2026-06

þÿ E n h a n c i n g   G r a d e   1 1   S t u d e n t s Thinking Skills In Chemical Equilibrium Through Inquiry-Based Learning: A Design-Based Research Approach

Derbew, Girma

BAHIR DAR UNIVERSITY

COLLEGE OF EDUCATION

SCHOOL OF TEACHER EDUCATION

DEPARTMENT OF SCIENCE AND MATHEMATICS EDUCATION

MED THESIS ON:

ENHANCING GRADE 11 STUDENTS' CRITICAL THINKING SKILLS IN CHEMICAL EQUILIBRIUM THROUGH INQUIRY-BASED LEARNING: A DESIGN-BASED RESEARCH APPROACH

BY

DERBEW GIRMA MINAYEHU

JUNE 26, 2026

BAHIR DAR, ETHIOPA

BAHIR DAR UNIVERSITY
COLLEGE OF EDUCATION
SCHOOL OF TEACHER EDUCATION
DEPARTMENT OF SCIENCE AND MATHEMATICS
EDUCATION

Enhancing Grade 11 Students' Critical Thinking Skills In Chemical Equilibrium Through Inquiry-Based Learning: A Design-Based Research Approach

By

Derbew Girma Minayehu

A thesis submitted in Partial Fulfillment of the Requirements for the Degree of Master of Education in chemistry

Advisor: Mirtachew T.Ali (Ph.D.)

June 2026
Bahir Dar, Ethiopia

BAHIR DAR UNIVERSITY

COLLEGE OF EDUCATION

SCHOOL OF TEACHER EDUCATION

DEPARTMENT OF SCIENCE AND MATHEMATICS EDUCATION

Approval Of Thesis For Defense Result

I hereby confirm that the changes required by the examiners have been carried out and incorporated in the final thesis.

Name of Student:Derbew Girma Minayehu Signature: _________Date: _________________

As members of the board of examiners, we examined this thesis entitled "Enhancing Grade 11 Students' Critical Thinking Skills in Chemical Equilibrium through Inquiry-Based Learning: A Design-Based Research Approach" by Derbew Girma. We hereby certify that the thesis is accepted for fulfilling the requirements for the award of the degree of Masters of education in "Chemistry."

Board of Examiners

Name	**Signature**	**Date**
Mirtachew T.Ali (Ph.D) (advisor)	______________	_____________
Dr. Derejaw (Internal examiner)	______________	______________
Dr. Tadesse H. (External examiner)		_______________
Dr.Mersha (chairpreson)	______________	________________

DECLARATION

This is to certify that the thesis entitled "*Enhancing Grade 11 Students' Critical Thinking Skills in Chemical Equilibrium through Inquiry-Based Learning: A Design-Based Research Approach*", submitted in partial fulfillment of the requirements for the degree of Master of Education in Chemistry under College of Education, Bahir Dar University, is a record of original work carried out by me and has never been submitted to this or any other institution to get any other degree or certificates. The assistance and help I received during the course of this investigation have been duly acknowledged.

Derbew Girma ________________ ____________________

Name of the candidate signature Date

June 2026

Bahir Dar University, Ethiopia

ACKNOWLEDGMENT

I would like to express my deepest gratitude to the Almighty God for giving me the health, strength, and determination to complete this research and my master's degree program.

I am profoundly grateful to my advisor, Dr. Mirtachew T. Ali, for his invaluable guidance, patience, and insightful feedback throughout this project. His academic expertise and continuous encouragement truly shaped this study and kept me moving forward.

I also want to thank Bahir Dar University, the College of Education, and the Department of Science and Mathematics Education for providing the institutional support and resources necessary for my studies.

My sincere thanks go to the administration of the public secondary school in Injibara City for welcoming this project. In particular, I am incredibly indebted to the classroom chemistry teacher, Mr. Addissu Ademe, for his exceptional cooperation in bringing the lesson plans to life, and to the Grade 11 students for their active participation and enthusiastic engagement during our six weeks together. This study would not have been possible without them.

Finally, I am forever grateful to my family, colleagues, and friends. Their unwavering moral support, understanding, and love provided the constant strength I needed throughout this academic journey.

ABBREVIATIONS

CECT	Chemical Equilibrium Conceptual Test
CER	Chemistry Education Research
DBR	Design Based Research
IBL	Inquiry Based Learning
CTT	Critical Thinking test
CEDT	Chemical Equilibrium Diagnoastic test

Table of Contents

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Chemical equilibrium is among the most conceptually demanding topics in secondary chemistry, with students frequently developing persistent misconceptions due to its dynamic nature and the prevalence of teacher-centered instruction that limits inquiry and reasoning opportunities. This study examined how a Design-Based Research Inquiry Based Learning (DBR–IBL) approach an instructional framework that integrates iterative design cycles with student-centered inquiry pedagogy affected Grade 11 students' conceptual understanding of chemical equilibrium and critical thinking skills.

Rooted in constructivism and Chemistry Education Research (CER), the study employed a mixed-methods design implemented over six weeks in a public secondary school in Injibara City, Ethiopia. Quantitative data were collected using a Critical Thinking Test and a Chemical Equilibrium Diagnostic Test administered pre- and post-intervention. Qualitative data were gathered through structured classroom observations, semi-structured interviews, reflective discussions, and analysis of student learning artifacts. The intervention was iteratively refined through DBR cycles to address evolving student learning needs.

Quantitative results showed significant achievement gains: mean scores rose from 29.30 (SD = 7.84) to 42.63 (SD = 3.48). A paired-samples t-test confirmed statistical significance, $t(29) = -13.75$, $p < 0.001$, with a very large effect size (Cohen's d = 2.51). Qualitative analysis revealed five interconnected themes: conceptual restructuring of chemical equilibrium understanding, growth in critical thinking and scientific reasoning, increased engagement in collaborative inquiry, challenges in adapting to student-centered learning, and positive perceptions of chemistry's real-world relevance.

Collectively, the findings indicate that the DBR–IBL approach enabled students to actively construct scientific knowledge, confront persistent misconceptions, and engage in evidence-based reasoning. The study contributes empirical support for design-oriented inquiry in complex chemistry instruction and recommends broader integration of DBR–IBL alongside further research into its long-term transferability across diverse educational settings.

***Keywords**: Chemistry Education Research, Design-Based Research, Inquiry-Based Learning, Chemical Equilibrium, Critical Thinking, Conceptual Understanding.*

CHAPTER ONE: INTRODUCTION

1. INTRODUCTION

Science education plays a crucial role in preparing students to understand scientific phenomena, solve real-world problems, and participate in an increasingly science-driven society (Morris, 2025; Olefin, 2023). In modern educational frameworks, the goal of science learning extends beyond acquiring factual knowledge to developing scientific knowledge. Scientific literacy involves the ability to interpret evidence, reason scientifically, and apply knowledge to new contexts (Osborne, 2023; Dibner & Snow, 2016). Among these competencies, critical thinking has been widely recognized as a key skill that enables students to analyze information, evaluate arguments, and make informed decisions in both academic and everyday situations(Alsace, 2020); Liu, Frankel, & Rohr, 2014).

