining, and problem-solving. |
| Metacognitive Awareness | Awareness and reflection on one's own thought processes and understanding gaps. |
| Collaborative Learning | Learning through interaction with peers, including discussion and joint problem-solving. |
| Instructional Influence | The effect of teacher's questioning style on students' learning and reasoning. |
| Learning Challenges | Difficulties or barriers encountered by students during lessons. |

**C4.** Illustrative Quotations by Theme

| Theme | Illustrative Quotation |
|---|---|
| Cognitive Engagement | "When the teacher kept asking why, I had to think more carefully about my answer." (Student T3, Experimental) |
| Metacognitive Awareness | "I found myself checking if my explanation made sense before answering." (Student T5, Experimental) |
| Collaborative Learning | "My classmates explained the concept differently, which helped me understand." (Student T8, Control) |
| Instructional Influence | "The Socratic questions made me think beyond memorization and helped me reason." (Student T2, Experimental) |
| Learning Challenges | "The idea of rate-determining step was confusing at first, but discussions helped." (Student T7, Control) |

**Appendix D:** Classroom Observation Checklist and Inter-Rater Reliability

**D1.** Classroom Observation Checklist

| Observation Item | Yes | No |
|---|---|---|
| Teacher poses open-ended questions | ☑ | |
| Students actively participate | ☑ | |
| Follow-up probing questions used | ☑ | |
| Evidence of critical thinking | ☑ | |
| Interactive classroom atmosphere | ☑ | |

- ✓ **Teacher poses open-ended questions:** Consistent in experimental group
- ✓ **Students actively participate:** Increased over four weeks

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✓ **Follow-up probing questions used:** To clarify and challenge ideas

✓ **Evidence of critical thinking:** Seen in group debates

✓ **Interactive classroom atmosphere:** Marked difference vs control

**Inter-Rater Reliability:** Two trained observers independently completed the checklist during 20% of sessions. Cohen's kappa was calculated to assess inter-rater agreement and yielded a value of 0.82, indicating almost perfect agreement (Landis & Koch, 1977). Discrepancies were resolved through discussion to maintain consistency.

**Appendix E:** Assessment Scoring Rubric and Sample Scoring Criteria

**E1.** Overall Scoring Rubric Summary

| Item Type | No. of Items | Points per Item | Normalized Score |
|---|---|---|---|
| Multiple Choice | 20 | 2 | 40 |
| Short Answer | 10 | 3 (×3 scale) | 30 |
| Problem-Solving | 5 | 5 (×6 scale) | 30 |
| **Total score** | | | **100** |

**E2. Scoring Rubric for Short-Answer Items (3-point scale)**

| Criteria | Excellent (3 pts) | Fair (2 pts) | Minimal (1 pt) | No Credit (0 pts) |
|---|---|---|---|---|
| **Accuracy of Content** | Accurate and scientifically correct response. | Some correct information; some errors present. | Attempted response but largely inaccurate. | No response or irrelevant. |
| **Completeness of Explanation** | Fully addresses all aspects with clear explanation. | Addresses part of the question; incomplete explanation. | Vague or incomplete explanation. | No explanation. |
| **Use of Scientific Terminology** | Correct and appropriate terminology used. | Some appropriate terminology, some misuse. | Minimal or inaccurate use of terminology. | No relevant terminology. |
| **Clarity and Organization** | Clear, coherent, logically organized response. | Adequate but somewhat disorganized. | Difficult to follow; unclear. | Illegible or irrelevant. |

**E3. Scoring Rubric for Problem-Solving Items (6-point scale)**

| Criteria | Excellent (6 pts) | Good (5 pts) | Fair (4 pts) | Partial (3 pts) | Minimal (2 pts) | No Credit (0–1 pt) |
|---|---|---|---|---|---|---|
| **Identification and Application of Formula/Method** | Correct formula/method identified and fully applied. | Minor error in formula application. | Formula applied but multiple steps flawed. | Partial application; major errors. | Incorrect or incomplete formula used. | No attempt or irrelevant. |
| **Accuracy of Calculation** | All steps correct; accurate final answer. | One minor computational error. | Several errors but method visible. | Multiple errors; approach partially right. | Major errors; final answer unreasonable. | No calculation or irrelevant. |
| **Reasoning and Justification** | Complete, logically linked reasoning. | Mostly clear reasoning; minor omissions. | Reasoning weak or unclear. | Limited reasoning visible. | Minimal or incoherent reasoning. | No reasoning. |
| **Units and Significant Figures** | All correct units and appropriate sig figs. | One minor unit/sig fig error. | Some errors. | Major errors; some units attempted. | Most units absent. | No units. |
| **Clarity and Logical Organization** | Clear, neat, logically organized. | Mostly clear and organized. | Adequate but disorganized. | Difficult to follow. | Disorganized and confusing. | Illegible. |
| **Final Correct Answer (with Units)** | Final correct answer, clear with units. | Minor unit/sig fig error. | Incorrect final answer but close value. | Final answer far off but attempted. | Major error; wrong answer. | No final answer. |

**Maximum score per Problem-Solving item: 6 points**

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**Appendix F:** Sample Test Item Analysis Report

| Item No. | Item Type | Difficulty Index | Discrimination Index |
|---|---|---|---|
| 1 | Multiple Choice | 0.65 | 0.45 |
| 2 | Multiple Choice | 0.60 | 0.40 |
| 5 | Short Answer | 0.70 | 0.50 |
| 7 | Problem-Solving | 0.55 | 0.40 |
| 10 | Multiple Choice | 0.50 | 0.35 |

*Free-response items were scored by two independent raters, with Cohen's kappa = 0.78, indicating strong inter-rater agreement.*

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## Available Data Statements

The data supporting the findings of this study are not publicly available due to privacy or ethical restrictions, but may be obtained from the corresponding author upon request and with appropriate institutional approvals.