2026-06

þÿPromoting 11th-Grade Student Engagement and Conceptual Understanding in Chemical Kinetics: A Design-Based Research Approach to Pogil with Interactive Simulation Laboratory Activities

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COLLEGE OF EDUCATION

SCHOOL OF TEACHER EDUCATION

DEPARTMENT OF SCIENCE AND MATHEMATICS

EDUCATION

PROMOTING 11TH-GRADE STUDENTS' ENGAGEMENT AND CONCEPTUAL UNDERSTANDING IN CHEMICAL KINETICS: A DESIGN-BASED RESEARCH APPROACH TO POGIL WITH INTERACTIVE SIMULATION LABORATORY ACTIVITIES

By: REDIET BOGALE

June, 2026

Bahir Dar

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By

Rediet Bogale

A thesis submitted in Partial Fulfilment of the Requirements for the Degree of Master of Education in Chemistry

Principal Advisor: Mirtachew Tahir (PhD.)

June 2026

Bahir Dar

DECLARATION

This is to declare that this thesis work, entitled “Promoting 11-th grade students’ engagement and achievement in chemical kinetics: “Promoting 11th-grade students’ engagement and conceptual understanding in chemical kinetics: a Design-based research approach to POGIL with interactive simulation laboratory activities” submitted in partial fulfilment of the requirements for a Master of Education in chemistry, is a record of original work completed by me and has never been submitted to this or any other institution to receive any other degree or certificate.

Rediet Bogale ________________ ___________________

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APPROVAL OF DISSERTATION FOR DEFENSE

We hereby certify that we have supervised, read, and evaluated this thesis entitled "Promoting 11th-grade students' engagement and conceptual understanding in chemical kinetics: a Design-based research approach to POGIL with interactive simulation laboratory activities" prepared under my guidance. I recommend that the Thesis be submitted to oral defense.

Approval of thesis for defense

Mirtachew Tahir (Ph.D)	____________________	June, 2026
Major Advisor's name	Signature	Date
Adem Mohammed (PhD, Assi. Prof.)	____________________	June, 2026
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APPROVAL OF DISSERTATION FOR DEFENSE RESULT

As members of the examination committee, we examined the dissertation entitled "Promoting 11th-grade students' engagement and conceptual understanding in chemical kinetics: a Design-based research approach to POGIL with interactive simulation laboratory activities" by Rediet Bogale. We hereby certify that the dissertation is accepted for fulfilling the requirements for the award of the "Master of Education in Science focused in Chemistry".

Board of Examiners

____________________________	________________	June, 2026
External Evaluator's name	Signature	Date
____________________________	________________	June, 2026
Internal Evaluator's name	Signature	Date
____________________________	________________	June, 2026
Chair Person's Name	Signature	Date

Acknowledgment

First and foremost, I thank Almighty God for granting me the wisdom, strength, and perseverance to complete this research successfully.

I would like to express my sincere gratitude to my supervisor, Dr. Mirtachew Tahir, for his valuable guidance, constructive feedback, and continuous encouragement throughout this study. His expertise and dedication greatly contributed to the quality of this work.

I am also thankful to Bahir Dar University and the Department of Mathematics and Science Education for providing the academic support and resources necessary for conducting this research.

My heartfelt appreciation goes to the Grade 11 students and the chemistry teacher at Tana Haik Secondary School for their willingness to participate in this study. Their contributions were essential to the success of this study.

I also extend my gratitude to my colleagues and friends for their encouragement, support, and helpful suggestions throughout the research and writing process.

Finally, I am deeply grateful to my family for their constant love, patience, understanding, and moral support throughout my academic journey. Their encouragement has been a source of strength and inspiration, and this achievement is shared with them.

Rediet Bogale

June 2026 GC

Abstract

Chemical kinetics is widely recognized as one of the most challenging topics in secondary school chemistry due to its abstract nature and the difficulty students experience in connecting observable phenomena with underlying particle interactions. This study investigated the effectiveness of integrating interactive simulations with process-oriented Guided Inquiry Learning (POGIL) laboratory activities to enhance Grade 11 students' conceptual understanding, achievement, confidence, and engagement in chemical kinetics.

The study employed a Design-based research (DBR) approach within a mixed-methods framework and was conducted with 63 Grade 11 students at Tana Haik Secondary School in Bahir Dar, Ethiopia. Quantitative data were collected through pre- and post-tests, confidence measures, and engagement questionnaires, while qualitative data were gathered through student interviews, teacher interviews, classroom observations, and group discussions. Quantitative data were analyzed using descriptive statistics, paired-samples t-tests, effect size measures, and percentage distributions, whereas qualitative data were analyzed thematically.

The findings revealed significant improvements across all learning outcomes. Students' achievement increased from a mean score of 9.65 to 21.19 out of 32 (d = 4.03), confidence from 6.38 to 13.08 out of 16 (d = 1.94), and engagement from 3.10 to 4.45 on a five-point scale (d = 2.30). Conceptual understanding also improved substantially. Qualitative findings showed that collaborative inquiry, simulation-based exploration, and guided learning enhanced students' participation, motivation, scientific reasoning, and ability to connect macroscopic, microscopic, and symbolic representations. However, some learners still required teacher support to interpret complex microscopic processes. The study concludes that integrating interactive simulations with POGIL laboratory activities creates a more engaging, student-centered, and conceptually meaningful learning environment for secondary school chemistry.

Keywords: *Chemical kinetics, Interactive simulations, POGIL, Design-Based Research, conceptual understanding, student engagement, chemistry education.*

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List of abbreviations and acronyms

Abbreviation	Full Meaning
DBR	Design-Based Research
PhET	PhET Interactive Simulations
DBL	Design-based learning
POGIL	Process Oriented Guided Inquiry Learning
SD	Standard Deviation
sig.	Significance
SPSS	Statistical Package for the Social Sciences
ZPD	Zone of Proximal Development
ICT	Information and Communications Technology
IRB	Institutional Review Board
NEAEA	National Educational Assessment and Examination Agency
DIFF	Difference of scores
RQs	Research questions

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CHAPTER ONE

Introduction

Science education, such as chemistry education, offers immense opportunities for learners beyond mere presentation or acquisition of scientific facts and skills. For example, it includes the development of new ways of thinking, reacting, and behaving (Clement et al., 2017). In addition, it supports industrial development, expansion, and international economic competition (Perera et al., 2014). From secondary school to universities, many students struggle to learn chemistry, and many do not succeed. Indeed, there is a plethora of research that shows several students struggle to grasp fundamental chemistry concepts (Atagana & Engida, 2014). Consequently, the poor performance of learners in chemistry is partly attributed to their lack of sound conceptual understanding, as chemistry is generally regarded as a complex subject by teachers and learners (Broman et al., 2011).

To make it worse, literature showed that teaching and learning of most of science education, particularly physical chemistry including chemical kinetics, is teacher-dominated in both secondary and tertiary levels (Chairam et al., 2009). Chemical kinetics is the study of reaction rates and influencing factors related to it. Besides, this topic is widely recognized as one of the most challenging topics in chemistry education at both secondary and higher levels elsewhere (e.g., Cakmakci, 2010) and in Ethiopia in particular. Due to this, chemical kinetics was chosen for this thesis work aimed at bridging the gap between theory and practice in the teaching and learning of this topic in the Ethiopian chemistry education context. The main reason for this is that chemical kinetics is commonly considered a conceptually demanding area, a cognitive task that frequently leads to persistent misconceptions and fragmented understanding (Karous et al., 2017). These highlight that students are required to integrate macroscopic observation with microscopic and symbolic levels of explanation.

To address these challenges, several studies reiteratively suggested that chemistry teaching and learning integrate theoretical explanations, for which well-thought-out laboratory work practices are promising (e.g., Kurbanoglu & Akim, 2010). As such, studies showed that guided inquiry-based laboratory instructions support students' active construction of scientific explanations and improvement of the necessary skills in experimental design and generating evidence-based reasoning, all of which are relevant for addressing the shortcomings of the taken-for-granted regular teacher-centered approaches (Cetin, 2021).

Additionally, design-based research (DBR) is considered beneficial for enhancing science learning and teaching practices across different levels of education. In this thesis context, DBR is defined as a method that is designed by and for educators to increase the impact, transfer, and translation of educational research into improved practices. Simply put, DBR can be situated in a real educational context, employing the designing and testing of significant interventions, using mixed methods that involve multiple iterations and collaborative partnership between researchers and practitioners, thereby leading to practical and impactful scientific practices (Anderson & Shattuck, 2012). Moreover, process-oriented guided inquiry-based learning (POGIL) is relevant for guiding students to develop content knowledge and key process skills (Straumanis & Simons, 2008). POGIL is a research-based learning environment where students are actively engaged in grasping course content and in developing essential skills by working in self-managed teams on guided inquiry activities (Cascolan & Ph, 2019). Most studies that integrated POGIL into interactive simulations used the lens of constructivist learning theories. As such, the present thesis emphasized the pedagogical design of such interventions that explicitly apply social constructivist theory, which posits that knowledge in science is co-constructed through mediated social activity and discourse (Driver et al., 2025; Simonson & Shadle, 2013). The role of the teachers' role will be to facilitate learning by guiding and monitoring learners and coaching their actions. Despite inquiry-based learning promoting active engagement, its effectiveness may be limited by students' insufficient prior knowledge, the high cognitive demands of open-ended investigations, and the substantial instructional support required for successful implementation (Muhamad et al., 2024).

Furthermore, simulation has great potential for the enhancement of the teaching and learning of scientific concepts (Widiyatmoko, 2018). If adequately implemented, simulations can enable learners to construct a meaningful understanding of chemical concepts (Jere & Mpeta, 2024). Teaching challenging topics, such as reaction kinetics, by using interactive simulations is one of the approaches to teaching that has the potential to assist learners in overcoming the learning difficulties they often encounter in learning complex concepts that make it less accessible to be comprehended by young learners (Jere & Mpeta, 2024). While interactive simulations can enhance conceptual understanding in science, their benefits may be reduced when students lack adequate guidance, leading to superficial exploration and misconceptions rather than deep learning (Jong et al., 2024).

Even though chemical kinetics is the foundation for understanding how fast reactions happen from factory production to how our bodies work, it is not uncommon to see students struggle to learn this topic meaningfully. Preliminary studies on Grade 12 students who were interviewed revealed it is one of the toughest topics, and they tend to score lower grades in this topic (National Educational Assessment and Examination Agency [NEAEA], 2017). For example, according to NEAEA (2017)students who have scored 75% and above at national exams are 2.6% and 6.4% in chemistry from grade 10 and 12, respectively.

Hence, looking for research-based instructional strategies that enhance students' engagement and achievement in the chemical kinetics topics is worth investigating. To this end, research indicated that engagement has the potential to highlight students' performance in a way that standardized assessment methods do not reveal. For example, by using students' prior knowledge and free exploration to teach them scientific concepts may have the advantage of engaging more students in the learning process and advancing their achievements (Doppelt et al., 2008).

Intending to enhance student engagement and deepen conceptual learning through successive cycles of implementation and analysis of laboratory activities, science education researchers highlighted that systematic and iterative application of DBR interventions can lead to fostering students' engagement in and conceptual learning of complex topics such as chemical kinetics (Emily B. Moore, 2013). This study thus employed a Design-Based Research (DBR) approach to address the persistent challenges regarding students' low engagement and achievement in chemical kinetics, a topic students often found abstract and difficult. The intervention is a theoretically grounded design that integrates POGIL laboratory activities with interactive simulations. This approach is expected to facilitate iterative learning processes by co-designing, performing, and refining experiments and lab activities developed, implemented and validated for practical teaching of chemical kinetics in a real chemistry classroom context. This approach is expected to allow the researcher and participating teacher to collaboratively develop and optimize a learning environment where the POGIL and simulations labs are scaffolded by the teachers for promoting concrete laboratory inquiry practices.

Statement of the problem

Despite the ongoing efforts to improve the quality of high school education in Ethiopia, national assessment results are evident to show that these students tend to score low achievement on science subjects, including chemistry. Current instructional practice in Ethiopia is mainly teacher-centered, which has apparently made a limited contribution in terms of supporting students to enhance their conceptual understanding and increasing sustained engagement in chemistry. Dejene et al., 2020). The commonly employed traditional teacher-centered teaching method in Ethiopia makes it less applicable to large class sizes, restricted laboratory resources, and insufficient professional development opportunities for teachers (Berhe et al., 2024).

Chemical kinetics is recognized as one of the main topics that are essential for developing students' scientific reasoning and understanding of real-world chemical processes. However, both national assessment reports and students' awareness revealed that students commonly hold misconceptions and encounter learning difficulties in chemical kinetics, including collision theory, activation energy, and the effects of concentration and temperature on reaction rates.

Traditional Ethiopian classrooms often completely neglect the submicroscopic level, which is exactly why PHET intervention is required. The use of the Johnstone triangle as a fundamental theoretical framework in chemistry education, i.e., macroscopic observations (like color change) with microscopic events (like molecular collision) and symbolic representation (rate equations), is suggested to be relevant in enhancing conceptual learning in science (Johnstone, 1991). Despite this, sometimes teachers themselves are frequently challenged in teaching chemical kinetics effectively because of the limited exposure to such practices as applying inquiry-based pedagogies, digital tools, and leading to increasing students' visualization abilities (Ntalindwa et al., 2024).

The central problem that the present thesis sought to address was to support chemistry educators in developing, testing, and refining a replicable instructional model that combines POGIL in the lens of hands-on and minds-on laboratory activities integrated with interactive simulations. This study thus would create opportunities for the integration of physical and virtual inquiry environments into the high school chemistry education that is commonly taught using the regular instruction already in use. This approach to practical teaching of chemistry is expected to play a central role in enhancing teachers' pedagogical content knowledge, multimedia learning, and cognitive load management in complex science topics, all of which are essential for promoting their students' conceptual development and engagement in chemistry lessons.

Some studies in Ethiopia revealed that combining physical and virtual environments could enhance conceptual learning at a macroscopic level on a quantitative basis. However, these quantitative studies at the same time stated that students tend to struggle in systematically connecting the macroscopic, sub-microscopic, and symbolic levels of representation of the associated chemical concepts in real-world scenarios (Hunegnaw et al., 2025). This clearly shows there is a critical research gap in the pedagogical strategies that lead to students' deep-level scientific learning and active engagement in science.

Hence, the primary aim of this thesis work was to bridge the existing gap between research and practice by closely investigating how the POGIL laboratory activities integrated with interactive simulations could be designed to actively engage students in connecting these three levels, thereby fostering a deeper and more coherent conceptual understanding and proactive engagement in chemical kinetics.

Research questions (RQs)

1. To what extent did the POGIL integrated with interactive simulation laboratory activities affect 11th-grade students' conceptual understanding and improve their achievement in chemical kinetics?
2. How could POGIL integrated with interactive simulation laboratory activities be designed and iteratively refined to support students' conceptual understanding of chemical kinetics?
3. How effective was the POGIL integrated with interactive simulation laboratory activities in influencing students' engagement and their ability to connect macroscopic, microscopic, and symbolic representations in chemical kinetics?

Objectives

General objectives

The main general objective of the thesis research was to design, implement, and evaluate a process-oriented guided inquiry laboratory [POGIL] integrated with an interactive simulation intervention to promote students' conceptual understanding, achievement, and engagement in learning chemical kinetics in the Ethiopian 11th-grade chemistry education context. In addition, this study has focused on strengthening the teachers' abilities in facilitating process-oriented guided inquiry-based instructional processes and applying technology-supported instructional strategies to improve the effectiveness of practical teaching laboratories.

Specific objectives

- To design a POGIL integrated with interactive simulation laboratory activities to address students' conceptual understanding about chemical kinetics.
- To implement POGIL integrated with interactive simulation laboratory activities to address students' conceptual understanding about chemical kinetics.
- To examine to what extent and to identify instructional features of the POGIL integrated with interactive simulation laboratory activities affect students' engagement and conceptual understanding about chemical kinetics.

Significance of the study

Chemical kinetics is widely recognized as one of the most challenging topics in Ethiopian high school chemistry, often resulting in low student engagement and achievement. This study is significant because it introduces and evaluates Process-Oriented Guided Inquiry Learning (POGIL) laboratory activities integrated with interactive simulations within the Ethiopian educational context using a Design-Based Research (DBR) framework. By doing so, the study seeks to create meaningful learning opportunities that enhance students' conceptual understanding of chemical kinetics while increasing their interest and active participation in the learning process.

The study also contributes to classroom practice by providing an innovative and practical instructional approach that can be implemented even in resource-constrained educational settings. Through the integration of POGIL and interactive simulations, students are encouraged to engage in both hands-on and minds-on learning experiences. This approach is designed to address common misconceptions in chemical kinetics while fostering scientific reasoning, collaboration, inquiry, and active engagement in scientific practices.

Furthermore, the findings of this study offer valuable insights for teachers, school leaders, curriculum developers, and educational policymakers. The intervention provides a potential model for improving laboratory instruction and serves as a guideline for designing more effective and student-centered science learning experiences. In addition, the study supports teachers' professional growth by demonstrating how technology-enhanced inquiry approaches can be used to improve learning outcomes.