Educational reforms at the international and national levels increasingly emphasize the development of higher-order thinking skills in science classrooms. Active learning approaches, such as inquiry-based learning, have been recommended as effective strategies to support these goals because they engage students in scientific practices such as questioning, investigating, analyzing evidence, and constructing explanations (Antonio & Prudent, 2024); Yadav & Singh, 2026). Recently, researchers have emphasized the importance of design-oriented learning approaches that allow students to design solutions, test ideas, and refine their understanding through iterative processes (Sawangboon & Chano, 2025).

Within this context, design-based research inquiry-based learning (DBR–IBL) represents a promising instructional approach that integrates inquiry learning with design-oriented problem solving. This approach has the potential to support students' conceptual understanding and critical thinking by actively engaging them in the process of knowledge construction. Therefore, the present study aims to explore how a design-based inquiry-Based learning approach can enhance the critical thinking skills of grade 11 students during the learning of chemical equilibrium in selected Ethiopian secondary schools.

1.1 Background of the Study

Science education aims to equip learners with the knowledge, skills, and attitudes necessary to understand the natural world and to participate effectively in scientific and technological development. Contemporary perspectives in science education emphasize the importance of scientific literacy, which includes the ability to ask meaningful questions, analyze and interpret data, evaluate evidence, and apply scientific reasoning to solve problems (Bybee, 2015; Lederman et al., 2023). Among these competencies, critical thinking plays a central role, as it enables students to evaluate information, draw logical conclusions, and make reasoned judgments. Therefore, developing students' critical thinking skills has become an important objective of science education worldwide.

To achieve these educational goals, researchers have increasingly advocated instructional approaches that actively engage students in the learning process. Conventional lecture-based teaching methods often emphasize memorization of facts and algorithmic problem-solving, which may limit students' opportunities to develop a deeper conceptual understanding and higher-order critical thinking skills. In contrast, active learning approaches encourage students to explore ideas, discuss explanations, and collaboratively construct knowledge. Studies in science education have consistently shown that active learning environments can significantly improve students' understanding, engagement, and critical thinking (Freeman et al., 2014; Lazenby, 2023).

Inquiry-Based Learning (IBL) is one of the most widely studied active learning approaches in science education. In this approach, students learn science by asking questions, designing investigations, analyzing data, and constructing explanations. Inquiry-based learning is grounded in *constructivist* learning theory, which emphasizes that learners actively construct knowledge through interaction with ideas, evidence and prior understanding. Research has shown that inquiry-based learning can improve students' conceptual understanding, scientific reasoning, and critical thinking skills in science classrooms (Sutiani et al., 2021; Arifin et al., 2025).

Despite the growing emphasis on student-centered learning approaches, science instruction in many Ethiopian secondary schools remains teacher-centered. Previous studies have indicated that classroom teaching is often dominated by lecture-based methods, with limited opportunities for students to engage in inquiry, discussion, and problem solving (Teshome, 2020; Tadesse et al., 2020). National education policy documents, including the Ethiopian Education Development Roadmap (MoE, 2018), emphasize the importance of improving active learning practices and promoting higher-order thinking skills, such as critical thinking, in science education. However, the implementation of these approaches in classroom practices remains inconsistent.

Chemical equilibrium is one of the most challenging topics in secondary school chemistry curricula. Students frequently struggle to understand the dynamic nature of equilibrium and often hold misconceptions, such as believing that reactions stop at equilibrium or that equilibrium implies equal concentrations of reactants and products (Bergquist & Heikkinen, 1990). These misconceptions can hinder students' ability to apply important concepts, such as equilibrium constants and Le Chatelier's principle. Understanding chemical equilibrium requires students to reason across multiple levels of representation, including macroscopic observations, symbolic equations, and particle-level explanations, which demand strong critical thinking skills.

Although inquiry-based learning has shown positive effects on students' conceptual understanding and reasoning, research suggests that its effectiveness depends on how learning activities are designed and implemented. Design-Based Research (DBR) offers a promising approach to developing and refining instructional strategies in authentic classroom settings. By integrating design-oriented tasks with inquiry processes, DBR can create learning environments that encourage students to design solutions, test ideas, evaluate outcomes and refine their understanding through iterative reflection (Kolodner et al., 2003; Tinoca et al., 2022).

Despite the growing use of design-based research in science education, its application in secondary school chemistry remains limited, particularly in the Ethiopian context. Few studies have explored how a design-based inquiry-based learning approach can support students' critical thinking and conceptual understanding of challenging topics such as chemical equilibrium. This gap highlights the need for context-specific research examining how design-oriented inquiry can be effectively implemented in Ethiopian chemistry classrooms.

Therefore, the purpose of this study is to design, implement, and evaluate a design-based research inquiry-based learning intervention for teaching chemical equilibrium and to investigate how this approach supports grade 11 students' critical thinking and conceptual understanding in a secondary school in Injibara City.

1.1.1 Bridging the Gap between Policy Expectations and Classroom Practices in Ethiopia

Ethiopia's national education policies prioritize the development of scientifically literate citizens who can think critically and apply knowledge to real-life situations. Likewise, the Ethiopian education and training roadmap and the secondary school curriculum framework highlight the importance of active learning, problem solving, and critical thinking as key outcomes of science education (MoE, 2018). Despite these policy intentions, several studies have reported that classroom practice in Ethiopian secondary schools remains largely teacher-centered, with limited opportunities for inquiry, reasoning, and student-driven learning, particularly in chemistry classrooms (Teshome, 2020; Tadesse et al., 2020; Girma, 2022).

Indeed, chemistry education research in Ethiopia has documented persistent challenges related to students' conceptual understanding, motivation, and critical thinking skills. For example, recent studies have indicated that students often struggle with abstract chemistry concepts because of their heavy reliance on lecture-based instruction and algorithmic problem-solving (Belayneh & Belachew, 2024). While some Ethiopian studies report the positive effects of active and inquiry-oriented approaches on students' engagement and understanding, they also highlight the need for well-structured instructional designs that support sustained reasoning and reflection (Wale & Bishaw, 2020; Girma, 2022). However, research focusing specifically on how instructional design influences the development of critical thinking in chemistry remains limited.