More broadly, this research helps bridge the gap between theoretical knowledge and practical application in chemistry education. By generating evidence on the design, implementation, and refinement of a POGIL-integrated simulation laboratory model within a DBR framework, the study contributes to efforts aimed at improving instructional quality, enhancing student achievement and engagement, and informing educational reforms. The findings may also support future investments in laboratory facilities, digital learning tools, and teacher development programs.

Interactive simulation-based laboratory activities, when used in synergy with POGIL, have considerable potential to make abstract chemistry concepts more accessible and meaningful. By enabling students to visualize molecular collisions, energy changes, and the factors influencing reaction rates, these approaches promote deeper conceptual understanding and more meaningful engagement with chemical kinetics.

Delimitation of the study

This study was conducted in a selected high school in Bahir Dar, Amhara Region, Ethiopia, and focused on Grade 11 chemistry students. The study was limited to the topic of chemical kinetics and its related subtopics. This study was implemented in a large class which consists 63 students, which made it very challenging to guide each student or let them manipulate the factors by themselves. It examined two key outcomes: students' conceptual understanding and engagement in learning chemical kinetics. The study employed a Design-Based Research (DBR) approach, with emphasis on both quantitative and qualitative data sets to guide the design, implementation, evaluation, and refinement of the instructional intervention.

Operational definitions

Design-based research (DBR): a systematic and iterative research approach that identifies educational problems, develops and implements instructional interventions, and continuously refines them based on evidence gathered during the implementation process.

POGIL laboratory activities: inquiry-based laboratory activities in which students work collaboratively in small groups to investigate chemical kinetics concepts through experimentation, observation, data analysis, and discussion.

Interactive simulations: computer-based learning tools that allow students to manipulate variables and observe their effects on chemical processes. In this study, PhET interactive simulations were used to support learning.

Integrated POGIL laboratory and interactive simulation approach: an instructional approach that combines POGIL laboratory activities with interactive simulations to connect macroscopic, submicroscopic, and symbolic representations, thereby supporting students' understanding of chemical kinetics concepts.

Achievement: students' level of academic performance and mastery of chemical kinetics concepts as demonstrated through assessment tasks.

Conceptual understanding: **s**tudents' ability to explain and apply chemical kinetics concepts by linking observable phenomena, particle-level processes, and symbolic representations.

No understanding: a condition in which students demonstrate incorrect or scientifically unacceptable understandings of chemical kinetics concepts.

Partial understanding: a condition in which students possess incomplete conceptual knowledge. This occurs when students correctly answer only one tier of a diagnostic test or provide a partially correct explanation with limited confidence or incomplete reasoning.

Conceptual understanding category: the highest level of understanding demonstrated by students on the three-tier diagnostic test, reflecting a scientifically acceptable understanding of the concept assessed.

Confidence level: students' self-reported degree of certainty regarding the correctness of their responses.

Student engagement: the extent to which students are behaviorally, emotionally, and cognitively involved in learning chemical kinetics.

Behavioral engagement: **s**tudents' active participation in learning activities, including their attention, effort, persistence, and involvement in classroom and laboratory tasks.

Emotional engagement: students' interest, enjoyment, enthusiasm, and positive feelings toward learning chemical kinetics.

Cognitive engagement: the mental effort students invest in understanding concepts, solving problems, and applying learning strategies to make sense of chemical kinetics.

Chemical kinetics: a branch of chemistry that studies the rates of chemical reactions and the factors that influence those rates, including concentration, temperature, surface area, catalysts, and activation energy.

CHAPTER TWO

Literature Review

Introduction

Education plays a vital role in ensuring the continuity and advancement of society by equipping individuals with the knowledge, skills, and values needed to understand and respond to an ever-changing world. Beyond the acquisition of knowledge, education develops learners' capacity for critical thinking, problem-solving, decision-making, and meaningful participation in society (Berhe et al., 2024; Dewey, 2001). In today's world, where scientific and technological developments increasingly shape daily life, science education has become an essential component of quality education. It prepares learners to navigate complex social, environmental, and technological challenges while contributing to national development and global competitiveness (Perera et al., 2014; Sunga, 2016).

Effective science education extends beyond the transmission of scientific facts and theories. It should also provide opportunities for learners to engage in scientific inquiry, develop reasoning and investigative skills, participate in authentic scientific activities, and appreciate the relationship between science and society (Hodson, 2008). Such learning experiences help students develop positive attitudes toward science and support the construction of meaningful scientific understanding.

Contemporary science education increasingly emphasizes learner-centered instructional approaches that actively engage students in the learning process. These approaches encourage learners to construct knowledge through exploration, collaboration, and reflection rather than through passive reception of information. In this regard, inquiry-based learning and technology-enhanced instructional strategies have gained considerable attention for their potential to improve students' engagement and achievement in science learning.

Chemistry education and conceptual understanding

Chemistry is often regarded as a challenging subject because it requires learners to understand phenomena across multiple levels of representation. According to (Gilbert & Treagust, 2009) meaningful understanding of chemistry requires students to connect three complementary levels of representation: the macroscopic, submicroscopic, and symbolic levels.

The macroscopic level involves observable chemical phenomena that learners can directly experience through laboratory investigations and everyday observations, such as color changes, temperature variations, and gas evolution. The submicroscopic level explains these observable phenomena through models of atoms, molecules, ions, and their interactions. The symbolic level represents chemical phenomena through formulas, equations, graphs, and other forms of scientific notation. Indeed, meaningful chemistry learning occurs when students can successfully connect these three levels and use them to explain chemical phenomena coherently (Gilbert & Treagust, 2009; Jere & Mpeta, 2024).

Developing conceptual understanding is a central goal of chemistry education. Conceptual understanding goes beyond memorizing facts and formulas; it involves the ability to explain scientific phenomena, apply concepts in different contexts, and connect observable events with underlying molecular processes. Research has consistently shown that meaningful learning occurs when students actively construct conceptual understanding rather than relying on rote memorization (Adadan et al., 2010).

However, many students experience difficulties in chemistry because they struggle to integrate macroscopic observations with submicroscopic explanations and symbolic representations. These difficulties often result in misconceptions and fragmented understanding, limiting students' ability to apply scientific concepts effectively. Consequently, instructional approaches that explicitly support connections among these representational levels are essential for improving students' learning outcomes in chemistry.

Chemical kinetics as a challenging topic in chemistry

Chemical kinetics is a fundamental component of high school and tertiary chemistry curricula because it provides the foundation for understanding how and why chemical reactions occur at different rates. The topic is closely linked to other important areas of chemistry, including thermodynamics, chemical equilibrium, particle theory, and reaction mechanisms (Habiddin & Page, 2023; Holme et al., 2015).

Chemical kinetics examines the rates of chemical reactions and the factors that influence those rates, such as concentration, temperature, surface area, catalysts, and activation energy. Understanding these factors requires learners to relate observable changes in chemical systems to molecular-level interactions and collision processes (Towns, 2016).

Despite its importance, chemical kinetics is widely recognized as one of the most difficult topics in chemistry education. Many of its central concepts are abstract and involve processes that cannot be directly observed. Students are often required to visualize molecular collisions, energy distributions, and reaction mechanisms while simultaneously interpreting symbolic representations such as equations, graphs, and mathematical relationships (Habiddin & Page, 2023).

Johnstone's (1991) model of chemical representation suggests that meaningful learning in chemistry requires coordination of the macroscopic, sub-microscopic, and symbolic levels of understanding. However, students frequently focus on one level while failing to connect it with the others, resulting in misconceptions and superficial learning. In chemical kinetics, this challenge becomes particularly evident when learners can describe observable changes in reaction rates but cannot explain the molecular processes responsible for those changes.

Addressing these challenges requires instructional approaches that make invisible chemical processes more accessible and support students in linking observable phenomena with scientific explanations. Inquiry-based laboratory experiences and interactive simulations offer promising opportunities to achieve this goal by allowing students to investigate chemical phenomena while simultaneously visualizing the molecular processes that underlie them.

Process-oriented guided inquiry learning (POGIL)

Process-oriented guided inquiry learning (POGIL) is a student-centered instructional approach that combines guided inquiry with cooperative learning. Originally developed in chemistry education, POGIL engages students in constructing their own understanding of scientific concepts while simultaneously developing important process skills such as critical thinking, problem solving, communication, teamwork, and self-directed learning (Loertscher, 2007).

In a POGIL classroom, students work collaboratively in small groups on carefully designed activities that guide them through a cycle of exploration, concept invention, and application. Rather than receiving information directly from the teacher, learners actively investigate data, identify patterns, construct explanations, and apply newly developed concepts to solve problems. The teacher's role shifts from that of information provider to facilitator, guiding students' learning through questioning and scaffolding.

Research has demonstrated that POGIL can improve students' conceptual understanding, scientific reasoning, and academic achievement while reducing reliance on passive learning strategies (Walker & Warfa, 2017). The approach is particularly relevant to chemical kinetics because many of the topic's core concepts, such as reaction rates, molecular collisions, and activation energy, require learners to actively construct explanations based on evidence and reasoning rather than memorizing isolated facts (Treagust & Duit, 2008).

Several studies have reported positive outcomes associated with POGIL implementation in chemistry classrooms and laboratories. For instance, students exposed to POGIL often demonstrate higher levels of engagement, improved problem-solving abilities, and stronger conceptual understanding compared with those taught through regular lecture-based methods (Moog & Spencer, 2008; Walker & Warfa, 2017). The collaborative nature of POGIL also promotes communication, peer learning, and the development of scientific reasoning skills that are essential for meaningful chemistry learning.

However, evidence from the literature suggests that the effectiveness of POGIL is not always consistent across contexts and learning environments. Some studies have found that the successful implementation of POGIL depends heavily on teacher expertise, classroom management, student readiness for inquiry-based learning, and the availability of sufficient instructional time (Eberlein & Kampmeires, 2008). In classrooms where students are unfamiliar with collaborative learning or where teachers have limited experience facilitating inquiry, the benefits of POGIL may be reduced.

Research has also shown that some students initially struggle with the increased responsibility required in POGIL environments. Compared with regular teacher-directed instruction, inquiry-based learning can place greater cognitive demands on learners, particularly those with limited prior knowledge or weak self-regulation skills (Kirschner et al., 2020). Without adequate scaffolding, some students may experience confusion, frustration, or difficulty constructing scientifically accurate explanations.

In laboratory settings, POGIL-based activities may require more preparation time, instructional resources, and facilitation skills than conventional laboratory approaches. While guided inquiry laboratories encourage deeper learning, they can also create challenges related to time management, completion of laboratory tasks, and coverage of curriculum content (A. V. I. Hofstein & Lunetta, 2004). Furthermore, some studies have reported that although POGIL improves engagement and process skills, its effects on achievement outcomes are sometimes comparable to, rather than significantly higher than, other well-designed active learning approaches (Eberlein & Kampmeires, 2008).

These findings suggest that POGIL should not be viewed as a universally effective solution for all chemistry learning challenges. Rather, its effectiveness appears to depend on how it is designed, implemented, and supported within specific educational contexts. Consequently, researchers have increasingly emphasized the importance of complementing POGIL with additional instructional supports that can enhance conceptual visualization, provide immediate feedback, and reduce cognitive barriers associated with complex scientific concepts.

In the context of chemical kinetics, where students often struggle to visualize molecular collisions, reaction mechanisms, and energy changes, integrating interactive simulations with POGIL may help address some of these limitations. Interactive simulations can provide dynamic representations of submicroscopic processes that are difficult to observe in cookbook-style laboratory settings, while POGIL offers the collaborative inquiry structure needed to guide students' exploration and reasoning. Therefore, combining POGIL with interactive simulation laboratory activities may provide a more comprehensive instructional approach for promoting both engagement and achievement in chemical kinetics.

By engaging students in collaborative inquiry, evidence-based reasoning, hands-on experimentation, and technology-supported visualization, the integrated approach creates opportunities for deeper understanding and sustained engagement in chemistry learning. These characteristics make it a promising strategy for addressing the conceptual difficulties commonly associated with chemical kinetics.

Laboratory learning as a pedagogical strategy

Laboratory learning has long been recognized as a fundamental component of science education because it provides students with opportunities to actively engage in scientific inquiry and develop a deeper understanding of scientific concepts. Unlike regular lecture-based instruction, laboratory activities allow learners to interact directly with scientific phenomena through observation, experimentation, data collection, and interpretation. Such experiences help students connect theoretical knowledge with practical applications, making learning more meaningful and relevant.

The educational value of laboratory learning extends beyond the acquisition of scientific knowledge. Well-designed laboratory activities promote the development of scientific process skills, including observation, measurement, hypothesis formulation, experimental design, data analysis, and evidence-based reasoning (Hofstein & Mamlok-naaman, 2007). These skills are essential for fostering scientific literacy and preparing students to think critically about scientific problems.

In recent years, science education reforms have emphasized inquiry-oriented laboratory experiences that actively involve learners in the construction of knowledge. Guided inquiry laboratories, in particular, encourage students to investigate scientific questions, generate explanations from evidence, and engage in scientific argumentation. Such learning environments support deeper conceptual understanding and help learners develop a more authentic view of scientific practice (Hofstein et al., 2005).

The role of laboratory instruction is especially important in chemistry education, where many concepts are abstract and difficult to visualize. Through laboratory investigations, students can observe chemical phenomena directly and relate these observations to scientific explanations. However, conventional laboratory activities often focus primarily on procedural tasks and verification of known results, limiting opportunities for conceptual development. Therefore, laboratory experiences should be carefully designed to promote inquiry, reflection, and conceptual reasoning rather than mere completion of experimental procedures.

Within the context of chemical kinetics, laboratory activities provide opportunities for students to investigate factors affecting reaction rates, observe chemical changes, and collect evidence that supports scientific explanations. When combined with guided inquiry approaches, laboratory learning can help students develop a more meaningful understanding of reaction processes and their underlying mechanisms, particularly when these approaches are integrated with interactive simulations; the experience will be rewarding.

Interactive simulations in chemistry education

Advances in educational technology have created new opportunities for enhancing science learning through interactive digital tools. Among these innovations, interactive simulations have emerged as powerful instructional resources for supporting the teaching and learning of complex scientific concepts. Interactive simulations are computer-based models that allow learners to manipulate variables, observe outcomes, test hypotheses, and explore scientific phenomena in dynamic and visual ways.

The use of simulations is particularly valuable in chemistry education because many chemical processes occur at the molecular level and cannot be directly observed. Interactive simulations enable students to visualize abstract concepts such as molecular collisions, particle interactions, energy changes, and reaction mechanisms, thereby making invisible processes more accessible and understandable (Smetana et al., 2014). By providing visual representations of scientific phenomena, simulations help students connect observable events with underlying molecular processes and support the development of conceptual understanding.

From a constructivist perspective, simulations provide learning environments in which students actively construct knowledge through exploration and experimentation. Rather than passively receiving information, learners interact with scientific representations, make predictions, test ideas, and revise their understanding based on feedback. This active involvement encourages deeper learning and supports conceptual change (Rannikmäe et al., 2020).

A growing body of research has shown that interactive simulations can positively influence students' conceptual understanding, motivation, engagement, and achievement in science learning (Rutten et al., 2012; Wieman et al., 2008). Simulations provide opportunities for repeated experimentation without the time, safety, and resource constraints often associated with physical laboratory activities. They also allow students to investigate scientific phenomena that may be difficult, expensive, or impossible to observe directly in school laboratory settings. In chemistry education, simulations have been particularly effective in helping students understand abstract concepts by making sub-microscopic processes visible and interactive.

Furthermore, interactive simulations support inquiry-based learning by enabling students to manipulate variables, investigate cause-and-effect relationships, test hypotheses, and receive immediate feedback on their actions. Such experiences can enhance scientific reasoning and encourage learners to take a more active role in the learning process (Smetana et al., 2014). For topics such as chemical kinetics, simulations can help students visualize reaction rates, molecular collisions, activation energy, and the effects of different variables on reaction processes, thus promoting deeper conceptual understanding.

Despite these advantages, research also indicates that interactive simulations are not always effective when used in isolation. While simulations can capture students' attention and increase interest in learning, meaningful learning does not automatically occur simply because technology is introduced into the classroom. Students may focus on manipulating features, exploring visual effects, or completing tasks without developing scientifically accurate explanations of the concepts being represented (Jond & Joolingen, 2017).

Several studies have reported that learners may experience cognitive overload when working with simulations, particularly when multiple variables and representations are presented simultaneously

(Jong, 2006). Students with limited prior knowledge may struggle to interpret simulation outputs, identify important relationships, or connect virtual experiences to underlying scientific principles. Consequently, some learners may develop fragmented understanding or reinforce misconceptions rather than achieve conceptual change.

Research comparing simulation-based instruction with guided instructional approaches suggests that simulations are most effective when accompanied by appropriate scaffolding, teacher guidance, and structured inquiry activities (Rutten et al., 2012). Without such support, students may engage in unproductive trial-and-error exploration that limits the educational value of the simulation. Similarly, studies have found that simulation-based learning environments often produce stronger learning outcomes when integrated with collaborative discussion, laboratory investigations, and inquiry-oriented instructional strategies than when used as stand-alone teaching tools (Jong, 2013).

Another limitation is that simulations cannot fully replace the educational value of hands-on laboratory experiences. Although simulations provide valuable opportunities for visualization and experimentation, they do not allow students to develop practical laboratory skills such as handling equipment, making measurements, conducting experiments, and dealing with real-world experimental uncertainties (A. V. I. Hofstein & Lunetta, 2004). As a result, many researchers recommend using simulations as a complement to, rather than a substitute for, laboratory instruction.