One chemistry topic that consistently presents significant learning difficulties is chemical equilibrium. Chemical equilibrium is conceptually demanding because it requires students to understand the dynamic nature of reversible reactions, interpret symbolic representations, and reason at macroscopic, submicroscopic, and symbolic levels (Bergquist & Heikkinen, 1990; Rahmawati et al., 2022). Research conducted both internationally and locally shows that many secondary school students believe that equilibrium is a static state, assume equal concentrations of reactants and products, or think that reactions stop at equilibrium misconceptions that persist even after traditional instruction (Bilgin, 2003; Suparman et al., 2024; NEAEA, 2022).

Inquiry-Based Learning has been shown to reduce such misconceptions and improve students' conceptual understanding of chemical equilibrium by encouraging active exploration and evidence-based reasoning (Annisa et al., 2018; Juniar & Sianipar, 2022). Moreover, IBL supports the development of critical thinking skills, which are essential for understanding equilibrium concepts and applying principles such as Le Chatelier's principle to novel situations (Arifin et al., 2020; Arifin et al., 2025). However, research indicates that inquiry alone does not guarantee meaningful learning outcomes. The effectiveness of IBL depends heavily on how inquiry tasks are designed, sequenced, and supported in real classroom contexts (Aditomo & Klieme, 2020).

Design-Based Research (DBR) offers a systematic approach to strengthening inquiry-based instruction by focusing on the iterative design, implementation, evaluation, and refinement of learning interventions in authentic educational settings (Juuti & Lavonen, 2012; Tinoca et al., 2022). DBR emphasizes collaboration between researchers and practitioners and aims to generate practical solutions and theoretical insights into teaching and learning. Recent studies in science education have shown that DBR informed instructional designs can enhance students' reasoning, engagement, and conceptual understanding (Scott et al., 2020; Obczovsky et al., 2024). Despite this potential, the application of DBR in secondary school chemistry, particularly for teaching chemical equilibrium and fostering critical thinking, remains limited, especially in the Ethiopian context.

Therefore, there is a clear need for research that integrates design-based research with inquiry-based learning to develop context-sensitive instructional approaches that address persistent learning difficulties in chemical equilibrium and promote critical thinking skills. By designing, implementing, and evaluating a design-based inquiry-based learning (DB–IBL) intervention for grade 11 chemical equilibrium instruction, this study seeks to bridge the gap between educational research and classroom practice and contribute to evidence-based insights into chemistry education in Ethiopian secondary schools.

1.2 Statement of the Problem

Chemical equilibrium is widely recognized as one of the most challenging topics in secondary school chemistry because it requires students to understand abstract and dynamic processes that cannot be directly observed. Numerous studies have reported that students frequently develop misconceptions concerning the dynamic nature of equilibrium, the interpretation of equilibrium shifts, and the relationship between reaction rates and concentrations (Bergquist & Heikkinen, 1990; Bilgin, 2003). These misconceptions often persist despite formal instruction and limit students' ability to apply equilibrium concepts in problem-solving and real-life situations.

To address these difficulties, chemistry education researchers have increasingly advocated student-centered instructional approaches. Evidence suggests that inquiry-based learning can enhance conceptual understanding, reduce misconceptions, and promote scientific reasoning by engaging students in active investigation and evidence-based explanation (Annisa et al., 2018; Juniar & Sianipar, 2022; Rahmawati et al., 2022). Similarly, inquiry-oriented instruction has been shown to support the development of critical thinking skills through opportunities for analysis, evaluation, and justification of scientific ideas (Sutiani et al., 2021; Wale & Bishaw, 2020; Arifin et al., 2025). However, the effectiveness of inquiry-based learning largely depends on how learning activities are designed, implemented, and refined to address students' specific learning needs.

In response to this concern, Design-Based Research (DBR) has emerged as a promising approach for developing and improving educational interventions through iterative cycles of analysis, design, implementation, evaluation, and refinement. While DBR has demonstrated potential for bridging educational theory and classroom practice, its application in secondary chemistry education remains limited. Moreover, existing studies have rarely examined how inquiry-based learning can be systematically integrated within a DBR framework to support conceptual change and critical thinking development in complex chemistry topics such as chemical equilibrium.

This gap is particularly significant in Ethiopia, where chemistry instruction is often characterized by teacher-centered practices that emphasize factual knowledge and procedural problem-solving. Such approaches may provide limited opportunities for students to engage in inquiry, collaborative reasoning, and reflective thinking. Although educational reforms have promoted learner-centered pedagogies, empirical evidence regarding the design, implementation, and effectiveness of integrated DBR–IBL interventions in Ethiopian secondary school chemistry classrooms remains scarce.

Therefore, there is a need for research that not only examines the effectiveness of inquiry-based learning but also investigates how inquiry-oriented instructional activities can be systematically designed and refined through iterative DBR processes. Accordingly, this study sought to design, implement, and evaluate a Design-Based Research–Inquiry-Based Learning (DBR–IBL) intervention for teaching chemical equilibrium and to examine its contribution to grade 11 students' conceptual understanding and critical thinking skills in an Ethiopian secondary school context.

1.3 Objectives of the Study

1.3.1 General Objective

The general objective of this study was to design, implement, and evaluate a design-based inquiry-based learning (DBR–IBL) intervention to enhance grade 11 students' critical thinking skills and conceptual understanding of chemical equilibrium in a secondary school in Injibara City, Ethiopia.

1.3.2 Specific objectives

This study specifically aims:

- To examine how the DBR–IBL approach influences grade 11 students' critical thinking skills during chemical equilibrium learning.
- To investigate changes in students' conceptual understanding of chemical equilibrium after participating in the DBR–IBL intervention.
- To explore students' lived experiences and reflections on learning chemical equilibrium through the DBR–IBL approach.

1.4 Research Questions

- How does the design-based inquiry-based learning approach influence grade 11 students' critical thinking skills in learning chemical equilibrium?
- How does students' conceptual understanding of chemical equilibrium change after participating in DBR–IBL intervention?
- How do grade 11 students experience and reflect on DBR–IBL learning activities during chemical equilibrium instruction?

1.5 Significance of the Study

This study is important for students, classroom teaching, and chemistry education research in Ethiopian secondary schools and beyond. First, this study helps to better understand how design-based inquiry learning (DBR–IBL) can support grade 11 students' understanding of chemical equilibrium. Previous studies have shown that inquiry-based learning can help students correct common misunderstandings, such as thinking that equilibrium is a fixed state or that reactants and products must have equal amounts (Bilgin, 2003; Annisa et al., 2018). However, research also shows that inquiry activities work well only when they are carefully planned and supported. By designing and testing an inquiry-based approach using a design-based research framework, this study shows how well-structured inquiry activities can help students understand difficult and abstract chemistry concepts in real classrooms.

Second, this study supports the development of students' critical thinking skills, which are key goals of science education. Research has shown that inquiry-based learning can help students learn to analyze information, explain their ideas, and think scientifically (Facione, 2011; Aditomo & Klieme, 2020). However, only a few studies have focused specifically on critical thinking in secondary school chemistry, especially on topics such as chemical equilibrium. By examining both students' understanding of content and their critical thinking skills, this study provides a clearer picture of how students learn through DBR–IBL instruction. Third, this study has practical value for classroom teaching. Many teachers report that it is difficult to use inquiry-based teaching because of limited time, lack of resources, and the absence of clear examples to follow (Tadesse et al., 2020). The lesson plans, inquiry tasks, and student materials developed in this study offer practical examples of how inquiry-based learning can be used in Ethiopian secondary schools. These materials may help teachers and teacher educators improve the teaching of chemical equilibrium in real classroom situations. Fourth, this study contributes to chemistry education research by demonstrating how design-based research can be used to improve teaching and learning in secondary school chemistry. Although DBR has been used in science education, it has not been widely applied in chemistry classrooms in Ethiopia. Previous research has shown that DBR helps connect educational theory with classroom practice by developing teaching ideas based on real evidence (Juuti & Lavonen, 2012; Scott et al., 2020). This study adds to the existing research by demonstrating how a DB–IBL approach works in a local school context and by offering design ideas that may guide future teaching improvements.

Finally, this study supports national education goals that focus on active learning, critical thinking, and better achievement in science subjects. National assessment reports show that many students continue to struggle with chemistry (NEAEA, 2022). Although this study does not claim to solve all these problems, it provides useful evidence-based ideas for improving teaching and learning in challenging chemistry topics such as chemical equilibrium.

1.6 Delimitation of the Study

This study focuses on how grade 11 students learn chemical equilibrium when a design-based research inquiry-based learning (DBR–IBL) approach is used. The content was limited to key topics found in the grade 11 chemistry syllabus, including the dynamic nature of equilibrium, equilibrium constants, reaction quotient, and Le Chatelier's principle. Other chemistry topics were not included in this study.

The study involved grade 11 students from a public secondary school in Injibara City. Students were the main focus of this study. The chemistry teacher's role was limited to implementing the lesson plans prepared for the study, and the research did not examine teachers' beliefs, teaching skills, or professional development. This study used a design-based research (DBR) cycle combined with Inquiry-Based Learning. The instructional intervention was carried out over a short period (approximately six weeks). Due to time and resource limitations, this study did not include multiple design cycles or follow-up studies to check for long-term learning. The study was conducted in one school only, which means that the findings were closely tied to this specific context. While the results may offer useful insights, they do not represent all secondary schools in Ethiopia.

In terms of data, this study examined changes in students' understanding of chemical equilibrium and their critical thinking skills. Data were collected through tests, classroom observations, student work samples, and interviews. This study did not examine students' attitudes, motivation, or long-term retention of knowledge.

1.7 Theoretical Framework

The common theoretical basis for this inquiry was based on *constructivist views of learning*. The key idea of constructivism that sets it apart from other theories of cognition is that knowledge cannot be transmitted directly from one knower to another; instead, learners have to actively construct their own knowledge rather than receive preformed information transmitted by others (Driver et al., 1994). Under constructivism, teaching becomes a matter of creating situations in which students can actively participate in activities that enable them to make their own individual constructions (Tobin & Tippins, 1993). A constructivist perspective also has implications for teaching and learning in school science laboratories, where students construct and develop knowledge through interactions with phenomena using their prior ideas. Teaching laboratories can stimulate students to find explanations for events and provide insight into the nature of scientific inquiry and their own investigative work. Leach and Scott (2003) also suggested that teaching science should be like the science that scientists do. Teachers should introduce scientific ideas to students and guide their learning as individual students make sense of the scientific point of view, because teachers play the role of planning the learning task and being a knowledge facilitator.

From a *constructivist* perspective, learning occurs through active engagement, social interaction, and reflection, all of which are central to inquiry-based learning and design-based approaches. DBR–IBL aligns with *constructivist* theory by allowing students to construct knowledge through iterative inquiry, design, testing, and refinement of ideas in authentic contexts. The teacher's role as a facilitator and guide further supports learners in making sense of scientific concepts, particularly abstract topics, such as chemical equilibrium.

Although Design-Based Research (DBR) and Inquiry-Based Learning (IBL) are closely related, they serve different purposes within this study. DBR functions as the overarching research and instructional design framework. It guides the systematic analysis, design, implementation, evaluation, and refinement of learning interventions in authentic classroom settings. In contrast, IBL is the pedagogical approach through which students engage in questioning, investigation, evidence-based reasoning, and knowledge construction.

In this study, DBR was not used merely as a research methodology but as a framework for continuously improving instructional activities. IBL constituted the instructional core of the intervention. Therefore, the DBR–IBL approach represents the integration of iterative design processes with inquiry-based pedagogy, whereby inquiry activities are continuously refined based on classroom evidence to enhance students' conceptual understanding and critical thinking skills.

Although Design-Based Research (DBR) and Inquiry-Based Learning (IBL) share certain procedural similarities both involving iterative cycles of activity, reflection, and refinement they serve distinct and complementary functions within this study. DBR operates as the overarching research and instructional design framework: it provides the systematic structure through which the intervention is analyzed, designed, implemented, evaluated, and iteratively refined across successive classroom cycles. IBL, by contrast, constitutes the pedagogical core of the intervention the instructional approach through which students engage with chemical equilibrium content by formulating questions, conducting investigations, interpreting evidence, and constructing explanations.

In this study, these two frameworks are therefore not synonymous but mutually reinforcing. The integrated approach, hereafter referred to as DBR–IBL, denotes a research-driven instructional design in which inquiry-based classroom activities are continuously refined through design-based iterative processes. This integration ensures that the pedagogical approach is both theoretically grounded and responsive to the authentic learning needs emerging from the classroom context.

1.8 Conceptual framework

The conceptual framework of this study illustrates how the DBR–IBL instructional approach is expected to improve students' conceptual understanding and critical thinking in chemical equilibrium. The framework begins with the learning problem, which is students' difficulty in understanding equilibrium concepts. To address this problem, the study applies a combination of design-based research and inquiry-based learning strategies. Through instructional activities such as problem-based lessons, inquiry questions, group discussions, demonstrations, and guided problem-solving tasks, students actively engage in scientific learning processes including observation, analysis, interpretation, and reasoning. These learning processes help students construct deeper understanding of important equilibrium concepts such as reversible reactions, dynamic equilibrium, equilibrium constant, and the Le Chatelier's principle. As a result, the intervention is expected to improve students' conceptual understanding and develop their critical thinking skills.