These findings suggest that the educational value of interactive simulations depends largely on how they are designed and integrated into instruction. Their effectiveness increases when they are embedded within pedagogical approaches that provide guidance, encourage inquiry, promote collaboration, and support reflection on learning. Therefore, combining interactive simulations with process-oriented guided inquiry learning (POGIL) may help address many of the limitations associated with simulation-based learning alone.

In the context of chemical kinetics, integrating simulations with POGIL laboratory activities offers a particularly promising approach. While simulations make molecular-level processes visible and accessible, POGIL provides the collaborative inquiry structure needed to guide students' exploration, interpretation, and reasoning. Together, these approaches can support connections among macroscopic observations, sub-microscopic explanations, and symbolic representations, essentially promoting deeper conceptual understanding, greater engagement, and improved achievement in chemistry learning.

Integrating POGIL with interactive simulations for chemical kinetics learning

Although both POGIL and interactive simulations have demonstrated positive effects on student learning, their integration offers unique opportunities for addressing the conceptual challenges associated with chemical kinetics. Each approach contributes distinct strengths that can complement and reinforce one another. Research increasingly suggests that combining inquiry-based pedagogies with technology-enhanced learning environments can promote deeper conceptual understanding and more meaningful student engagement than either approach alone (Fukuda et al., 2024; Wu et al., 2021).

On one hand, POGIL provides a structured inquiry environment in which students collaboratively construct knowledge through guided exploration and discussion. Interactive simulations, on the other hand, provide visual and dynamic representations of molecular-level processes that are otherwise invisible to learners. When integrated effectively, these approaches create a learning environment that combines inquiry, visualization, collaboration, and reflection. Such integration aligns with contemporary views of science learning that emphasize active knowledge construction and multiple representations of scientific concepts (Rannikmäe et al., 2020).

In the context of chemical kinetics, such integration is particularly important because students are expected to understand relationships between observable reaction behavior and molecular-level interactions. Physical laboratory investigations allow students to observe changes in reaction rates and collect empirical evidence at the macroscopic level. Interactive simulations simultaneously enable learners to visualize particle collisions, energy distributions, and reaction mechanisms at the sub-microscopic level. Through guided-inquiry activities, students can connect these experiences to symbolic representations such as chemical equations, graphs, and mathematical relationships. Studies have shown that learning environments that support movement across these representational levels significantly improve students' conceptual understanding of chemistry concepts (Habiddin & Page, 2023; Jere & Mpeta, 2024).

This integrated approach supports the development of representational competence by helping students establish meaningful connections among macroscopic, sub-microscopic, and symbolic levels of chemical representation. Furthermore, the collaborative nature of POGIL encourages students to discuss observations, justify explanations, challenge misconceptions, and construct scientific understanding collectively. Recent studies have reported that simulation-supported inquiry learning enhances students' reasoning, conceptual understanding, and engagement by enabling learners to test hypotheses, visualize invisible phenomena, and receive immediate feedback on their ideas (Fukuda et al., 2024).

The present thesis research is built upon the assumption that combining POGIL laboratory activities with interactive simulations can create a richer and more effective learning environment than either approach alone. By integrating hands-on experimentation with dynamic visualization and guided inquiry, the intervention seeks to promote deeper conceptual understanding, higher levels of engagement, and improved achievement in chemical kinetics. This assumption is supported by research indicating that instructional approaches that combine inquiry, collaboration, and technology-enhanced visualization are particularly effective for learning complex and abstract chemistry concepts (Habiddin & Page, 2023; Wu et al., 2021).

Design-based research [DBR] as a framework for educational innovation

Design-based research (DBR) has gained increasing recognition as an effective methodology for developing and studying educational innovations in authentic learning environments. Unlike cookbook-style experimental approaches that primarily focus on evaluating predetermined interventions, DBR emphasizes the iterative design, implementation, evaluation, and refinement of instructional solutions aimed at addressing real educational challenges.

A defining characteristic of DBR is its close connection between theory and practice. Researchers and practitioners work collaboratively to identify educational problems, design interventions informed by theory, implement those interventions in real settings, and continuously refine them based on evidence gathered during implementation (Cochrane, 2020).

DBR typically involves four interconnected phases: analysis and exploration, design and construction, evaluation and reflection, and theory development. Through repeated cycles of implementation and refinement, researchers generate both practical solutions and theoretical insights that contribute to educational improvement.

The present study adopts a DBR approach because improving students' engagement and achievement in chemical kinetics requires more than simply testing an instructional strategy. It involves designing, implementing, and refining an integrated POGIL-simulation laboratory model that responds to the realities of classroom practice. By examining how students interact with the intervention and how learning outcomes evolve over time, DBR provides a suitable framework for generating evidence-based instructional innovations.

Social constructivism as the theoretical foundation of the study

This study is grounded in social constructivist theory, which views learning as a social process through which knowledge is actively constructed through interaction, collaboration, and shared meaning-making (Vygotsky, 1978). According to this perspective, learning occurs most effectively when learners engage in dialogue, exchange ideas, and work collaboratively to solve problems within supportive learning environments.

Social constructivism emphasizes the importance of social interaction, language, and cultural tools in cognitive development. Learning is not viewed as the *passive* acquisition of information but as an *active* process of constructing understanding through participation in meaningful activities. Teachers play a facilitative role by providing guidance, scaffolding, and opportunities for collaborative inquiry.

The principles of social constructivism align closely with both POGIL and interactive simulation-based learning. In POGIL environments, students work collaboratively to explore concepts, interpret evidence, and develop explanations. Similarly, interactive simulations serve as cognitive tools that support exploration, visualization, and discussion of scientific phenomena. Through guided inquiry and collaborative learning, students are encouraged to construct understanding collectively while receiving support from peers, teachers, and instructional resources.

The integration of laboratory investigations, simulations, and collaborative inquiry in this study reflects the central assumptions of social constructivism and provides a strong theoretical foundation for promoting meaningful learning in chemical kinetics.

Student engagement in science learning

Student engagement is widely recognized as one of the most important factors influencing learning outcomes in science education. Engaged students are more likely to participate actively in learning activities, invest effort in understanding concepts, persist when faced with challenges, and achieve higher academic outcomes. Research consistently identifies engagement as a key predictor of academic success, retention, and meaningful learning across educational contexts (Fredricks et al., 2004; Sinatra et al., 2015). As science education increasingly emphasizes inquiry, problem-solving, and conceptual understanding, student engagement has become a central indicator of educational quality and effectiveness.

Contemporary literature conceptualizes student engagement as a multidimensional construct consisting of behavioral, emotional, and cognitive dimensions (Fredricks et al., 2004). These dimensions are closely interconnected and collectively influence how students interact with learning experiences. According to (Fredricks et al., 2004) meaningful engagement occurs when students are not only physically involved in learning activities but also emotionally connected to the learning environment and cognitively invested in understanding the content.

Behavioral engagement refers to students' active participation in classroom and laboratory activities. It includes behaviors such as attentiveness, effort, persistence, participation in discussions, and completion of learning tasks. Students who demonstrate high behavioral engagement are actively involved in the learning process and are more likely to take responsibility for their own learning. In science classrooms, behavioral engagement is often reflected in students' willingness to participate in investigations, laboratory activities, and collaborative problem-solving tasks (Appleton, 2008).

Emotional engagement relates to students' feelings, attitudes, and emotional responses toward learning. It encompasses interest, enjoyment, enthusiasm, curiosity, and a sense of belonging within the learning environment. Positive emotional engagement contributes to motivation and encourages students to remain involved in learning activities. Research suggests that students who experience enjoyment and interest in science are more likely to develop positive attitudes toward the subject and pursue further learning opportunities in science-related fields (katrin Vaino, 2012; Sinatra et al., 2015).

Cognitive engagement refers to the mental effort students invest in learning. It involves the use of deep learning strategies, critical thinking, self-regulation, and a willingness to understand complex concepts rather than relying on surface-level memorization. Students with high cognitive engagement actively seek to make sense of information, connect new knowledge with prior understanding, and apply learning in meaningful ways. Cognitive engagement is particularly important in science learning because conceptual understanding often requires students to challenge existing misconceptions and reconstruct their understanding of scientific phenomena (Chi & Wylie, 2014).

Inquiry-based instructional approaches have been shown to enhance all three dimensions of engagement by shifting the focus of learning from passive reception of information to active knowledge construction. Through questioning, investigation, collaboration, and evidence-based reasoning, students become participants in the learning process rather than recipients of information (Attard et al., 2021; National Research Council, 2012). Studies have demonstrated that inquiry-oriented learning environments promote greater student ownership of learning, increased motivation, and stronger engagement in scientific practices (Marie et al., 2012).

Similarly, technology-enhanced learning environments, particularly those involving interactive simulations, can further strengthen engagement by providing dynamic and interactive learning experiences that encourage exploration and discovery. Interactive simulations enable students to manipulate variables, test ideas, visualize invisible processes, and receive immediate feedback, all of which contribute to increased behavioral, emotional, and cognitive engagement (Rutten et al., 2012; Wieman et al., 2008). Recent studies have further indicated that simulation-supported inquiry activities can enhance students' interest, participation, and conceptual understanding by creating opportunities for active exploration and collaborative learning(Fukuda et al., 2024).

In the context of chemical kinetics, maintaining student engagement is particularly important because the topic involves abstract concepts that many learners find difficult to understand. Students are expected to connect observable changes in reaction rates with molecular-level interactions and symbolic representations, which often present significant conceptual challenges (Habiddin & Page, 2023). Integrating POGIL laboratory activities with interactive simulations has the potential to enhance behavioral, emotional, and cognitive engagement by providing students with meaningful opportunities to investigate chemical phenomena, visualize molecular processes, collaborate with peers, and construct scientific explanations. Such learning environments align with contemporary recommendations for science instruction that emphasize active learning, inquiry, and multiple representations to support deeper engagement and understanding (National Research Council, 2012;Jere & Mpeta, 2024).

Given its strong relationship with learning outcomes, conceptual understanding, and academic achievement, student engagement serves as one of the primary outcome variables in the present study. Examining engagement across its behavioral, emotional, and cognitive dimensions provides valuable insights into how students interact with the integrated POGIL and interactive simulation intervention and how these interactions contribute to meaningful learning in chemical kinetics.

Student achievement and conceptual understanding in chemistry

Student achievement is a key indicator of educational success and reflects the extent to which learners attain intended learning outcomes. In chemistry education, achievement involves more than the ability to recall facts and apply formulas; it includes the development of meaningful conceptual understanding, scientific reasoning, and the ability to apply knowledge to explain phenomena and solve problems in different contexts(Taber, 2018). As a result, contemporary chemistry education increasingly emphasizes understanding rather than memorization as a measure of academic success.

Conceptual understanding is particularly important in chemistry because many chemical concepts are abstract and require learners to connect observable phenomena with molecular-level explanations and symbolic representations. According to (Johnstone, 1991) meaningful learning in chemistry depends on students' ability to move between the macroscopic, submicroscopic, and symbolic levels of representation. Students who possess strong conceptual understanding can explain scientific ideas using appropriate reasoning, transfer knowledge to new situations, and establish meaningful connections among related concepts (Adadan et al., 2010; Gilbert & Treagust, 2009).

However, developing conceptual understanding remains a major challenge in chemistry education. Many students struggle to relate observable chemical phenomena to underlying particle interactions and symbolic representations, resulting in fragmented knowledge and persistent misconceptions (Taber, 2018; Talanquer, 2011). These difficulties are particularly evident in topics such as chemical kinetics, where learners are expected to understand abstract concepts including molecular collisions, activation energy, reaction mechanisms, and factors affecting reaction rates (Habiddin & Page, 2023).

Research has consistently shown that instructional approaches emphasizing active learning, inquiry, collaboration, and conceptual exploration produce greater achievement gains than traditional teacher-centered methods (Freeman et al., 2014; Hattie, 2009). Active learning environments encourage students to engage with scientific ideas, discuss alternative explanations, test hypotheses, and construct understanding through evidence-based reasoning. Such experiences promote deeper learning and support long-term retention of knowledge.

In chemistry education, student-centered approaches such as Process-Oriented Guided Inquiry Learning (POGIL) have been associated with improved conceptual understanding, higher achievement, and stronger scientific reasoning skills (Moog & Spencer, 2008; Walker & Warfa, 2017). Through collaborative inquiry and guided exploration, POGIL encourages learners to develop scientific concepts actively rather than passively receiving information from the teacher. Similarly, simulation-based learning environments have demonstrated positive effects on student achievement by enabling learners to visualize abstract processes, manipulate variables, test ideas, and explore scientific concepts in interactive ways (Jong, 2013; Rutten et al., 2012).

Recent research further suggests that instructional approaches combining inquiry-based learning with technology-enhanced visualization can significantly improve students' conceptual understanding of complex scientific concepts. By supporting connections among multiple representations and providing opportunities for active exploration, such approaches help learners develop more coherent and scientifically accurate understandings of chemistry concepts (Jere & Mpeta, 2024).

Achievement and engagement are closely related constructs. Students who are actively engaged in learning are more likely to invest effort, persist through challenges, employ effective learning strategies, and develop deeper conceptual understanding, which ultimately contributes to improved academic performance (Fredricks et al., 2004; Sinatra et al., 2015). Likewise, students who achieve success in learning often develop stronger motivation and confidence, creating a positive relationship between engagement and achievement. Consequently, educational interventions that successfully promote engagement frequently contribute to improved achievement outcomes.

Within the Ethiopian educational context, national assessment reports have indicated persistent challenges in students' achievement in science subjects, including chemistry, highlighting the need for innovative instructional approaches that support conceptual understanding and active participation in learning (NEAEA, 2017). Studies conducted in Ethiopian secondary schools have identified factors such as teacher-centered instructional practices, limited laboratory resources, inadequate instructional materials, and insufficient opportunities for inquiry-based learning as major contributors to low achievement and weak conceptual understanding in chemistry(Berhe et al., 2024; Demelash, 2023).

Given these challenges, the present study seeks to improve students' achievement in chemical kinetics through the integration of POGIL laboratory activities and interactive simulations. By promoting inquiry, visualization, collaboration, and active learning, the intervention is expected to strengthen students' conceptual understanding of chemical kinetics concepts and contribute to improved academic performance. Furthermore, by helping students connect macroscopic observations with submicroscopic explanations and symbolic representations, the intervention aims to support meaningful learning and reduce common misconceptions associated with chemical kinetics.

Empirical review and research gap

A substantial body of research has examined the effectiveness of student-centered instructional approaches in improving science learning outcomes. Among these approaches, Process-oriented guided inquiry learning (POGIL) has received considerable attention in chemistry education because of its emphasis on guided inquiry, collaborative learning, and the development of process skills. Empirical studies have generally reported positive effects of POGIL on students' conceptual understanding, scientific reasoning, problem-solving abilities, and academic achievement. For example, (Moog & Spencer, 2008) found that students participating in POGIL-based instruction demonstrated greater conceptual understanding and higher levels of engagement than those taught through traditional lecture-based methods. Similarly, (Walker & Warfa, 2017) reported that POGIL enhanced students' critical thinking, collaborative learning skills, and academic performance in science courses.

Despite these positive findings, evidence regarding the effectiveness of POGIL is not entirely consistent. Some studies have indicated that the success of POGIL depends on factors such as teacher expertise, classroom culture, student preparedness, and the quality of instructional implementation (Eberlein & Kampmeires, 2008). Other researchers have noted that inquiry-based approaches may place substantial cognitive demands on learners, particularly when adequate scaffolding is not provided (Kirschner et al., 2020). These findings suggest that while POGIL has considerable potential for promoting meaningful learning, its effectiveness may be strengthened when combined with complementary instructional supports that facilitate visualization, conceptual connections, and learner guidance.

Parallel to the development of inquiry-based learning approaches, growing attention has been given to the use of interactive simulations in science education. Research has consistently demonstrated that simulations can enhance students' understanding of abstract scientific concepts by providing visual and interactive representations of phenomena that are difficult to observe directly (Rutten et al., 2012). In chemistry education, simulations have been particularly effective in helping students visualize molecular-level processes, explore cause-and-effect relationships, and engage in scientific inquiry (Wieman et al., 2008).

Several studies have reported positive effects of simulation-based learning on students' conceptual understanding, motivation, engagement, and achievement. For example, (Rutten et al., 2012) found that simulation-supported learning environments improved students' conceptual understanding when integrated with appropriate instructional guidance. Similarly (Jong, 2013) concluded that virtual learning environments can effectively complement laboratory instruction by providing opportunities for exploration, visualization, and experimentation. More recent studies have shown that simulation-supported inquiry learning promotes students' reasoning, engagement, and conceptual development, particularly when learners are guided through structured inquiry activities (Fukuda et al., 2024).

However, research also indicates that simulations alone do not automatically lead to meaningful learning. Students may focus on manipulating features without fully understanding the underlying scientific concepts if adequate scaffolding is absent (Jong, 1998). Moreover, simulations cannot entirely replace hands-on laboratory experiences because they do not provide opportunities to develop practical laboratory skills or engage directly with physical phenomena (A. V. I. Hofstein & Lunetta, 2004). Consequently, researchers increasingly recommend integrating simulations with inquiry-based pedagogies and laboratory activities to maximize their educational value.