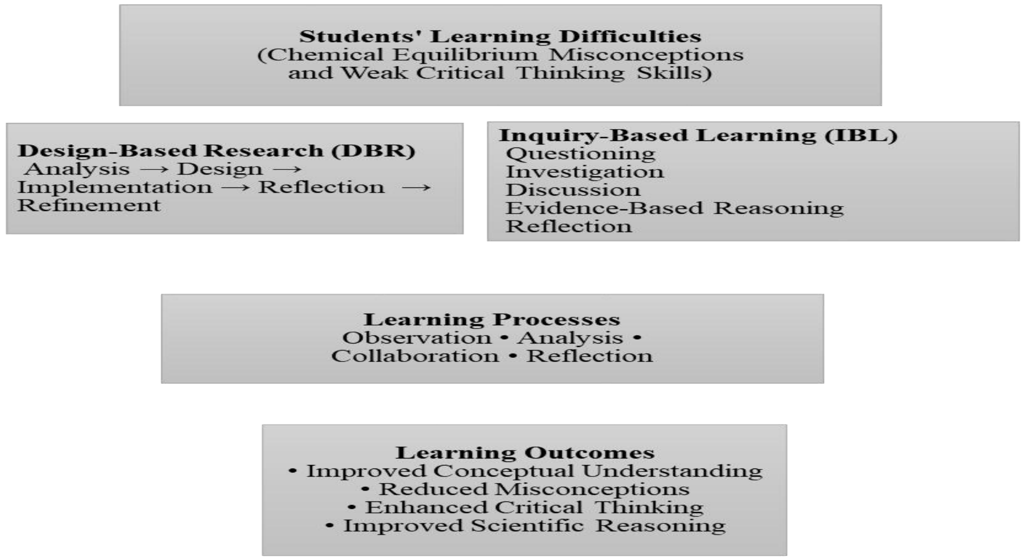


Figure 1: conceptual framework diagram

CHAPTER TWO: LITERATURE REVIEW

2.1 Chemistry Education Research (CER)

Chemistry Education Research (CER) is the study of how chemistry is taught and how students learn chemistry. It examines what happens in chemistry classrooms and attempts to understand why some teaching approaches are more effective than others. CER employs both qualitative methods, such as interviews and classroom observations, and quantitative methods, such as tests and surveys, to study teaching and learning in chemistry (Cooper & Stowe, 2018).

Researchers in CER have studied many aspects of chemistry learning. They examine how students develop an understanding of chemistry concepts and what difficulties or misconceptions prevent learning. CER also focuses on creating research tools that measure students' understanding, attitudes, motivation, and interest in chemistry education. In addition, CER studies how research evidence about student learning can be used to design better curricula and how changes in teaching and curricula affect student learning outcomes (Cooper & Stowe, 2018).

In simple terms, CER can be described as research that aims to understand and improve how chemistry is learned. Herron and Nurrenbern (1999) described CER as a type of scholarship that focuses on improving chemistry learning. Bunce and Robinson (1997) referred to CER as the "third branch" of the chemistry profession, in addition to chemical research and teaching. They explained that CER seeks to answer key questions, such as how and why students learn chemistry, why chemistry is often difficult for students, and what helps teachers teach chemistry more effectively.

2.2 Chemistry Education Research on Chemical Equilibrium

Chemical equilibrium has been widely studied in CER because many students struggle to understand it even after instruction. Research shows that traditional teaching methods, which mainly involve lectures and problem-solving, often do not help students fully understand equilibrium concepts (Bergquist & Heikkinen, 1990).

Early studies in this area found that many students think chemical equilibrium is a static state where reactions stop. Equilibrium is a dynamic condition in which forward and reverse reactions continue at equal rates. When students do not understand this, they have difficulty in applying ideas such as Le Chatelier’s principle and equilibrium constants to real-lives (Bergquist & Heikkinen, 1990).

More recent studies have focused on teaching approaches that actively involve students in learning. Inquiry-based learning, cooperative learning, and the use of computer simulations have been shown to improve students’ understanding of chemical equilibrium. These approaches help students explore concepts, discuss their ideas, and connect macroscopic observations with particle-level explanations (Annisa & Rohaeti, 2018; Rahmawati et al., 2022).

Researchers have also developed special assessment tools to identify students’ misconceptions about equilibrium. Two-tier and four-tier tests allow teachers and researchers to see not only whether students choose the correct answer, but also whether they understand the reasoning behind it (Bilgin, 2003; Lazenby, 2023). These tools are useful for evaluating the effectiveness of different teaching methods.

2.3 Students’ Conceptions of Chemical Equilibrium

Many CER studies show that students have similar misunderstandings about chemical equilibrium across different countries and educational levels. One common misconception is the belief that reactions stop when equilibrium is reached. Students often do not realize that both forward and reverse reactions continue to occur at the same rate (Bergquist & Heikkinen, 1990).

Another major problem is confusion between reaction rates and concentrations. Some students think that equal reaction rates mean equal amounts of reactants and products. Others believe that one reaction becomes slower until it completely stops at equilibrium (Bilgin, 2003). These ideas prevent students from correctly predicting how a system will respond to changes in concentration, temperature, or pressure.

Students also struggle to connect different ways of representing equilibrium. They often find it difficult to link chemical equations and equilibrium constants with particle-level explanations and real laboratory observations (Rahmawati et al., 2022) .As a result, their understanding remains fragmented and depends on the context of the question.

Importantly, many studies report that these misconceptions remain even after traditional teaching. Research suggests that students are more likely to change their ideas when instruction directly addresses misconceptions, encourages questioning, and allows students to reflect on their thinking (Annisa et al., 2018; Suparman et al., 2024).

Table 1:Some examples of studies on Chemical Equilibrium in Chemistry Education Research.

Author(s)	Year	Method	Sample	Key Finding
Bergquist & Heikkinen	1990	Interviews	University students	Students viewed equilibrium as a static state
Bilgin	2003	Quasi-experimental	High school students	Cooperative learning improved understanding
Annisa et al.	2018	Inquiry-based experiment	Secondary students	IBL reduced misconceptions
Rahmawati et al.	2022	Mixed methods, simulations	Senior secondary students	Simulations improved conceptual links
Lazenby	2023	Systematic review	Multiple studies	Need for better theory–practice alignment
Suparman et al.	2024	Bibliometric review	International studies	Misconceptions remain widespread

Overall, chemistry education research consistently shows that students' misconceptions about chemical equilibrium are robust and resistant to change through traditional instruction. These misconceptions persist because students often lack opportunities to engage in reasoning, explanation, and reflection. This body of research suggests that instructional approaches must go beyond procedural problem solving and instead promote inquiry, conceptual change, and critical thinking. However, few studies have examined how design-oriented inquiry can systematically address these challenges in secondary chemistry classrooms.

2.4 Research-Based Pedagogies and Instructional Strategies in Chemistry

Research-based pedagogies in chemistry are teaching approaches that are supported by findings from chemistry education research. These approaches focus on helping students understand chemistry concepts deeply, rather than relying on memorization or routine problem solving. Recent CER studies emphasize that effective chemistry learning happens when students actively engage with ideas, connect new knowledge to prior understanding, and reflect on their thinking (Cooper & Stowe, 2018; Lazenby, 2023).

One of the most widely studied research-based approaches in chemistry is Inquiry-Based Learning (IBL**).** In IBL, students learn chemistry by asking questions, investigating problems, collecting and analyzing data, and explaining their results. The teacher guides the learning process instead of delivering all information directly. Recent studies show that IBL improves students' conceptual understanding, reasoning skills, and engagement in chemistry classrooms, especially for abstract topics such as chemical equilibrium (Annisa et al., 2018; Rahmawati et al., 2022).

Another important strategy supported by recent research is active learning. Active learning includes instructional methods such as group discussions, collaborative problem solving, peer instruction, and short classroom activities that require students to think and explain ideas. Large-scale studies in science education show that active learning leads to better learning outcomes and reduces failure rates compared to traditional lecture-based instruction (Freeman et al., 2014; Lazenby, 2023). Recent CER work confirms that these benefits also apply to chemistry courses.

Conceptual change–oriented instruction is also strongly supported by recent CER. This approach focuses on identifying students' misconceptions and helping them replace incorrect ideas with scientifically accurate ones. To this end studies show that many chemistry misconceptions persist after traditional instruction unless they are addressed directly through targeted activities and discussion (Bergquist & Heikkinen, 1990; Suparman et al., 2024). This approach is particularly important for difficult topics such as chemical equilibrium.

The use of multiple representations is another well-established research-based strategy. Chemistry learning involves linking macroscopic observations, symbolic equations, and particle-level explanations. Recent studies show that students understand chemistry better when teachers explicitly help them connect these representations, rather than presenting them separately (Rahmawati et al., 2022; Lazenby, 2023).

Technology-supported instruction, including computer simulations and virtual laboratories, has become increasingly important in recent years. Interactive simulations allow students to visualize molecular-level processes that are difficult to observe in real experiments. Recent CER studies show that simulations are most effective when they are used with guided inquiry and teacher support (Rahmawati et al., 2022).

Finally, assessment-informed instruction is a key feature of research-based pedagogy in chemistry. Diagnostic and formative assessments help teachers identify students' learning difficulties and adjust instruction accordingly. Recent research highlights the value of two-tier and four-tier diagnostic tests for identifying misconceptions and monitoring conceptual change in chemistry topics (Suparman et al., 2024).

Overall, recent chemistry education research shows that effective chemistry teaching relies on active learning, inquiry, conceptual change strategies, the use of multiple representations, and evidence-based assessment. These research-based pedagogies support deeper understanding, improve student engagement, and enhance higher-order thinking skills in chemistry.

2.5 Inquiry based learning in chemistry education

Inquiry-Based Learning (IBL) is a dynamic, student-centered approach that has gained attention in chemistry education, especially abstract topics like chemical equilibrium. Recent literature provides a nuanced understanding of IBL's definition, classroom implementation, empirical outcomes, and its role in making abstract concepts accessible.

IBL in chemistry is defined as a pedagogical approach where students actively engage in the scientific process by posing sound questions, designing and conducting experiments, analyzing data, and constructing explanations while teachers act as coaches and facilitators (Adauyah &

Aznam, 2024; Luvanga, 2023; Pedaste et al., 2015). The IBL process is often structured around phases such as Orientation, Conceptualization (including questioning and hypothesis generation), Investigation (experimentation and data interpretation), Conclusion, and Discussion (reflection and communication) (Pedaste et al., 2015). Guided inquiry, a common IBL model, balances teacher direction with student autonomy, confronting students with problems and investigations that require evidence-based reasoning (Adauyah & Aznam, 2024).

2.6 Empirical Research on Inquiry-Based Learning in Chemistry Classrooms

The application and efficacy of Inquiry-Based Learning (IBL) in chemistry classrooms has been the subject of an increasing amount of empirical research. When compared to traditional teacher-centered instruction, these studies generally show that IBL improves students' conceptual understanding, engagement, and higher-order thinking abilities. IBL enhances students' comprehension of basic chemistry concepts, according to several studies. As an example, Sutiani et al. (2021) found that students' conceptual understanding and scientific literacy significantly improved when an inquiry learning model was implemented in secondary chemistry classrooms. According to their findings, meaningful learning in chemistry is supported by active participation in inquiry, experimentation, and explanation. The effectiveness is also supported by empirical research on chemical equilibrium, a conceptually difficult subject.

IBL is also effective for topics that are conceptually difficult, such as chemical equilibrium (Juniar and Sianipar, 2022), which showed that students who were taught chemical equilibrium using guided inquiry outperformed students taught with conventional methods in conceptual understanding and science process skills, and that inquiry activities helped students recognize the dynamic nature of equilibrium and reduced common misconceptions. In addition, IBL can improve critical thinking skills; secondary school students who studied using inquiry-based instruction exhibited significant growth in critical thinking, specifically in analysis, interpretation, and evaluation (Wale and Bishaw, 2020), and a meta-analysis confirmed that inquiry-based learning has a positive effect on students' critical thinking in chemistry and other science subjects (Arifin et al., 2025).

Research, however, suggests that the success of IBL is heavily influenced by the way it is implemented (Aditomo and Klieme, 2019), such as structured and guided inquiry leading to better learning outcomes than unguided inquiry. More recent studies examining inquiry-based chemistry instruction with authentic problems and collaborative learning (Vilela et al., 2025) found that inquiry-based chemistry lessons with real-world contexts enhanced students' reasoning, communication, and engagement, which indicates that IBL is most effective when it is intentionally designed to complement learning objectives and prior knowledge. Although there is strong international evidence supporting IBL, studies conducted in Ethiopia show that it has not yet been widely implemented in the classroom. In many secondary schools, chemistry teaching is dominated by traditional lecture-based instruction (Girma, 2022; Teshome, 2020; Tadesse et al., 2020).

2.7 Design-Based Research (DBR) and Pedagogical Design in Chemistry Education

Research shows that design-based activities improve higher-order thinking, as students must justify their decisions, compare options, and think critically about their solutions (Arnold et al., 2018).

2.7.1 Definition of Design-Based Research

DBR is a cooperative research approach that combines the structured creation, application, and examination of educational interventions in real-world environments. It consists of repeated phases of creating, executing, evaluating, and refining interventions targeting both the development of solutions and the enhancement of theoretical insights. DBR is distinguished by its responsiveness to context methodology (frequently using a mix of qualitative and quantitative techniques) and strong partnership, between researchers and practitioners (Tinoca et al. 2022; Hoadley & Campos 2022; Barthmann et al., 2025; Vaezi et al., 2019). The approach is not limited to evaluating interventions but seeks to understand the underlying mechanisms of learning and the conditions under which innovations succeed (Hoadley & Campos, 2022; Tinoca et al., 2022; Vaezi et al., 2019).