Recognizing the complementary strengths of inquiry-based instruction and interactive simulations, several studies have explored integrated learning environments that combine these approaches. Findings suggest that students benefit when opportunities for scientific investigation are accompanied by visual representations that support understanding of underlying mechanisms. Simulation-supported inquiry environments have been associated with improvements in conceptual understanding, engagement, and scientific reasoning compared with conventional instructional methods (Wu et al., 2021). These findings are particularly relevant to chemistry education, where students often struggle to connect observable phenomena with molecular-level explanations.

Within chemistry education, chemical kinetics has consistently been identified as one of the most conceptually challenging topics for students. Research has shown that learners frequently experience difficulties understanding collision theory, activation energy, reaction mechanisms, and the factors influencing reaction rates because these concepts require coordination of macroscopic, submicroscopic, and symbolic representations (Habiddin & Page, 2023; Talanquer, 2011). Studies have further revealed persistent misconceptions regarding reaction rates and molecular interactions, even among students who can successfully perform mathematical calculations related to kinetics (Towns, 2016). These findings highlight the need for instructional approaches that support conceptual visualization, inquiry, and representational competence in the teaching of chemical kinetics.

In the Ethiopian context, research examining innovative instructional approaches in chemistry education remains relatively limited. Available studies suggest that active learning and technology-enhanced instructional strategies can positively influence students' engagement and achievement. For example, (Demelash, 2023, 2024) reported that simulation-supported chemistry instruction enhanced students' behavioral, emotional, and cognitive engagement while also improving academic achievement. Nevertheless, much of the existing research has focused on evaluating learning outcomes rather than systematically designing and refining instructional interventions to address context-specific educational challenges.

Another notable limitation in the literature concerns methodological approaches. While many studies have investigated the effectiveness of instructional interventions through experimental and quasi-experimental designs, relatively few have employed Design-based research (DBR) methodologies. DBR offers unique advantages because it enables researchers to develop, implement, evaluate, and iteratively refine instructional innovations in authentic educational settings while simultaneously generating theoretical and practical knowledge (Anderson & Shattuck, 2012). The limited use of DBR in chemistry education suggests a need for studies that examine not only whether an intervention works, but also how and why it works in real classroom contexts.

Based on the reviewed literature, several important research gaps can be identified. First, although POGIL and interactive simulations have independently demonstrated positive effects on learning, there is limited research examining their integrated use within chemistry laboratory instruction. Second, relatively few studies have focused specifically on chemical kinetics despite its recognized conceptual complexity and persistent learning difficulties. Third, existing studies rarely investigate the combined influence of integrated POGIL and simulation-based learning on both student engagement and achievement simultaneously, particularly at the secondary school level. Fourth, there is a shortage of research employing Design-Based Research methodologies to systematically design, implement, evaluate, and refine integrated instructional interventions in authentic science classrooms. Finally, evidence from Ethiopian secondary schools remains scarce, creating a need for contextually relevant research that addresses local educational challenges and resource constraints.

The present study seeks to address these gaps by designing, implementing, and refining an integrated POGIL laboratory and interactive simulation intervention for teaching chemical kinetics through a Design-Based Research framework. By examining its effects on students' behavioral, emotional, and cognitive engagement, conceptual understanding, and academic achievement, the study aims to contribute both practical and theoretical insights to chemistry education. Furthermore, the study is expected to provide evidence-based guidance for teachers, curriculum developers, and policymakers seeking to enhance the quality of chemistry instruction in Ethiopian secondary schools and similar educational contexts.

Conceptual framework of the study

The conceptual framework of this study is grounded in social constructivist theory (Vygotsky, 1978) and informed by the principles of inquiry-based learning, technology-enhanced instruction, and design-based research (DBR). The framework is based on the assumption that meaningful learning occurs when students actively construct knowledge through interaction with peers, teachers, instructional materials, and learning environments. From this perspective, learning is viewed as a collaborative and reflective process in which students develop understanding through exploration, discussion, and engagement with scientific phenomena.

The central instructional intervention in this study is the integration of Process-Oriented Guided Inquiry Learning (POGIL) laboratory activities with interactive simulations. This integrated approach serves as the independent variable and is designed to support students' learning of chemical kinetics through guided inquiry, collaborative problem-solving, hands-on experimentation, and technology-supported visualization. The intervention seeks to address the conceptual challenges associated with chemical kinetics by enabling students to investigate reaction processes, manipulate relevant variables, and construct evidence-based explanations.

The framework assumes that the instructional intervention influences learning through several interconnected mechanisms. POGIL activities provide opportunities for active inquiry, peer interaction, scientific discussion, and collaborative knowledge construction. Interactive simulations complement these experiences by making invisible molecular processes visible, allowing students to explore particle collisions, activation energy, reaction mechanisms, and factors affecting reaction rates. Together, these learning experiences help students connect macroscopic observations, submicroscopic explanations, and symbolic representations, which are widely recognized as essential components of meaningful chemistry learning (Gilbert & Treagust, 2009; Johnstone, 1991).

The framework further proposes that participation in integrated POGIL and simulation-based learning activities promotes student engagement across three dimensions: behavioral, emotional, and cognitive engagement (Fredricks et al., 2004). Behavioral engagement is reflected in students' active participation in laboratory and inquiry activities; emotional engagement is reflected in their interest, enjoyment, and positive attitudes toward learning chemical kinetics; and cognitive engagement is reflected in the mental effort they invest in understanding concepts, solving problems, and applying scientific reasoning. These dimensions of engagement are expected to interact and reinforce one another during the learning process.

Increased engagement is anticipated to facilitate deeper conceptual understanding of chemical kinetics concepts. As students actively investigate phenomena, discuss ideas with peers, and visualize molecular-level processes, they are expected to develop more scientifically accurate and coherent understandings of reaction rates, collision theory, activation energy, catalysts, and related concepts. Improved conceptual understanding is, in turn, expected to contribute to higher levels of academic achievement, as students become better able to explain, apply, and transfer their knowledge to new contexts.

The design-based research process provides the methodological framework for developing, implementing, evaluating, and refining the intervention. Through iterative cycles of analysis, design, implementation, evaluation, and revision, the instructional model is continuously improved based on evidence collected from classroom practice. This iterative process ensures that the intervention remains responsive to learners' needs and classroom realities while simultaneously generating practical and theoretical insights for chemistry education.

Accordingly, the conceptual framework proposes that the integration of POGIL laboratory activities and interactive simulations enhances students' behavioral, emotional, and cognitive engagement, which supports the development of conceptual understanding and ultimately leads to improved achievement in chemical kinetics. The framework also recognizes the iterative role of design-based research in refining the intervention and strengthening its effectiveness within authentic educational settings. The conceptual framework of this thesis research is summarized in Figure 1.

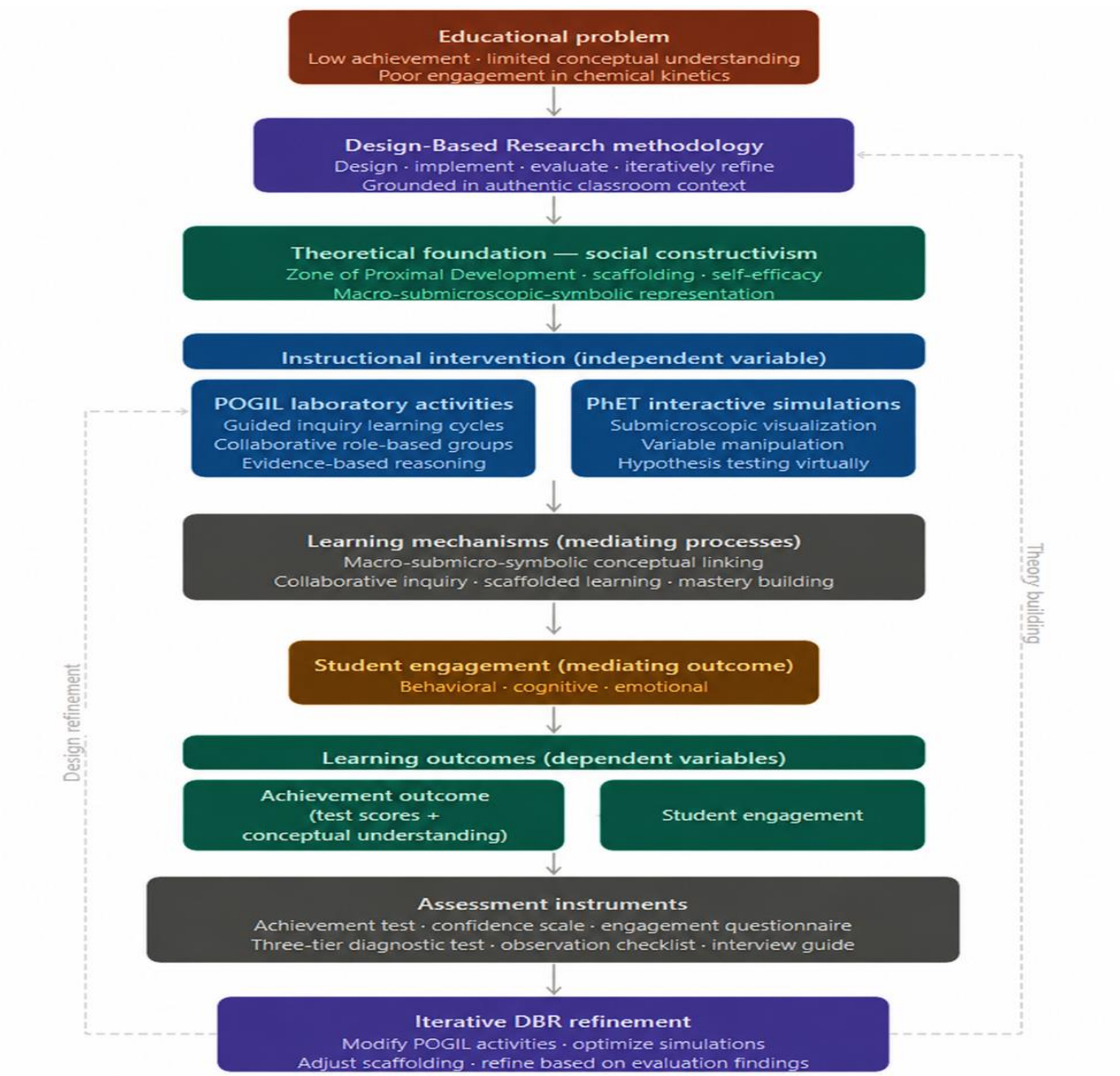

Figure 1 Conceptual framework of the study

CHAPTER THREE

Methodology

Research design and approach

This study is based on the pragmatist paradigm, which focuses on practical solutions to real-life problems. Pragmatism values both objective and subjective knowledge and emphasizes "what works" in a specific context (Morgan & Morgan, 2014). In this view, research is judged by its usefulness in improving practice and outcomes.

Consistent with this approach, the study uses a mixed-methods research design. Qualitative data are used to explore students' experiences and contextual challenges, while quantitative data measure the impact of the intervention on learning outcomes, as noted by (Hasselgreen et al., 2016). This combination provides a more complete understanding of the teaching and learning process.

The study also adopts a design-based research (DBR) approach. DBR is an iterative method designed for solving complex educational problems in real classroom settings. It involves designing, implementing, evaluating, and refining an intervention through repeated cycles.

DBR requires close attention to the learning context and continuous adjustment based on evidence from practice (Mundy & Seery, 2024). It was chosen because this study aims to design and improve a POGIL-based laboratory learning environment supported by PhET simulations to enhance students' engagement and achievement in chemical kinetics.

A key advantage of DBR is collaboration with teachers and flexibility in design. The intervention can be tested in real school conditions and improved by following step-by-step procedures resulting from each cycle.

Study Setting, Participants, and Sampling Procedures

This study was conducted at Tana Haik Government Secondary School, located in Bahir Dar City, Ethiopia. The school was selected purposively because the design-based research (DBR) approach requires a collaborative environment in which school administrators, teachers, and students are willing to actively participate in the design, implementation, and evaluation of an educational intervention. The school's accessibility to the researcher and the willingness of the administration and chemistry teacher to support the study also contributed to its selection.

The school follows the Ethiopian Ministry of Education secondary school curriculum, in which chemical kinetics is taught as part of the Grade 11 chemistry syllabus. In addition, the school possesses facilities that were essential for implementing the intervention, including a chemistry laboratory for POGIL-based practical activities and a computer laboratory with internet access for PhET simulation sessions. To minimize disruption to normal school operations, all intervention activities were conducted during the regularly scheduled chemistry class periods.

The participants in the study consisted of 63 Grade 11 chemistry students from an intact classroom. The students represented varying levels of academic achievement, as indicated by their pre-test scores, which ranged from 0 to 19 out of 32. Both male and female students participated in the study, providing a diverse group of learners with different backgrounds and learning needs.

The chemistry teacher who participated in the study held a Master of Science (M.Sc.) degree in Chemistry Education and had several years of experience teaching chemistry at the secondary school level. His professional experience and willingness to engage in the intervention process were important for the successful implementation of the study.

In line with the DBR framework, the school was selected purposively because it provided an appropriate context for implementing and refining the intervention. However, a random sampling technique was used to select the Grade 11 classroom that participated in the study. This approach helped ensure fairness in classroom selection while maintaining the contextual relevance required by DBR.

For the qualitative component of the study, purposive sampling was employed to select ten students for post-intervention interviews. The students were chosen from lower-, middle-, and higher-achieving groups based on their assessment results. They were also selected because they were able and willing to clearly express their learning experiences, opinions, and reflections regarding the intervention. Including students from different achievement levels allowed the study to capture a wide range of perspectives and experiences.

The combination of purposive and random sampling strengthened the study by ensuring both the practical requirements of the DBR process and the collection of rich, meaningful data from participants with diverse learning experiences.

Source of Data

Data for this study were collected from both primary and secondary sources. Primary data were gathered directly from the 63 student participants using a combination of quantitative and qualitative instruments. Quantitative data were collected from the students through pre-tests and post-tests administered before and after the intervention. Qualitative data were obtained through classroom observations, semi-structured interviews with ten selected students, and an interview conducted with the chemistry teacher who voluntarily participated in the study.

The chemistry teacher taught the lessons using the POGIL–PhET simulation approach and shared his experiences, perceptions, and reflections during the interview. His insights provided valuable context and were used to complement and strengthen the findings obtained from the student interviews.

Additionally, secondary data were collected from relevant literature and Ethiopian curriculum documents. These sources were consulted during the literature review and instrument development stages to ensure that the study was grounded in existing research and aligned with the national curriculum context.

Data collection instruments

To obtain a comprehensive understanding of students' learning outcomes and experiences, this study employed both quantitative and qualitative data collection instruments. These instruments were used to examine changes in students' conceptual understanding, engagement, and perceptions throughout the Design-Based Research (DBR) process.

Three-tier diagnostic test for conceptual understanding

A 32-item three-tier diagnostic test was used as both a pre-test and post-test to assess students' conceptual understanding of chemical kinetics. Unlike conventional tests that focus only on correct answers, this instrument assessed students' content knowledge, reasoning, and confidence in their responses.

The first tier measured students' understanding of chemical kinetics concepts through content-based questions. The second tier required students to provide or select reasons for their answers, allowing the researcher to examine their thinking processes. The third tier measured students' confidence in their responses, helping to distinguish between genuine understanding, uncertainty, guessing, and misconceptions.

The test items incorporated the three levels of chemical representation commonly used in chemistry learning. Students' responses were categorized into conceptual understanding, partial understanding, and no or limited understanding using the diagnostic rubric developed by (Mahmudi & Setyowidodo, 2021). This provided a more detailed picture of students' conceptual development than traditional achievement tests.

Student engagement questionnaire

A Likert-scale questionnaire was used to measure students' engagement in learning. Developed from the multidimensional engagement framework of (Fredricks et al., 2004), the instrument assessed behavioral, cognitive, and emotional engagement.

The questionnaire was administered before and after the intervention to determine changes in students' participation, interest, and involvement in learning activities.

Classroom observation checklist

A structured observation checklist with yes/no response categories was used throughout the study to document classroom interactions and learning behaviors. Observations were conducted during the baseline, POGIL, simulation, and post-intervention phases.

The checklist focused on students' engagement, participation, collaboration, inquiry practices, and conceptual development. These observations provided evidence of how students interacted with the integrated POGIL–PhET learning activities and how their learning behaviors changed over time.

Semi-Structured Interviews

Semi-structured interviews were conducted with ten students and the chemistry teacher after the intervention. Students were selected from different achievement levels to ensure diverse perspectives. The interviews explored participants' learning experiences, engagement, challenges encountered, and perceptions of the effectiveness of the integrated POGIL–PhET approach.

The teacher interview provided additional insights into the implementation process and complemented and validated the students' perspectives.

In addition, focus group discussions were conducted during the design, implementation, and evaluation stages of the DBR cycles. These discussions enabled students to share experiences, reflect on their learning, and provide feedback on the intervention. The information obtained helped inform ongoing refinement of the instructional design throughout the study.

Data collection procedure

Data collection was conducted in three phases: pre-intervention, intervention, and post-intervention. Before the intervention, the three-tier diagnostic test and student engagement questionnaire were administered to establish baseline measures of conceptual understanding and engagement. During the intervention, classroom observations and focus group discussions were conducted to document students' participation, inquiry processes, and learning experiences across the DBR cycles.

After the intervention, the diagnostic test and engagement questionnaire were re-administered to assess changes in learning outcomes and engagement. Semi-structured interviews with selected students and the chemistry teacher were then conducted to gain deeper insights into participants' experiences and perceptions of the intervention.

All data were collected by the researcher, and informed consent was obtained from participants prior to the commencement of the study.

Intervention design, implementation, and refinement

The intervention was designed and implemented using a design-based research (DBR) approach. DBR emphasizes the continuous cycle of designing, implementing, evaluating, and refining an educational innovation in a real classroom setting. In this study context, the intervention integrated Process-oriented guided inquiry learning (POGIL) and PhET simulations to improve Grade 11 students' conceptual understanding of chemical kinetics and increase their engagement in chemistry learning at Tana Haik High School.

The intervention was conducted over approximately four weeks. The first week was used to obtain informed consent from participants and administer the pre-test instruments. The instructional intervention was then implemented over two weeks during regular chemistry lessons. The final week was used for post-testing and data collection from interviews.

Design of the intervention

The intervention was designed based on the new Grade 11 Ethiopian chemistry curriculum, particularly the chemical kinetics unit. The learning activities focused on major concepts such as reaction rate, collision theory, factors affecting reaction rates, and reaction mechanisms.

The instructional activities were organized according to the three stages of the POGIL learning cycle: exploration, concept invention, and application. During the exploration stage, students worked in small groups to examine data, diagrams, models, and simulation outputs related to chemical kinetics concepts. Instead of receiving direct explanations from the teacher, students were encouraged to discuss observations, identify patterns, and generate their own explanations.

In the concept invention stage, students used evidence from their investigations to develop scientific explanations. The teacher facilitated learning by asking guiding questions and helping students connect their observations to scientific concepts.

During the application stage, students applied their understanding to solve problems, interpret chemical phenomena, and explain situations involving reaction rates and chemical changes.

PhET simulations were incorporated into the learning activities to help students visualize chemical processes that are difficult to observe in ordinary classroom situations. Using the simulations, students explored how factors such as temperature, concentration, and surface area influence reaction rates by observing particle collisions and molecular interactions. The PhET simulation lab activities are indicated in Figure 2 below.

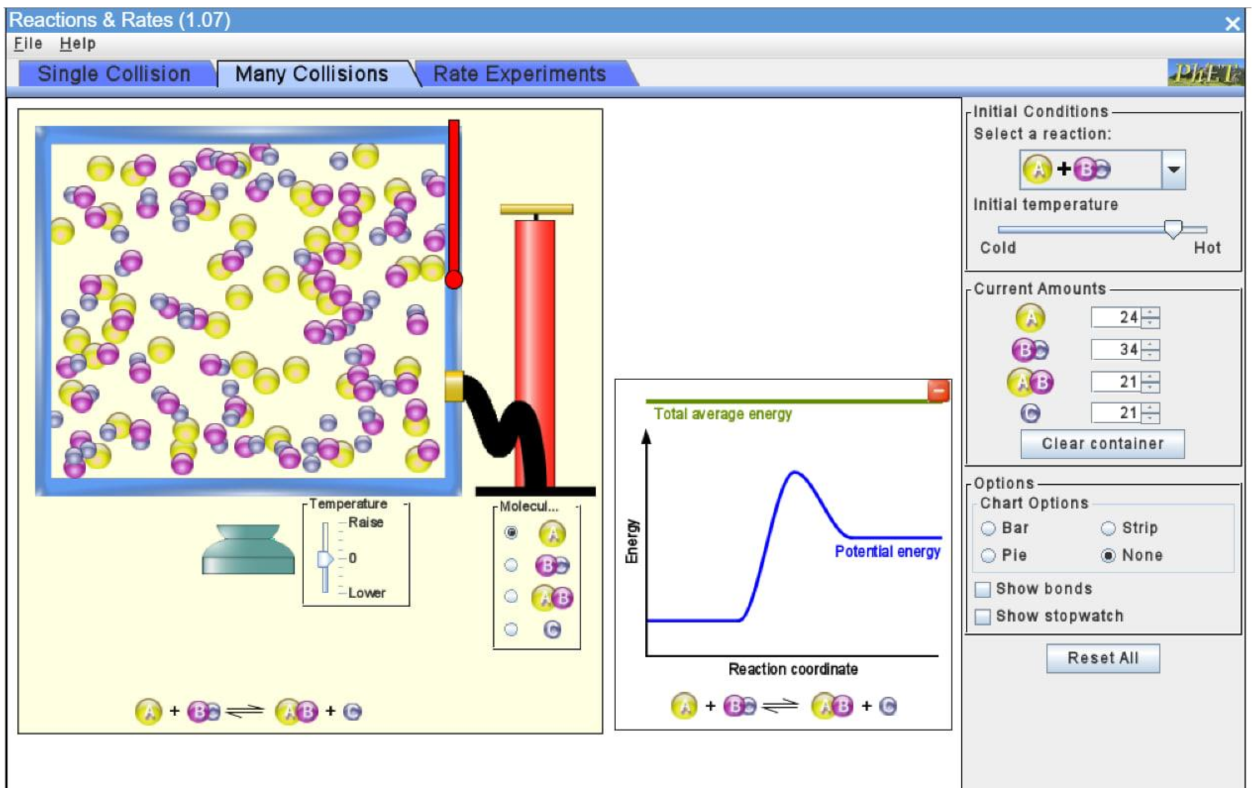

Figure 2 PhET simulations for chemical kinetics in many collisions

Integration of POGIL and PhET Simulations

The intervention integrated POGIL and PhET simulations into a single learning process rather than treating them as separate instructional methods. During each lesson, students worked in small groups and progressed through the POGIL learning cycle of exploration, concept invention, and application while using PhET simulations as a source of evidence for inquiry.

For example, when studying factors affecting reaction rates, students were first asked to predict how changes in temperature, concentration, and surface area would influence the rate of a reaction. In their groups, they discussed their predictions and provided reasons based on their prior knowledge. Students then used PhET simulations to manipulate these variables and observe changes in particle movement, collision frequency, and successful collisions.

Students recorded their observations in guided worksheets, compared simulation results with their initial predictions, and discussed why some predictions were correct while others were not. They were required to explain how increasing temperature increased particle kinetic energy, leading to more frequent and effective collisions. Similarly, students investigated how increasing concentration or surface area affected reaction rates and used evidence from the simulations to support their explanations.

To strengthen the connection between theory and practice, students also analyzed reaction-rate graphs, interpreted simple experimental data, and related simulation observations to collision theory and chemical equations. At the end of each activity, groups presented their findings to the class and participated in whole-class discussions to compare explanations and address misconceptions.

Throughout the lessons, the teacher acted as a facilitator by asking probing questions, guiding discussions, and encouraging students to justify their ideas using evidence rather than simply providing answers. Selected photographs documenting the implementation of the intervention are provided in Appendix F.

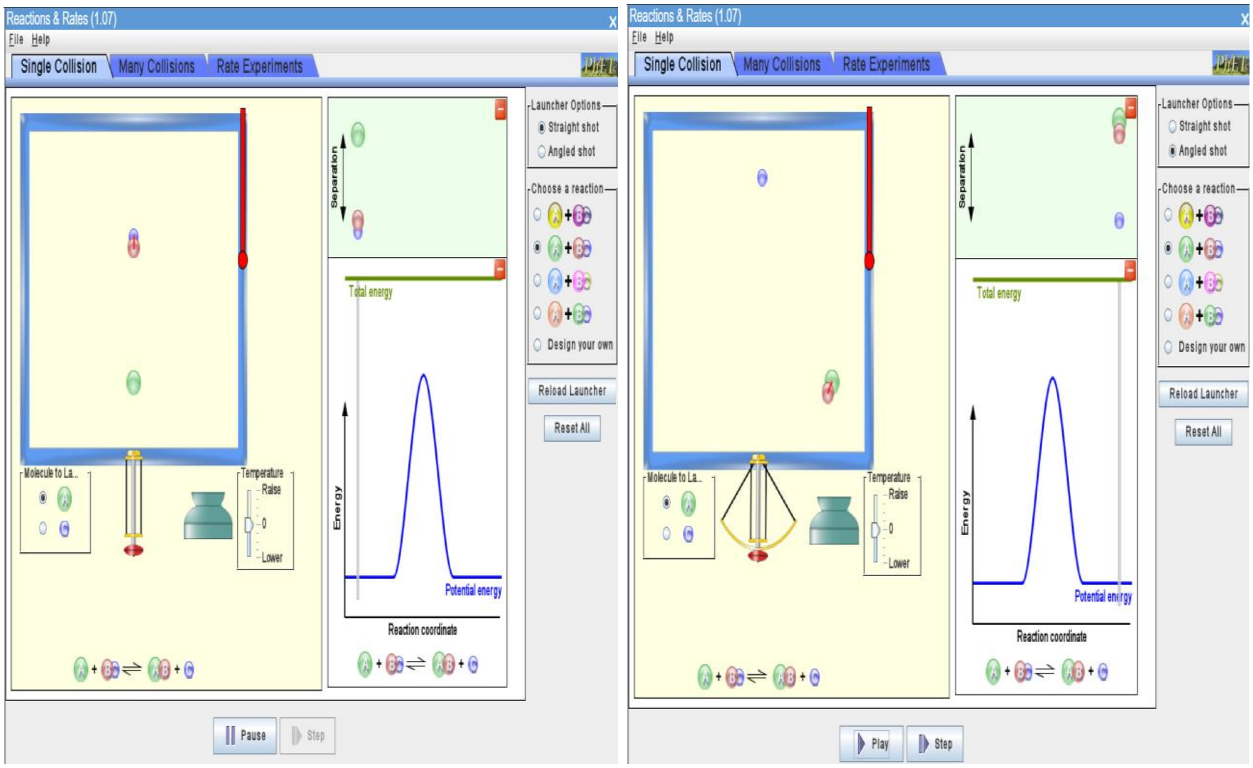

Figure 3 PhET simulations for chemical kinetics in single collisions in straight and angled shots

DBR iterations and refinement process

Following the design-based research approach, the intervention was refined through successive cycles of implementation, observation, reflection, and revision.

First Iteration

During the initial implementation, students showed high interest in using the simulations because they offered a more interactive learning experience than the traditional lecture-based approach commonly used in many Ethiopian secondary schools. However, classroom observations indicated that some students were more focused on operating the simulation tools than on interpreting the scientific meaning of their observations.

Some students also struggled to connect the particle-level representations shown in the simulations with the chemical concepts presented in their textbooks.

Based on these findings, the activity worksheets were revised to include more structured observation tasks, prediction questions, and explanation prompts. Students were required not only to describe what they observed but also to explain why those changes occurred using scientific concepts.

Second Iteration

The revised materials led to more focused inquiry and richer discussions. Students became better at using evidence from the simulations to support their explanations. Nevertheless, observations showed that a few students dominated group discussions while quieter students participated less actively.

To improve participation, specific group roles such as leader, recorder, presenter, and timekeeper were assigned. Additional reflection questions were included to ensure that every student contributed to the discussion and justified their ideas.

These changes increased student participation and improved the quality of collaborative learning within groups.

Third Iteration

The final refinement focused on strengthening students' ability to connect the three levels of chemical representation: macroscopic, microscopic, and symbolic.

For instance, after observing increased collision frequency in the simulations, students were asked to explain the phenomenon using collision theory, interpret reaction-rate graphs, and relate their observations to relevant chemical equations. Whole-class reflection sessions were also introduced to discuss common misconceptions and compare findings across groups.

These improvements helped students develop a more integrated understanding of chemical kinetics and strengthened the links between what they observed, what happened at the particle level, and how those processes were represented symbolically.

Evaluation of the Intervention

The effectiveness of the intervention was evaluated using multiple sources of evidence. Students' conceptual understanding of chemical kinetics was measured through three-tier diagnostic pre-tests and post-tests. Student engagement was assessed using questionnaires and classroom observations, while interviews and focus group discussions provided deeper insights into students' learning experiences and perceptions of the integrated POGIL–PhET approach.

The iterative DBR process enabled continuous improvement of the intervention based on evidence gathered during implementation. Through repeated cycles of design, implementation, evaluation, and refinement, the integrated POGIL–PhET approach became increasingly responsive to the learning needs of Grade 11 students and the realities of chemistry teaching in Ethiopian secondary schools.

Validity and Reliability

The validity of the research instruments was ensured through expert review and careful alignment with the study objectives, the chemical kinetics content area, and the overall design-based research (DBR) intervention framework. Experts in chemistry education reviewed the instruments and provided constructive feedback on clarity, relevance, and content coverage. Based on their suggestions, necessary revisions were made before the instruments were finalized for data collection.

The reliability of the instruments was tested using Cronbach’s alpha coefficient. According to (Taber, 2018)a value of $\alpha \geq 0.80$ indicates good internal consistency. In this study, the pre-test yielded a reliability coefficient of $\alpha = 0.824$, while the post-test showed $\alpha = 0.856$. These results indicate good reliability for both instruments.

Overall, the findings suggest that the instruments consistently measured students’ conceptual understanding of chemical kinetics and were suitable for use throughout the DBR process.

Data Analysis

Before the main analysis, curricular documents, teacher guides, lesson plans, and the intervention design were reviewed to ensure consistency and alignment between the Ethiopian Grade 11 chemistry curriculum and the implemented intervention.

Quantitative data were analyzed using IBM SPSS Statistics version 23. Descriptive statistics, including mean, standard deviation, frequency, and percentage, were computed for all pre-test and post-test measures to summarize students' performance and engagement levels.

Before inferential analysis, assumptions of normality were checked using skewness and kurtosis z-scores, with values evaluated against ±1.96. This assessment was applied to the difference scores to justify the use of the paired samples t-test (Field, 2018).

A paired samples t-test was then conducted to determine whether there were statistically significant differences between pre-test and post-test results, using a significance level of $p < 0.05$. In addition, effect size was calculated using Cohen's d, obtained by dividing the mean difference by the standard deviation of the difference scores. The results were interpreted using (Cohen, 1988) guidelines to determine the magnitude of the intervention effect.

For the three-tier diagnostic test, students' responses were categorized into three levels: no understanding, partial understanding, and conceptual understanding, based on the established rubric. Frequency distributions of these categories were compared between pre-test and post-test results to describe changes in students' conceptual development over time.

Qualitative data from interview transcripts were analyzed using a multiphase Reflexive Thematic Analysis (RTA) approach (Braun et al., 2020; Braun & Clarke, 2023). This approach was appropriate because it allows an interpretive, data-driven understanding of participants' experiences while recognizing the researcher's active role in constructing meaning.

The analysis began with repeated reading of transcripts to develop familiarity with students' experiences of learning chemical kinetics through guided inquiry and simulation-based activities. In the initial coding phase, an inductive bottom-up process was used to generate 95 meaning units (codes), developed collaboratively with the thesis supervisor. These codes closely reflected students' lived experiences, including improved visualization of particle interactions, increased engagement in group work, growing confidence in learning chemistry, difficulties in interpreting microscopic processes, and challenges related to limited laboratory resources.

Through iterative review, overlapping and redundant codes were refined resulting in the removal of five codes and the renaming of several others for clarity. The remaining codes were then grouped into 12 analytical dimensions, representing broader patterns of meaning. For example, ideas related to visualization and abstract concept understanding was clustered under scientific representation, while participation, motivation, and group interaction formed engagement and participation. Issues such as safety, reduced anxiety, and learning comfort formed a separate dimension related to learning environment.

These 12 dimensions were further refined into five overarching themes with sub-themes through constant comparison with the raw data and classroom evidence. The final themes captured: (1) meaningful engagement in science learning through active participation, collaboration, and experiential learning; (2) conceptual understanding through scientific representation supported by simulation and teacher scaffolding; (3) development of scientific thinking and learner independence; (4) the role of a supportive learning environment in enhancing engagement; and (5) barriers to effective learning.

Overall, consistent with (Braun et al., 2020; Braun & Clarke, 2023), the analysis was reflexive and iterative rather than linear. It evolved alongside the DBR cycles, ensuring that interpretations remained grounded in students' authentic learning experiences while also capturing how the integrated POGIL–PhET approach functioned within the realities of Ethiopian high school chemistry classrooms. The generated themes and sub-themes with sample codes and excerpts are indicated in Table 3. The classroom observation and field notes data were analyzed qualitatively.

Ethical Considerations

This study was conducted in accordance with the research guidelines of the College of Education, School of Teacher Education. The research proposal was reviewed and approved by the College of Education Institutional Review Board (IRB) before data collection.

After approval, an official permission letter was obtained from the College of Education and submitted to the school administration to gain access to the Grade 11 chemistry classroom at Tana Haik Government Secondary School.

All participants, including the school administration, the chemistry teacher, and Grade 11 students, were clearly informed about the purpose of the study, the procedures involved, and the expected benefits. Participation was voluntary, and all participants were informed of their right to withdraw from the study at any time without any academic or personal consequences.