2.7.2 Applications and Recent Trends

DBR is especially appropriate for tackling "messy'' educational problems that lack clear structure depending on context and do not respond easily to straightforward fixes. Its iterative process supports adjustment of interventions based on new insights, making it well-suited for settings where factors are constantly changing and complex (Hoadley & Campos 2022; Tinoca et al. 2022; Barthmann et al. 2025; Ford et al. 2017). DBR's collaborative ethos ensures that interventions are grounded in real-world practice, and its adaptability enables researchers to respond to evolving educational needs, such as those arising from technological change or diverse learner populations (Cochrane et al., 2024; Aung & Rashid, 2025; Ford et al., 2017). This makes DBR especially effective for problems where traditional experimental methods may fall short due to their lack of contextual sensitivity (Barthmann et al., 2025; Vaezi et al., 2019).

In science and chemistry education, DBR has been employed to create and enhance teaching resources, curricula and learning settings that foster conceptual comprehension and tackle ongoing difficulties in student learning. For instance, DBR has been utilized to explore learning ecologies in biology and physiology resulting in advancements, in student performance and the formulation of transferable design principles (Scott et al. 2020; Juuti & Lavonen 2012). In science education more broadly, DBR supports the creation of widely usable educational artefacts and fosters reflective practice among teachers and researchers, enhancing the relevance and impact of research on classroom practice (Obczovsky et al., 2024; Juuti & Lavonen, 2012). Recent work highlights DBR's role in fostering interdisciplinary collaboration and generating actionable knowledge for both theory and practice (Scott et al., 2020; Obczovsky et al., 2024; Tinoca et al., 2022).

DBR is increasingly used in K-12 and higher education, including STEM fields, to support teacher professional development, curriculum innovation, and the integration of technology (Tinoca et al., 2022; Scott et al., 2020; Cochrane et al., 2024). In chemistry and broader science education, DBR facilitates the iterative development of interventions that are responsive to the complexities of real classrooms, supporting both student learning and teacher growth (Scott et al., 2020; Obczovsky et al., 2024; Juuti & Lavonen, 2012).

Recent studies indicate that DBR instructional designs in science can increase student engagement, reasoning, and conceptual understanding (Ogegbo et al., 2025; Kotsis, 2025; Obczovsky et al., 2024; Tinoca et al., 2022). However, there is limited research on applying DBR to chemistry, especially for topics like chemical equilibrium in Ethiopia. This gap highlights the need for context-specific DBR studies that explore how design-oriented inquiry can improve student learning and thinking. Despite the growing use of design-based research in science education, its application in secondary school chemistry, particularly for teaching chemical equilibrium, remains limited. Moreover, few studies have examined DBR as a pedagogical approach that directly supports inquiry-based classroom instruction and critical thinking development. This highlights the need for context-sensitive DBR studies in Ethiopian chemistry classrooms.

2.8 Enhancing Critical Thinking through Inquiry-Based Learning and Design-Based Research

Critical thinking [CT] is a key goal of science education. CT means the ability to analyze information, evaluate evidence, make logical conclusions, and reflect on one's own thinking (Facione, 2011). In chemistry, critical thinking is important for interpreting experiments, understanding abstract concepts, and applying knowledge to new situations.

Inquiry-Based Learning (IBL) helps students develop critical thinking by involving them in asking questions, designing experiments, analyzing data, and explaining results. Studies show that students who learn through IBL have better critical thinking skills, including analysis, evaluation, and reasoning (Arifin et al., 2025; Sutiani et al., 2021; Wale & Bishaw, 2020). These skills are especially important in chemistry, where students need to understand concepts at multiple levels, from particles to chemical equations.

Using DBR together with IBL can further strengthen critical thinking. In DBR, students design solutions, test ideas, evaluate outcomes, and refine their understanding based on feedback. This iterative process encourages reflection and helps students think about how and why their solutions work, which is a key part of critical thinking (Kolodner et al., 2003).

Research suggests that combining IBL with DBR creates learning environments that improve reasoning, conceptual understanding, and evidence-based thinking (Arnold et al., 2018; Ogegbo et al., 2025). However, there are few studies in chemistry education, especially regarding chemical equilibrium for secondary school students. Investigating this approach can provide important insights into how design-based inquiry improves critical thinking and learning in challenging chemistry topics.

Collectively, these studies indicate that inquiry-based learning consistently improves conceptual understanding and scientific reasoning. However, most previous studies focused on short-term interventions and did not employ iterative DBR cycles, particularly in Ethiopian secondary schools. The present study addresses this gap by designing, implementing, and evaluating a DBR–IBL intervention grounded in chemistry education research and classroom practice.

2.9 Connecting DBR and IBL: Rationale for Integration

The foregoing review of the literature reveals two parallel developments in science education research: first, a robust and growing evidence base demonstrating that Inquiry-Based Learning (IBL) supports conceptual understanding, scientific reasoning, and critical thinking in chemistry classrooms (Sutiani et al., 2021; Juniar & Sianipar, 2022; Arifin et al., 2025); and second, an emerging body of scholarship illustrating that Design-Based Research (DBR) provides a rigorous, iterative, and context-sensitive framework for developing educational interventions that are simultaneously theoretically informed and practically effective (McKenney & Reeves, 2024; Tinoca et al., 2022; Obczovsky et al., 2024).

However, these two traditions have developed largely in parallel in the existing literature. Studies applying IBL to chemical equilibrium typically evaluate fixed instructional sequences without iterative refinement (Annisa et al., 2018; Rahmawati et al., 2022), while DBR studies in science education have rarely focused specifically on chemical equilibrium or critical thinking development in secondary school contexts (Scott et al., 2020). This gap represents both a theoretical underdevelopment and a practical missed opportunity.

The present study addresses this gap by systematically integrating DBR's design methodology with IBL's pedagogical approach. In this integrated framework, IBL provides the instructional content and student-facing learning activities, while DBR provides the iterative research architecture through which those activities are continuously evaluated and refined. The combination resolves a key weakness identified across the IBL literature that inquiry activities frequently produce variable outcomes when implemented without systematic design and adaptation (Aditomo & Klieme, 2020; Lazonder & Harmsen, 2016). By embedding IBL within DBR cycles, the present study is positioned to contribute both to theoretical understanding of how iterative design can strengthen inquiry-based chemistry instruction and to practical knowledge about effective chemical equilibrium teaching in Ethiopian secondary schools.

CHAPTER THREE: METHODOLOGY

3.1 Research Design and Approach

This study employed a design-based research approach (DBR). DBR is an educational research method that focuses on designing, implementing, and improving instructional strategies in real classroom settings (McKenney & Reeves, 2024). It enabled the researcher to test innovative teaching approaches while observing how students learned and interacted with instructional activities.