Before conducting interviews and recordings, oral consent was obtained from participants. Confidentiality was strictly maintained throughout the study by ensuring that all collected data were securely stored and used solely for academic purposes.

In addition, the intervention was carefully aligned with the Ethiopian Grade 11 chemistry curriculum to ensure that it supported regular classroom instruction without disrupting the normal teaching and learning process. Throughout the study, ethical standards were consistently upheld to protect participants’ rights and ensure responsible research practice.

Themes	**Sample codes**	**Sample excerpts**
Theme 1: Supporting Conceptual Understanding through Guided Inquiry and Scientific Representation	POGIL and Simulation activities need to be interpreted carefully through teachers’ scaffolding	*“The simulation is a solution for removing confusion inherent in my scientific conceptual learning using POGIL”* (student 3)
Sub-theme 1: Making sense of scientific concepts through multiple representations	A pedagogical approach that is suitable to concretize abstract concepts at the microscopic level	*"I had previously struggled to understand effective collision and activation energy because they involve microscopic interactions that cannot be seen by my naked eyes. The simulation resolved that confusion, and the laboratory made my understanding deeper and more lasting."* *(*Student 7)
Sub-theme 2: Retrieving and applying scientific knowledge for deeper understanding	Improved memorization as opposed to regular approach already in use	*"Before, I had memorized definitions without truly understanding them. The simulation and laboratory activities changed that*

		completely — I could now see and test the concepts myself." *(*Student 5)
Sub-theme 3: Scaffolding conceptual learning through responsive teaching	Teachers' scaffolding for enhanced learning of science using simulation and POGIL	*"The most challenging aspect of the simulation was interpreting the particle-level visual representations in the early sessions without the teacher guidance, but if the teacher guides step by step, the difficulty would be resolved."* *(*Student 9)
Theme 2: Fostering Meaningful Engagement in Science Learning	The approach to POGIL leads to fruitful engagement in the learning activities	*"The simulations helped me to investigate and make decisions based on my own observations, which greatly enhanced my understanding — just not following the flow."* ***(***Student 3) *"Since I have started learning chemistry, this is the most motivating, engaging, and effective method."* *(*Student 6)
Sub-theme 1: Active engagement and participation in learning science	promoted leaning by manipulating ideas and variables	*"Being able to control the variables myself during the simulation made me more confident about what I was learning."* *(*Student 4)
Sub-theme 2: Learning science as first-hand experiences	The approach provides first-hand, real practical experience with learning science	*"This simulation-based approach changed the way I learn chemistry. For the first time, I could actually see what happens at the particle level when temperature or concentration changes."* (Student 2)
Sub-theme 3: Learning boost	The approach builds confidence in learning science practically	*"This approach reshaped my relationship with chemistry in a very positive way. It*

		made me more curious, confident, and engaged than ever before." (Student 9)
Sub-theme 4: Students' lived experiences with POGIL integrated with interactive simulations	Simulations as activators of prior practical knowledge for promoted learning of science	*"This simulation-integrated teaching method has been the most engaging chemistry learning experience I have had since I started learning chemistry. Watching and controlling microscopic events by myself gave me a level of understanding that ordinary instruction could not provide."* (Student 10)
Theme 3: Cultivating Scientific Thinking and Independent Inquiry	Increasing sense of control in own learning	*"Actively working through problems makes me feel like I am a scientist."* (Student 7) *"Making decisions based on my own observations strengthened both my confidence and enhanced my understanding."* (Student 9)
Sub-theme 1: Developing scientific ways of thinking	Integrated lab activities require students' active focus to give them own decision-making ability	*"This approach builds evidence-based understanding rather than passive memorization. It actively engaged me, encouraged me to participate, and deepened my understanding at the microscopic, macroscopic, and symbolic levels."* (Student 1)

Sub-theme 2: Responsive learning for involvement in independent scientific endeavor	Increased courage to learn science independently	*"I was able to make decisions on my own by analyzing what I saw during the experiments rather than simply accepting the teacher's explanation."* (Student 5)
Theme 4: Learning Environment as a Catalyst for Science Learning	Minimizing anxiety to learn science	*"Because of chemicals' hazardous properties, simulation becomes a safe teaching approach."* (Student 3) *"This instructional method made students actively participate, ask questions, investigate ideas, and discuss concepts in a better way."* (Teacher)
Sub-theme 1: Creating conducive learning environment for better conceptual learning of science	Simulations are safer to learn and better grasp scientific concepts than through real lab experiments	*"The simulation gave me a safe way to explore conditions that would be difficult or dangerous to test in a real lab setting."* (Student 7)
Sub-theme 2: Classroom interactions that facilitate engagement and understanding	Students' improved learning abilities and active engagement in classroom learning	*"The approach genuinely excited students and drew them into active participation — they were asking questions, investigating ideas, discussing concepts with each other, and engaging with the material in ways I have not observed before."* (Teacher)
Theme 5: Barriers to Meaningful Participation in Science Learning	Limited lab facilities hamper practical learning	*"Large class size, laboratory infrastructure, and limited resources were the main challenges that disturbed our activities."* (Student 8) *"Without sufficient chemical supplies, laboratory activities cannot be conducted meaningfully."*

		(Teacher)
Sub-theme 1: Restricted opportunities for science learning	Limited role of simulation for unveiling invisible processes makes it confusing to learn science through virtual experiments	*"The simulation without teacher guidance was confusing, which made it challenging to understand easily."* (Student 2)
Sub-theme 2: Challenges limiting engagement in scientific practices	Challenges caused by large class size and limited laboratory facilities	*"The primary challenges for the laboratory were large class sizes, limited equipment, and insufficient chemicals."* (Student 3)

Table 1 Theme, sub-themes, and codes generated from individual interviewed students' viewpoints on POGIL integrated with interactive simulation

CHAPTER FOUR

Results and Discussion

This chapter presents and discusses the findings from two cycles of intervention designed to enhance Grade 11 students' conceptual understanding, engagement, confidence, and learning experiences in chemical kinetics through the integration of interactive simulations with Process-Oriented Guided Inquiry Learning (POGIL) laboratory activities.

The results are organized according to the research questions and are used to evaluate how effectively the intervention supported students' learning. Both quantitative and qualitative data were used to build a comprehensive understanding of the outcomes.

The quantitative findings report changes in students' achievement test scores, confidence levels (measured through the third-tier diagnostic responses), and shifts in levels of conceptual understanding. These were analyzed using descriptive statistics, frequency and percentage distributions, paired-samples t-tests, and effect size measures to determine whether meaningful differences existed before and after the intervention.

The qualitative findings draw on student and teacher interviews, group discussions, and classroom observations. These were analyzed thematically to capture patterns in learners' experiences, perceptions, engagement, and challenges during implementation. These insights were then used to explain and deepen the interpretation of the quantitative results.

Finally, the chapter brings both datasets together through triangulation, allowing for a more complete interpretation of the intervention's impact. It also highlights key refinements that emerged during the Design-Based Research process, informing how the intervention evolved across iterations.

Quantitative findings

Conceptual

The findings indicate a clear and meaningful improvement in students' achievement following the implementation of the integrated Interactive Simulations and POGIL laboratory intervention. The mean score increased from 9.65 (30.2%) on the pre-test to 21.19 (66.2%) on the post-test, reflecting an absolute gain of 11.54 points and an overall improvement of 36.1% of the total score. The normalized gain value (g = 0.516) placed the intervention in the medium-to-high effectiveness range, showing substantial instructional impact within the chemical kinetics unit. The achievement findings are summarized in Table 4.

	N	Min.	Max.	Mean	SD	Skewness	Kurtosis
Students' pre-test total result	63	0	19	9.65	5.739	0.44	-1.77
Students' post-test total result	63	9	32	21.19	7.032	-0.79	-2.05
Valid N	63						

Table 2 Descriptive statistics of achievement score

Variability in performance also changed across the intervention. The standard deviation increased from 5.739 to 7.032, alongside the removal of the earlier floor effect, where many students initially scored very low (41.3% scoring between 0–8). After the intervention, this lowest performance category was no longer present, and no student remained at the earlier low-achievement level. At the same time, 31.7% of students reached scores of 25 or above, including three students who achieved the maximum score of 32, indicating both broad improvement and stronger differentiation in higher-level performance.

The distribution of scores showed a clear upward shift across the entire cohort. Overall, 50.8% of students moved out of the very low achievement range after the intervention, suggesting that gains were not limited to a small group but were experienced across the class. Alongside this cognitive improvement, students' confidence levels also rose markedly, increasing from 0% at high confidence levels before the intervention to 74.6% afterward, showing parallel growth in understanding and self-belief.

Across the cohort, improvement was universal in direction, although it varied in magnitude. This pattern reflects differences in how students responded to the intervention based on prior knowledge and learning readiness. Some students made rapid gains, while others progressed more gradually, contributing to the broader spread of post-test scores.

Overall, the findings show a consistent upward shift in both achievement and confidence across all students, with no evidence of stagnation at the lower end of performance after the intervention.

1. Normality of data

The pre and post-test achievement score data distribution was checked by taking the plots of skewness and kurtosis both graphically and numerically (Table 2).

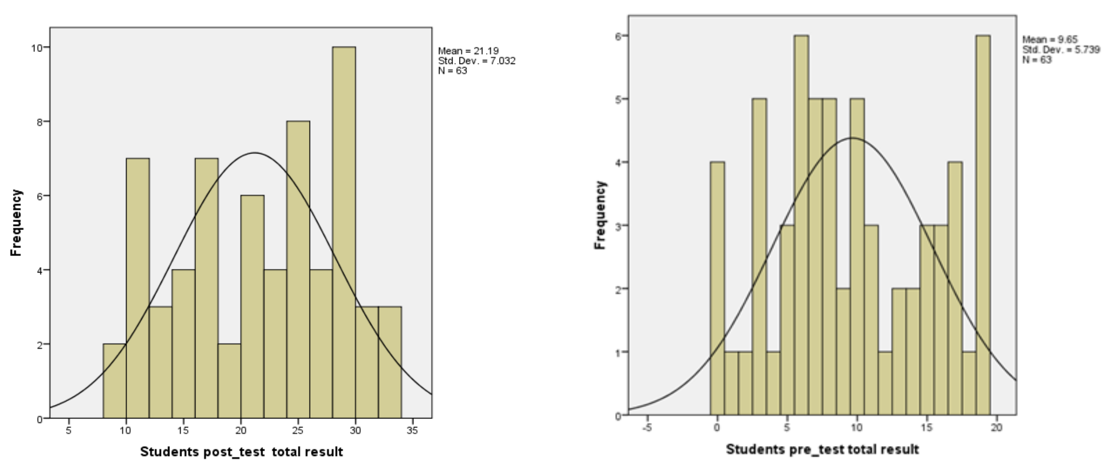

Figure 4 Assessment of the Normality of Achievement Scores

From the visual inspection of the graph plot 1, both the pre- and post-test scores of the achievement variable for the intervention group seems both normally skewed and kurtosis. This shows that the assumption of normality of data was not markedly violated.

Similarly, this assumption was also checked by taking skewness and kurtosis test values and the results were indicated in table A.

The skewness values for both pre-test (z = 0.44) and post-test (z = -0.79) were within the acceptable range (±1.96), indicating that both distributions were approximately symmetrical with no significant departure from normality.

The kurtosis values for the pre-test (z = -1.77) and post-test (z = -2.05) showed a slightly platykurtic pattern, suggesting relatively flatter distributions and a wider spread of scores, likely reflecting differences in students' prior knowledge levels within a heterogeneous sample.

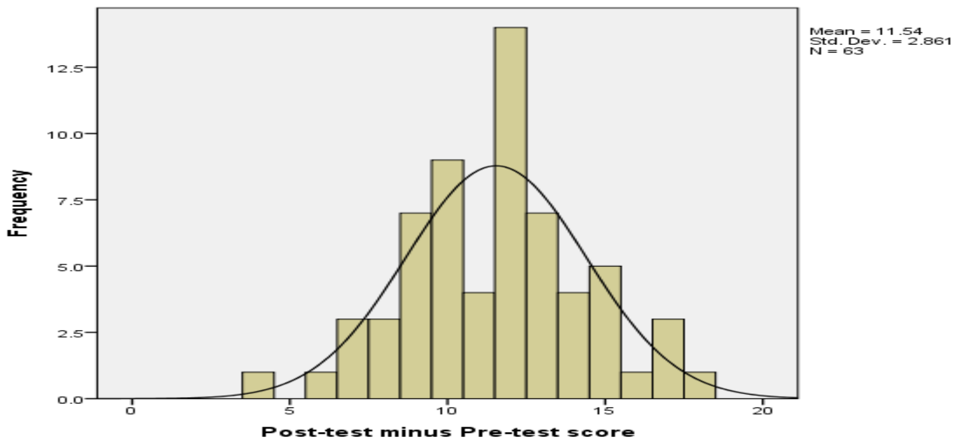

Figure 5 Test of normality for achievement difference scores

The normality assumption for the paired-samples t-test was assessed using the difference scores (post-test minus pre-test), as recommended by Field (2018), rather than the individual pre- and post-test distributions. The DIFF scores showed near-zero skewness (z = -0.056) and kurtosis (z = 0.032), both well within the ±1.96 range, indicating an approximately normal and symmetric distribution, further supported by a smooth bell-shaped histogram.

In addition, the relatively small standard deviation (2.861) compared to the mean gain (11.54) reflects low variability in change scores, suggesting that most students benefited in a consistent manner. Given the paired nature of the data (63 students measured twice), the assumptions for a paired-samples t-test were satisfied, confirming its appropriateness for this analysis within a DBR framework.

Paired sample Test										
Variable	mean	SD	SE	95%CI		t	df	Sig.	skeewness	kurtosis
				Lower	Upper					
Post-test minus Pre-test achievement score	11.540	2.861	0.361	10.819	12.260	32.009	62	0.000	-0.056	0.032

Table 3 Paired-samples t-test results for achievement score differences

The paired-samples t-test showed a statistically significant increase in students' achievement from pre-test (M = 9.65, SD = 5.739) to post-test (M = 21.19, SD = 7.032), t(62) = 32.009, $p < .001$, indicating a strong and reliable improvement after the intervention.

The 95% confidence interval [10.819, 12.260] lay entirely above zero and was relatively narrow, confirming that the observed gain was precise and consistent across the 63 students, directly addressing RQ3 by demonstrating a substantial improvement in achievement following the POGIL-integrated simulation intervention.

Mastery Level	Pre-test %	Post-test %	Change
Very Low (0–8)	41.3%	0%	−41.3%
Low (9–15)	33.3%	19.0%	−14.3%
Moderate (16–23)	25.4%	30.2%	+4.8%
High (24–32)	0%	50.8%	+50.8%

Table 4 Percentage of pre and post-test achievement scores

The 95% confidence interval was narrow (width = 1.441), indicating a high level of precision in the estimated mean difference. Frequency distribution analysis showed a clear upward shift in achievement after the intervention, with no students initially scoring in the high mastery range (24–32) and 41.3% in the very low range.

After the intervention, 50.8% of students reached high mastery, and the very low category was completely eliminated. Notably, the lowest post-test score (9/32) was equal to the pre-test mean

(9.65/32), indicating that all students showed measurable improvement regardless of their starting level.

The effect size analysis indicated a very large practical effect (d = 4.03), substantially exceeding conventional benchmarks for educational impact. However, this magnitude should be interpreted with caution due to possible ceiling effects and the absence of a control group, which may have influenced the variability and attribution of gains.

CONFIDENCE

Students' confidence levels before and after the implementation of the integrated POGIL laboratory and interactive simulation intervention. Table D summarizes the distribution of students' confidence responses and shows changes in their self-reported certainty about chemical kinetics concepts.

Measure	Pre-test	Post-test	Change
Mean	6.38	13.08	+6.698
SD	2.082	3.530	+1.448
% of maximum scale	39.9%	81.75%	+41.9%
Very low (0-4)	12.7%	4.8%	−7.9%
Low (5-8)	69.8%	4.8%	−65.0% ⬇
Moderate (9-11)	17.5%	15.9%	−1.6%
High (12-16)	0%	74.6%	+74.6% ⬆

Table 5 Complete students' confidence comparison

Table E. Paired sample t-test for students' confidence level based on their pre-test and post-test difference

Paired sample Test								
Variable	mean	SD	SE	95%CI		t	df	Sig.
				Lower	Upper			
Total students' pre-test confidence level – total students Post-test confidence level	-6.698	3.448	0.434	-7.567	-5.830	-15.418	62	.000

Table 6 Paired sample t-test for students' confidence

Analysis of students' confidence levels (16-point scale) showed a clear increase following the POGIL–simulation intervention. The paired-samples t-test (Table E) indicated a statistically significant difference between pre-test and post-test confidence scores ($p < .05$), with an overall rise in the mean confidence score.

The effect size was large (Cohen's d = 1.94), exceeding the conventional threshold for a strong educational effect (Cohen, 1988). In terms of distributional change, 74.6% of students reached high confidence after the intervention, compared to 0% at pre-test, while the low-confidence group dropped from 69.8% to 4.8%, showing a substantial shift across categories.

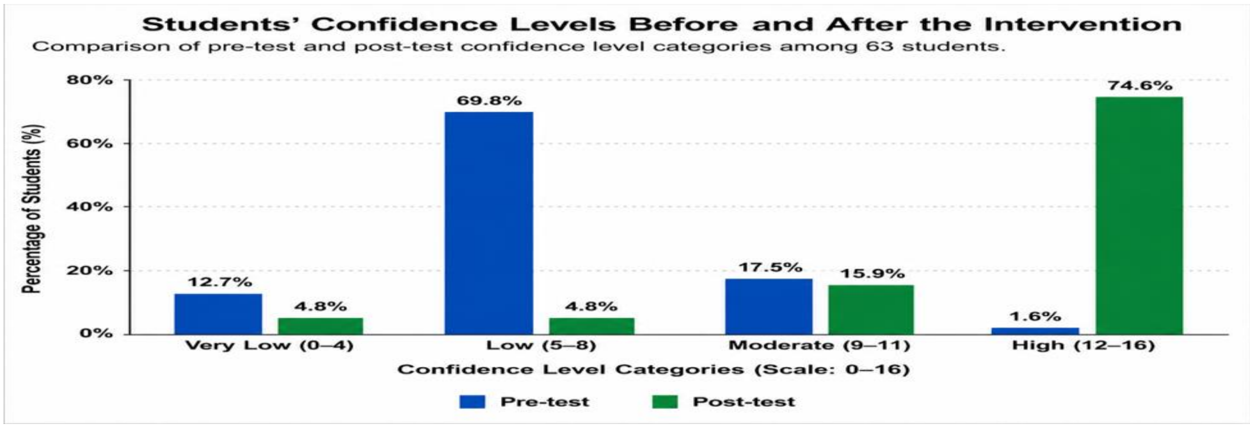

Figure 6 Confidence level categories before and after the intervention

The bar chart shows a clear shift in students' confidence from pre-test to post-test, with a marked decrease in the low-confidence group and a substantial increase in the high-confidence group after the intervention. Post-test results showed a significant reduction in low-confidence students, while 74.6% of students reached high confidence compared to 0% at pre-test. The low-confidence category decreased from 69.8% to 4.8%. The standard deviation increased from 2.082 to 3.530, indicating greater variation in post-test confidence scores across students. A total of 38.1% of students achieved the maximum confidence score (16/16), while even the lowest scores improved from 0 to 2 after the intervention.

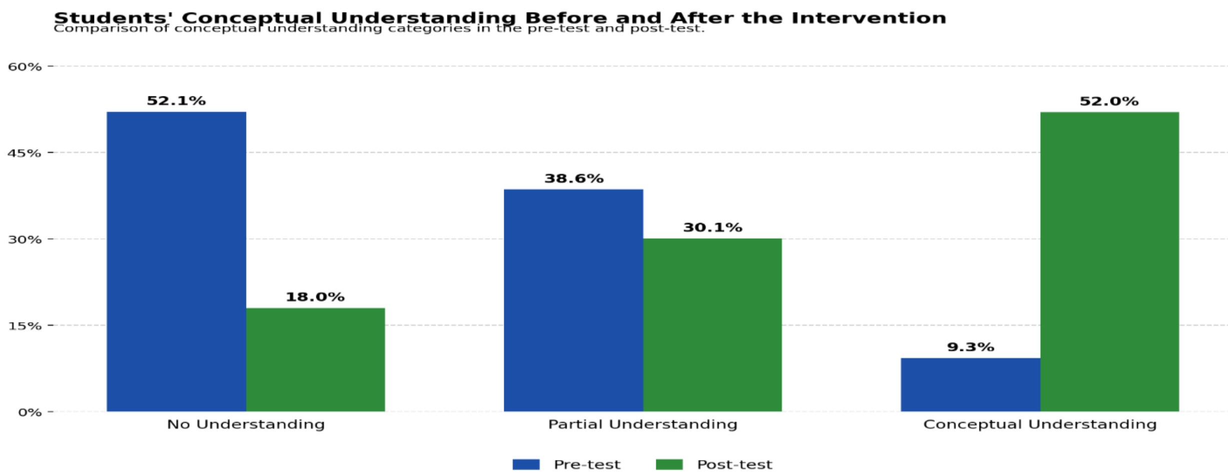

Figure 7 Students conceptual understanding categories

Students' conceptual understanding showed a clear and substantial shift following the integrated POGIL–simulation intervention. Before the intervention, 52.1% of students demonstrated no understanding of chemical kinetics concepts, while only 9.3% showed conceptual understanding. After the intervention, the proportion of students with conceptual understanding increased sharply to 52.0%, representing a gain of 42.7 percentage points.

At the same time, the no-understanding category decreased by 34.1%, and partial understanding decreased from 38.6% to 30.1%, indicating a general upward movement across categories. Overall, more than half of student responses shifted into the conceptual understanding level after the intervention, reflecting a broad and consistent improvement in students' grasp of chemical kinetics concepts.

ENGAGEMENT

This section presents and discusses findings on students' engagement before and after the implementation of the integrated interactive simulation intervention and POGIL laboratory activities. Student engagement was measured using a seven-item Likert-scale questionnaire administered before and 16 questions after the intervention.

This assumption was checked using skewness and kurtosis test values, and the results are shown in the following table.

Variable Name	N	Mean Score	SD	Skewness	Kurtosis
Pre-engagement	63	3.10	.349	0.59	1.32
Post-engagement	63	4.45	.440	1.50	0.13

Table 7 Descriptive Statistics of Engagement data

Both pre- and post-engagement data showed skewness and kurtosis, but remained within acceptable limits, indicating that normality assumptions for the paired-samples t-test were not violated.

The pre-test engagement mean was M = 3.10 (SD = .349), representing 62.0% of the maximum score and indicating a moderate level of engagement at baseline. After the intervention, the post-test mean increased to M = 4.45 (SD = .440), corresponding to 89.0% of the maximum score and reflecting a shift toward strong engagement.

The mean gain was 1.35 points, showing a clear upward movement from moderate to high engagement. The standard deviation increased slightly from 0.349 to 0.440, indicating some variation in the extent of engagement gains across students, although most responses clustered near the upper end of the scale.

Normality of data

The pre and post-test mean score of engagement data distribution was checked by taking the plots of skewness and kurtosis both graphically and numerically.

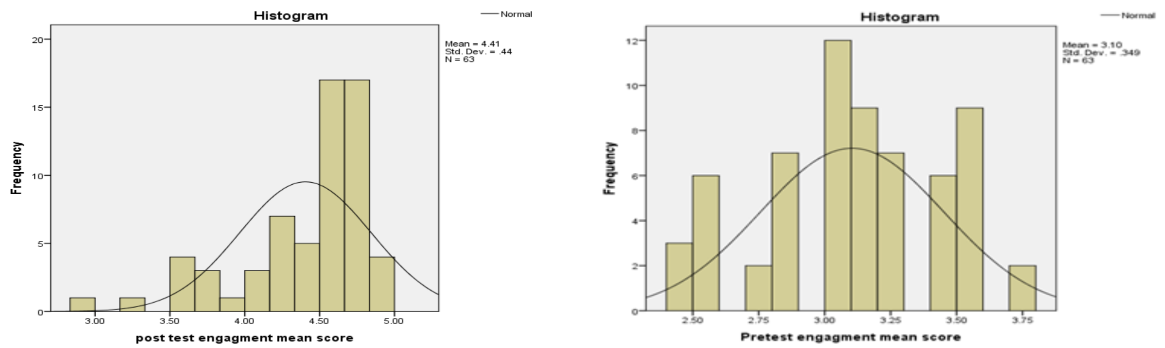

Figure 8 Normality score pre and post-test score of engagement

Visual inspection of the engagement data showed that both pre- and post-test distributions were approximately normal, with only minor deviations in skewness and kurtosis. The pre-test values were skewness = 0.59 and kurtosis = 1.32, while the post-test values were skewness = 1.50 and kurtosis = 0.13, all falling within acceptable limits for normality.

Although some z-scores exceeded strict cut-offs, the histogram plots for both datasets showed clear bell-shaped distributions, supporting approximate normality in the engagement scores. The data were therefore considered suitable for parametric analysis, with homogeneity of variance further examined using Levene's test.

variable	F	Df1	Df2	Sig.
Pre-engagement mean score	.681	3	59	.567
Post-engagement mean score	1.557	3	59	.209

Table 8 Test of homogeneity of variances for engagement scores

Levene's test results (Table F) showed no significant variance differences between engagement scores, with pre-test F (3, 59) = 0.681, p = 0.567 and post-test F (3, 59) = 1.557, p = 0.209.

Since both p-values were above 0.05, the assumption of homogeneity of variance was met for both pre- and post-test engagement scores. This confirmed that the variability in engagement scores was comparable across groups, supporting the use of parametric analysis.

Paired sample Test								
Variable	mean	SD	SE	95%CI		t	df	Sig.
				Lower	Upper			
Pre-test engagement mean score – post-test engagement mean score	-1.35	0.565	0.071	-1.44	-1.16	-18.29	62	.000

Table 9 Paired sample t-test of engagement scores

The satisfaction of the homogeneity of variance assumption indicates that engagement scores were distributed consistently across students in both pre- and post-test conditions (Levene's test: pre-test F (3,59) =0.681, p=0.567; post-test F (3,59) =1.557, p=0.209), with no statistically significant differences in variance observed (p>0.05). This confirms that the paired-samples t-test was appropriate for analyzing engagement effects, as variability remained stable across the same group of 63 students in line with the DBR context of naturally diverse classroom populations.

The paired-samples t-test results showed a statistically significant increase in engagement following the intervention (t(62)=18.29, p<0.001), with a mean gain of 1.30 on a five-point Likert scale and a 95% confidence interval [1.16, 1.44], indicating a precise and consistent improvement across all students. The effect size was large (Cohen's d = 2.30), with post-test engagement reflecting higher levels across behavioral, cognitive, and emotional dimensions, and no statistically significant differences were found between male and female students (p>0.05), indicating similar engagement gains across gender groups.

Variable	Pre Mean	Post Mean	Mean Gain	t	df	p	Cohen's d
Achievement (out of 32)	9.65	21.19	11.54	32.009	62	< 0.001	4.03
Confidence (out of 16)	6.38	13.08	6.698	15.418	62	< 0.001	1.94
Engagement (out of 5)	3.10	4.45	1.30	18.29	62	< 0.001	2.30

Table 10 Summary of quantitative data collected in the study

The quantitative findings show that the integrated interactive simulation with POGIL laboratory activities produced substantial and statistically significant improvements across all measured dimensions of student learning. Effect sizes were larger than both (Cohen, 1988) threshold for large effects and (Hattie, 2009) benchmark of d = 0.40 for typical educational interventions. Within the DBR framework, the results demonstrate clear practical effectiveness in an authentic classroom setting and contribute to design-based knowledge on instructional implementation. Overall, the findings indicate strong and consistent improvements across cognitive, affective, and motivational measures through the combined intervention in Grade 11 chemistry.

The three-tier diagnostic data show that 18.0% of post-test responses still reflected No Understanding and a further 30.1% reflected only Partial Understanding, indicating that certain misconceptions in chemical kinetics persisted despite the intervention. Similarly, a small proportion of students (4.8%) remained in the Low confidence category at post-test, suggesting that the intervention did not equally resolve anxiety or self-doubt for every learner. These patterns align with implementation-related challenges identified in the qualitative findings, including large class sizes, limited laboratory materials, and initial difficulty interpreting particle-level simulation visuals without adequate teacher scaffolding, which collectively suggest that the benefits of the intervention, although considerable, were not experienced uniformly by all students and should be weighed against these constraints when evaluating the overall impact of the study.

Qualitative Findings

This study explored how integrating POGIL with interactive simulation laboratory activities influenced Grade 11 students' engagement, conceptual understanding, and scientific thinking in chemical kinetics. The qualitative data were drawn from student and teacher interviews and classroom observations, and analyzed using reflexive thematic analysis. Five interrelated main themes were generated, each supported by sub-themes. Together, these findings explain how the intervention shaped students' lived learning experiences and directly respond to the three research questions by illuminating both meaningful improvements and remaining challenges in engagement, conceptual understanding, and scientific reasoning.

Field note: During early implementation sessions, several students who previously remained silent began leaning toward group screens and actively pointing at simulation outputs. The observer noted that *"even low-participation students are now physically drawn into group discussion spaces."*

Theme 1: Fostering Meaningful Engagement in Science Learning

A central outcome of the intervention was a clear overall increase in students' engagement, characterized by active participation, collaboration, and experiential learning. However, this engagement was not uniform; it developed strongly in structured group contexts while remaining weaker for some students who struggled with abstract interpretation or group dependence.

Under the sub-theme active participation and collaborative knowledge construction, students consistently described a shift from passive listening toward shared responsibility in learning. One student explained, "We were not just listening to the teacher; we were discussing and solving problems together" (S7), while another noted, "Everyone had a role in the group work" (S2). This was supported by T1, who observed that "even students who usually stay quiet became active once roles were clearly structured." At the same time, T1 noted a contrasting pattern that "a few learners still depended heavily on stronger group members," indicating that collaboration increased participation overall but did not fully equalize contribution.

Field note: In one group activity, three students dominated the simulation controls while others observed quietly. The researcher recorded*, "Participation is visible, but cognitive engagement is uneven within groups."*

In the sub-theme learning science through first-hand exploration and experience, students described simulations as creating a sense of doing real science. One student stated, "It felt like we were doing real experiments even with simulations" (S8). Supporting this, T1 explained that "students could experiment safely and repeatedly, which increased willingness to explore." However, the teacher (T1) also cautioned that "some students focused on playing with the simulation rather than interpreting results," suggesting that experiential engagement sometimes lacked conceptual depth without guidance.

Field note: Several students repeatedly adjusted variables in the simulation without recording observations. The observer noted*, "Exploration is high, but systematic inquiry is still developing."*

Under enhanced motivation and learning gains, many students reported increased interest in chemistry. One student said, "Now chemistry is interesting; I want to study more after class" (S3), while another added, “The lesson was impressive because we could try things ourselves” (S10). T1 similarly noted that “students showed strong enthusiasm, but it varied depending on prior achievement levels,” indicating that motivation gains were uneven but still broadly positive.

Overall, this theme addresses RQ3 by showing that engagement improved through collaboration, simulation-based exploration, and inquiry participation, though sustained engagement required structured guidance and did not develop equally for all learners.

Theme 2: Supporting Conceptual Understanding through Guided Inquiry and Scientific Representation

The second theme explains how the intervention improved conceptual understanding by connecting macroscopic, microscopic, and symbolic representations. Importantly, this development was progressive and sometimes fragile, depending on the level of teacher support.

Under the sub-theme making sense of scientific concepts through multiple representations, students emphasized that simulations made invisible processes more accessible. One student explained, “Before I was confused about collision theory, but now I can see how particles move and collide” (S9). Another added, “The diagrams, equations, and simulation all made sense together” (S4). T1 confirmed this alignment, stating that “students could finally connect equations with particle behavior”; however, he offered a cautionary view, noting that “some students still interpreted motion superficially without linking it to energy and rate concepts,” suggesting partial conceptual integration.

Field note: During simulation tasks on collision frequency, some students accurately described particle movement visually but failed to relate it to reaction rate changes when questioned. The observer noted, *“Visual understanding is ahead of verbal explanation for several learners.”*

Under retrieving and applying scientific knowledge for deeper understanding, students reported better retention and understanding. A student stated, “I remember better because I see and do it instead of just memorizing” (S6), while T1 observed that “understanding improved, but only when students actively engaged rather than passively watching.” This indicates that conceptual gains depended strongly on participation quality.

In scaffolding conceptual learning through responsive teaching, both students and teachers emphasized the need for guided explanation. One student noted, “Sometimes the simulation is confusing unless the teacher explains it step by step” (S2). Similarly, T1 explained, “Without guidance, students may misread what they observe at the microscopic level.”

Field note: When teacher explanations were briefly reduced, several groups interpreted faster reaction rates incorrectly as *“more particles appearing,” highlighting conceptual fragility without scaffolding.*

Overall, this theme addresses RQ1 by showing that conceptual understanding improved through multiple representations and guided inquiry, but also that meaning-making remained dependent on structured teacher mediation.

Theme 3: Cultivating Scientific Thinking and Independent Inquiry

This theme captures a gradual but uneven development of scientific reasoning and learner independence.

Under developing scientific ways of thinking, students reported moving from memorization toward explanation. One student stated, “Now I try to explain why things happen, not just give answers” (S8), while another added, “We learned how to think like scientists” (S9). T1 observed a similar shift but noted variation, stating that “stronger students asked deeper questions, while others still relied on answers.”

Field note: During questioning sessions, only a subset of students asked ‘why’ questions about reaction rate changes, while others focused on completing worksheet steps.

In responsive learning for independent scientific endeavors, students described growing autonomy. One student explained, “We can try different things in simulation and see what happens” (S6), while another noted, “I feel more confident to study chemistry on my own now” (S5). T1, however, added a balancing perspective: “Independence increased, but some students still needed continuous prompting.”

This theme addresses RQ2 by showing that the intervention supported both guided inquiry and gradual independence, but independence was conditional rather than universal.

Theme 4: Learning Environment as a Catalyst for Science Learning

The learning environment emerged as both an enabling and constraining factor.

Under creating supportive and interactive learning environments, students described reduced anxiety. One stated, “Simulation is safer and makes me less afraid of making mistakes” (S4). T1 supported this, noting that “students participated more freely because failure felt less risky.” However, T1 observed that “some students remained passive even in safe environments.”

Field note: Even in low-risk simulation settings, a few students consistently avoided interaction until directly prompted by peers or teacher.

In classroom interactions that facilitate engagement and understanding, peer learning was central. A student explained, “We help each other when someone does not understand” (S7), while T1 noted that “peer explanations sometimes worked better than teacher explanations.” At the same time, and observed a limitation: “peer discussions sometimes spread misunderstandings when not corrected.”

Contextual constraints also shaped experiences. A student stated, “We don’t have enough lab materials, so simulation helps a lot” (S2), while T1 pointed out that “large class sizes limit individual feedback.”

Field note: Teacher circulation during group work was limited; some groups waited several minutes for clarification, leading to uneven pacing across the class.

This theme contributes to RQ2 by showing that learning outcomes were shaped not only by pedagogy but also by classroom ecology and resource availability.

Theme 5: Barriers to Meaningful Participation in Science Learning

Despite overall positive outcomes, several persistent barriers remained. Under restricted science learning opportunities, students reported difficulty interpreting microscopic processes. One explained, "Sometimes I get confused because I cannot see what is really happening at the particle level" (S9). Another added, "Collision theory is still difficult even in simulation" (S7). T1 similarly noted that "students need repeated explanation before they can connect visuals to theory."

Field note: Misinterpretations were most frequent when students relied solely on visual simulation output without teacher explanation or peer discussion.

In factors limiting engagement in scientific practices, structural issues were evident. A student stated, "Large class sizes make it hard for teachers to support everyone" (S3), while another pointed to "shortage of laboratory materials" (S1). T1 added that "time pressure reduces depth of inquiry for some groups." These barriers led to unequal participation experiences.

This theme informs RQ2 by identifying necessary refinements, particularly stronger scaffolding, improved resources, and more adaptive pacing.

In summary, across the three research questions, the qualitative findings collectively show that integrating POGIL with interactive simulation laboratory activities significantly enhanced students' engagement, conceptual understanding, and scientific thinking in chemical kinetics, while also revealing important limits in consistency and depth. Field observations further confirm that while engagement visibly increased in group-based and simulation-rich settings, conceptual understanding still required sustained teacher mediation to stabilize meaning. Overall, both student and teacher perspectives suggest that the intervention created a more engaging and conceptually meaningful science learning environment, while also emphasizing that sustained effectiveness depends strongly on teacher scaffolding, contextual support, and attention to learner variability.

Discussion of Findings

The combined quantitative and qualitative findings provide strong evidence that integrating Process-Oriented Guided Inquiry Learning (POGIL) with interactive simulations meaningfully enhanced Grade 11 students' learning in chemical kinetics. The results demonstrate not only significant gains in achievement, conceptual understanding, and engagement, but also how these changes emerged through structured inquiry, collaborative learning, and multimodal representation. This section discusses the findings in relation to the three research questions, supported by relevant literature.

RQ1: To what extent do the integrated POGIL–interactive simulation laboratory activities affect students' conceptual understanding and improve students' achievement in chemical kinetics?

The findings show a substantial improvement in students' achievement following the intervention, with mean scores increasing from 9.65 to 21.19 out of 32 and a large normalized gain ($g = 0.516$). This level of improvement aligns with research showing that guided inquiry approaches significantly outperform traditional lecture-based instruction in promoting conceptual learning in chemistry (Chi & Wylie, 2014). The shift of more than half of students into the high mastery category further indicates that learning gains were broadly distributed rather than concentrated among high-achieving students.

Conceptual understanding followed a similar pattern, with students moving from predominantly "no understanding" (52.1%) to over half demonstrating conceptual understanding (52.0%) after the intervention. This transformation is consistent with conceptual change theory, which emphasizes that learners reconstruct prior misconceptions when confronted with cognitively engaging and representationally rich learning environments (Posner et al., 1982). The combination of POGIL and simulation appears particularly effective because it simultaneously challenges misconceptions and provides visual-molecular evidence to support restructuring of understanding.

Interactive simulations contributed by making abstract kinetic processes visible at the particle level, as well as emphasizing the importance of multiple representational fluency in chemistry learning. Similarly, (Rutten et al., 2012) found that simulations are most effective when embedded in guided inquiry structures, rather than used as stand-alone tools. This is reflected in the present findings, where simulations alone were not sufficient; students still required structured questioning to connect visual observations to formal kinetic reasoning.

However, the data also reveal persistent conceptual fragility. Some students could describe particle motion but failed to link it to reaction rate theory, a challenge widely reported in chemistry education literature (Taber, 2018). This suggests that while simulations enhance perceptual access to invisible phenomena, they do not automatically ensure conceptual integration without sustained scaffolding.

RQ2: How can an Interactive Simulation–Integrated POGIL Laboratory Activities be designed and iteratively refined to support students' conceptual understanding of chemical kinetics?

The design-based implementation of the intervention highlights several critical design principles that emerged through classroom iteration. First, structured role assignment within POGIL groups was essential for ensuring equitable participation. This aligns with findings from (Johnson & Johnson, 2009), who emphasize that cooperative learning requires explicit structuring of interdependence to avoid dominance effects in group work.

Second, the integration of simulations required careful alignment with inquiry prompts. While students were highly engaged in manipulating simulation variables, observations showed that some initially engaged in "exploratory play" rather than scientific inquiry. Similar findings have been reported by (Jong, 2013), who note that simulations must be carefully scaffolded to avoid cognitive overload and off-task exploration.

Teacher mediation emerged as a central design component. Students frequently required step-by-step guidance to interpret particle-level representations, highlighting the importance of what Vygotsky (1978) describes as learning within the Zone of Proximal Development. The teacher's role in translating visual data into conceptual meaning was therefore not supplementary but essential.

Iteratively, the intervention points to three important design refinements that can strengthen its effectiveness. First, embedding structured inquiry prompts within simulations helps guide students' attention toward the most relevant variables and prevents unstructured exploration. Second, incorporating explicit representational linking tasks supports students in connecting microscopic, macroscopic, and symbolic levels of chemical kinetics, as emphasized by (Talanquer, 2011). Finally, using adaptive scaffolding strategies allows teachers to gradually reduce support over time as students develop greater conceptual fluency and independence in their understanding.

These refinements align with contemporary design-based research perspectives, which emphasize continuous improvement of learning environments in authentic classroom contexts (Reeves, 2018).

RQ3: How does the integration of interactive simulations and POGIL laboratory activities influence students' engagement and their ability to connect representations in chemical kinetics?

Engagement increased significantly from moderate to high levels, with strong improvements across behavioral, cognitive, and emotional dimensions. This finding is consistent with research showing that active learning environments significantly increase student engagement in STEM disciplines (Freeman et al., 2014). The magnitude of engagement gain suggests that the combination of collaborative inquiry and simulation-based visualization created a learning environment that was both cognitively stimulating and emotionally engaging.

Students described the experience as "doing real science," which reflects authentic inquiry learning principles (National Research Council, 2012). Classroom observations confirmed increased participation, peer interaction, and sustained attention during simulation tasks. However, engagement was not always deeply conceptual; some students focused on manipulating simulations without interpreting results, reflecting a known limitation of technology-enhanced learning environments where behavioral engagement can exceed cognitive engagement (Fredricks et al., 2004).

The integration of simulations and POGIL also strengthened representational understanding. Students increasingly connected particle-level behavior with symbolic equations and macroscopic outcomes, consistent with findings by (Gilbert & Treagust, 2009), who argue that chemistry understanding depends on fluency across multiple representational levels. Interactive simulations supported visualization of invisible processes, while POGIL structured reasoning and discussion, together enabling "synergistic representational learning."

Despite these gains, representational fluency was uneven. Some students still struggled to articulate microscopic explanations in symbolic terms, particularly without teacher scaffolding. This highlights the importance of guided representational translation tasks, as emphasized in recent chemistry education research (Talanquer, 2011).

Across all three research questions, the findings converge on a consistent pattern: the integration of POGIL and interactive simulations produced meaningful and interconnected improvements in achievement, conceptual understanding, and engagement. The strongest effects were observed when students actively participated in structured inquiry supported by visual-molecular representations.

However, the results also highlight important tensions. While engagement increased substantially, it did not always guarantee deep conceptual processing. Similarly, while simulations made abstract processes visible, they required careful scaffolding to prevent superficial interpretation. These findings align with broader research emphasizing that technology-enhanced inquiry learning is most effective when combined with strong pedagogical structure rather than used independently (Jong et al., 2024).

From a learning sciences perspective, the intervention demonstrates the importance of integrating cognitive, social, and representational dimensions of learning. Achievement gains were not only a function of content exposure but emerged through collaborative meaning-making, guided inquiry, and multimodal representation. This supports contemporary views of science learning as an active, socially mediated process rather than passive knowledge acquisition (Taber, 2014).

Overall, the intervention created a learning environment where students could actively explore, visualize, and reason about chemical kinetics. While the gains were substantial, sustaining deep conceptual understanding requires continued refinement in scaffolding, representational guidance, and structured participation to ensure that all learners benefit equally from the learning design.

CHAPTER FIVE

Conclusion

This study examined the effect of integrating POGIL with interactive simulations on Grade 11 students' achievement, conceptual understanding, and engagement in chemical kinetics. Overall, the findings show a clear and consistent improvement across all three areas after the intervention.

Students' achievement increased substantially, conceptual understanding shifted from mostly no understanding to majority conceptual understanding, and engagement rose from moderate to high levels. These improvements were not isolated but occurred across the whole class, showing broad learning gains rather than gains limited to a few students.

The results also show that these outcomes were driven by structured inquiry, collaborative learning, simulation-based visualization, and teacher scaffolding. However, some students still required additional support to fully interpret abstract concepts. Overall, the intervention proved to be an effective approach when properly guided for supporting learning in chemical kinetics.

Implications

The findings suggest that students learn more effectively through active, inquiry-based approaches rather than passive instruction. The combination of POGIL and simulations was particularly effective in improving understanding of abstract chemical concepts.

Interactive simulations helped students visualize invisible processes, but their effectiveness depended on structured questions and guided discussion. This highlights the continued importance of the teacher's role in supporting interpretation and correcting misconceptions.

The study also shows that effective science learning requires a balance between student autonomy and instructional guidance, especially when dealing with complex conceptual content. In addition, the findings reinforce the value of iterative, classroom-based refinement in improving instructional design.

Recommendations

Teachers are encouraged to integrate simulations with structured POGIL activities using clear inquiry questions to guide learning. Instruction should include explicit links between macroscopic, microscopic, and symbolic representations to strengthen understanding.

Teachers should also use gradual scaffolding, offering strong support at the beginning and reducing it as students become more confident. Curriculum designers are encouraged to embed guided inquiry and simulation-based learning into science topics that involve abstract concepts.

Future research should examine long-term retention, compare different scaffolding approaches, and test the intervention in different contexts and with comparison groups to strengthen generalizability.

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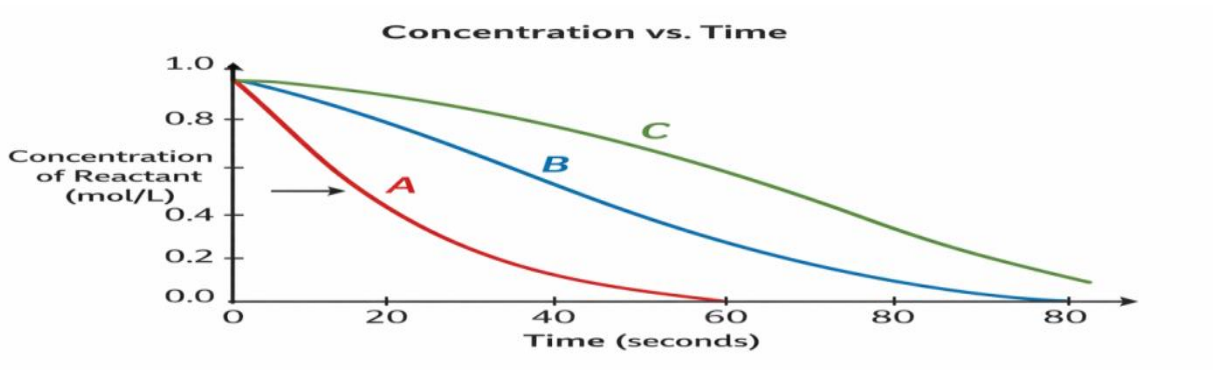
Appendices

Appendix A

Three experiments were conducted using the same reactant and same initial concentration. The only difference was temperature. Which experiment was carried out at the highest temperature?



The graph above shows the change in concentration of the reactant with time.

a) Experiment A b) Experiment B c) Experiment C d) All have the same temperature

Choose the reason that best explains your answer.

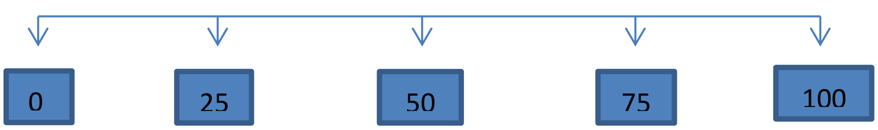
a) The reaction that finishes first has the highest rate

b) Temperature increases initial concentration

c) The curve with the largest slope represents the fastest rate

d) Temperature does not affect reaction rate

Indicate your confidence (%)



2. Farmers often observe that farm tools rust faster during the rainy season. In which condition will rusting occur fastest?

a) Dry indoor storage b) Outside during rainy season

c) Painted metal surface d) Airtight container

Choose the reason that best explains your answer.

a) Lack of water slows reaction

b) Water and oxygen increase effective collisions

c) Paint blocks contact with air and water

d) No oxygen means no reaction

Indicate your confidence (%)

0 | 25 | 50 | 75 | 100

Appendix B

Interview Guide Questions (Semi-Structured)

1) How do you evaluate your conceptual learning experiences with reaction rate (and its associated factors) using the POGIL embedded with interactive simulations approach in a large classroom setting as compared to the regular approaches in use?

2) What particular learning strategies and processes do you think are crucial for your enhanced conceptual learning of and engagement in chemical kinetics topics?

During your active engagement in the assigned laboratory activities, did you think you got sufficient opportunities for investigating, asking questions, and making decisions on your own? Explain.

3) Which chemical concepts do you think became clearer, and which are still confusing? Why?

4) How did interactive simulations help you understand difficult or abstract concepts and increase your active engagement in the practical activities? What exactly made them helpful? Can you mention particular examples?

5) What features of the POGIL embedded with interactive simulations do you find the most challenging?

6) What is your overall impression about this approach regarding affecting your interest, engagement, and overall learning of chemistry lessons?

Appendix C

Interview Guide Questions (Semi-Structured)

1) How do you describe your overall experiences with implementing a DBR approach to process-oriented guided inquiry learning [POGIL] embedded with an interactive simulation approach?
2) How did you integrate POGIL laboratory activities with interactive simulations, and how manageable were the learning processes? Do you think the processes of designing the learning activities were directed towards developing students improved conceptual learning of and engagement in the learned topics?
3) In what ways did local, real-life examples support or limit your students' understanding of and engagement in learning chemical kinetics?
4) What challenges did you encounter during the implementation of this approach in a real classroom context?
5) Based on your experiences with this approach, would you like to continue using it in your chemistry teaching? What particular areas of improvement would you suggest/recommend to make this approach more effective and efficient in the near future? Why?

Appendix D

Pre-test students' engagement scale

Please indicate how much you agree with each statement by ticking (✓) one option.

Scale	Meaning
1	Strongly Disagree
2	Disagree
3	Neutral
4	Agree
5	Strongly Agree

No	Statement	1	2	3	4	5
1	I pay attention during chemistry lessons.					
2	I participate actively in chemistry class activities.					
3	I ask questions when I do not understand chemistry concepts.					
4	I enjoy participating in chemistry lessons and try to relate chemistry concepts to real-life situations					
5	I make effort to understand difficult chemistry concepts.					
6	I lose interest quickly during chemistry lessons.					
7	I often feel confused when learning chemistry because some concepts cannot be seen in our eyes.					

Appendix E

Post-test student engagement scale

Please indicate how much you agree with each statement by ticking (✓) one option.

Scale	Meaning
1	Strongly Disagree
2	Disagree
3	Neutral
4	Agree
5	Strongly Agree

No	Statement	1	2	3	4	5
1.	I was interested in learning chemical kinetics during these lessons.					
2.	I actively participated in class activities.					
3.	I paid more attention in these lessons than usual.					
4.	Laboratory activities helped me understand chemical kinetics concepts better.					
5.	I was able to think and investigate during laboratory activities.					
6.	Doing experiments made learning more interesting.					
7.	I learned better by watching what was performed in the experiments.					
8.	Simulations helped me understand difficult concepts.					

9.	Simulations made abstract ideas easier to visualize.					
10.	I found the simulations easy to use.					
11.	Using simulation together with laboratory activities improved my understanding.					
12.	Real-life examples (e.g., coffee, cooking, and refrigerator) helped me understand the lesson.					
13.	I could relate the chemistry concepts to my daily life.					
14.	This teaching method is better than traditional teaching methods.					
15.	I found some concepts in chemical kinetics difficult to understand.					
16.	I had difficulty using simulations during the lesson.					

APPENDIX F