In this study, the DBR approach was used to design and implement instructional activities for teaching chemical equilibrium to grade 11 chemistry students. The intervention followed a cyclical process including planning, implementation, observation, and reflection. Based on classroom observations and students' responses, the instructional activities were revised and refined to improve their effectiveness.

Towards this, inquiry-based learning (IBL) served as the main instructional strategy within the DBR framework. Through this approach, students actively participated in the learning process by asking questions, investigating chemical phenomena, discussing ideas, and drawing conclusions based on evidence. Rather than receiving information solely through lectures, students explored chemical equilibrium concepts through problem-solving tasks, group discussions, and guided inquiry activities.

The integration of DBR into IBL is reckoned to be beneficial for creating an interactive learning environment that, in turn, might promote deeper conceptual understanding and enhanced students' critical thinking skills in chemical equilibrium.

3.2 Population, sample size, and sampling technique

The target population for this study comprised 11-th grade high school chemistry students enrolled in the educational institution where the intervention was conducted. This population was chosen because the curriculum directly requires the development of higher-order cognitive processing and the mastery of complex, abstract scientific concepts.

This study utilized a non-probability, purposive sampling technique through the selection of intact classroom students**.** The implementation of an intact class structure was necessitated by administrative constraints within the educational institution, which strictly prohibited the reorganization of the student body or the random assignment of individual participants. Using a pre-existing classroom ensured minimal disruption to the school's instructional schedule while allowing the researcher to evaluate the intervention in a natural educational setting.

Initially, the selected intact classroom comprised a total enrollment of 42 students (N = 42). However, during the initial phase of data collection, a segment of the cohort was absent and subsequently missed the pre-test session. Because a parametric paired-samples *t*-test strictly requires fully matched pairs across both measurement intervals, the 12 students who missed the baseline assessment were systematically excluded from the final computational dataset, comprising 30 participants in total.

3.3 Sources of Data

The study used several types of data to ensure triangulation and enhance the credibility of the findings. Primary data included students' critical thinking test scores, chemical equilibrium diagnostic test results, classroom observation notes, fidelity of implementation checklists, samples of student work (worksheets, design tasks, and laboratory activities), and semi-structured interviews with students. These data helped triangulate the quantitative findings and support the interpretation of the results to capture the comprehensive understanding of the investigated phenomena.

3.4 Data gathering instruments

3.4.1 Critical Thinking Test

Students' critical thinking skills were measured using a researcher-developed test aligned with Facione's (2011) critical thinking framework and the higher-order cognitive levels of Bloom's taxonomy. The test included both open-ended and structured questions that required students to demonstrate analysis, evaluation, inference, and justification of reasoning within chemical equilibrium contexts. Content validity was established through expert review by chemistry educators and science education specialists. Reliability was assessed using Cronbach's alpha.

3.4.2 Multi-Tier Chemical Equilibrium Diagnostic Tests

Students' conceptual understanding was assessed using a four-tier diagnostic test adapted for this study. The first tier (multiple-choice) assessed content knowledge by asking students to select the correct response to a chemical equilibrium problem. The second tier probed students' confidence in their Tier 1 answer (Certain/Not Certain). The third tier required students to select the reasoning that best explained their Tier 1 answer from a set of options including common misconceptions. The fourth tier assessed students' confidence in their chosen reason.

Scoring followed a dual-criterion system: a response was classified as 'scientifically correct' only when both the content answer (Tier 1) and the reasoning (Tier 3) were correct, regardless of confidence levels. Responses with a correct Tier 1 answer but an incorrect Tier 3 reason were classified as ‘correct answer with misconception-based reasoning,’ indicating surface-level knowledge without underlying conceptual understanding. Responses with incorrect answers in both tiers were coded as ‘misconception present.’ This classification system enabled the researcher to distinguish between genuine understanding, rote memory, and persistent misconception a distinction that is not possible with single-tier instruments (Saputra & Parbuntari, 2025).

3.4.3 Classroom Observation and Fidelity Checklists

Structured classroom observations were conducted during the implementation of the DB–IBL intervention to document students’ engagement, inquiry behaviors, collaboration, and reasoning. Field notes were used to capture contextual factors and instructional dynamics relevant to the design-based research (DBR) process.

3.4.4 Interviews and Document Analysis

Student-generated artifacts, including worksheets, design products, written explanations, and reflections, were collected as key sources of qualitative data sources. Meeting minutes from recurring reflection sessions with student groups were documented to capture learning challenges, emerging ideas, and design refinements throughout the intervention. Semi-structured individual interviews were conducted with selected students from the DBR–IBL group after the intervention. The interviews explored students’ learning experiences, perceived challenges, and reflections on the DBR–IBL process.

3.5 Instructional Strategies

To maintain consistency and control for extraneous variables, the intervention was implemented by a single instructor, a qualified secondary school chemistry teacher. Prior to the intervention, students’ baseline knowledge and understanding of chemical equilibrium were assessed using a pre-test to ensure relative homogeneity within the class. The pre-test also identified common misconceptions and nonscientific ideas, which informed the design of targeted instructional activities. The intervention employed hands-on, inquiry-based learning activities that were aligned with the standard curriculum and textbook content while placing additional emphasis on concepts that were underrepresented in the textbook. This approach ensured that the instructional strategies were systematically tailored to the learning needs of the class, promoting conceptual understanding and supporting the objectives of the study.

3.5.1 Instructional Intervention Procedure

During the implementation of the design-based research–inquiry-based learning (DBR–IBL) instruction for chemical equilibrium, the lessons were organized as a sequence of inquiry-oriented activities that built on students' progressive understanding of the teaching-learning activities and processes employed therein. Each lesson began with a problem situation or inquiry question that encouraged students to observe, discuss, and explain chemical phenomena. The teacher guided students through discussions, demonstrations, and problem-solving tasks related to key concepts such as reversible reactions, dynamic equilibrium, equilibrium constants, and Le Chatelier's principle.

Most importantly, the lessons were connected in a progressive manner so that concepts learned in one lesson supported learning in subsequent lessons. When students demonstrated limited understanding of a concept, the teacher revisited the recurrent ideas through additional inquiry questions and integrated them into subsequent instructional lesson activities. For example, when students did not fully understand reversible reactions, further questioning and demonstrations were incorporated into the following lesson while introducing dynamic equilibrium. This continuous connection between lessons enabled students to refine their ideas through discussion, reflection, and investigation.

Through this iterative process, students gradually developed deeper conceptual understanding and stronger critical thinking skills, consistent with the learning objectives outlined in Bloom's taxonomy and the critical thinking framework proposed by Facione (2011).

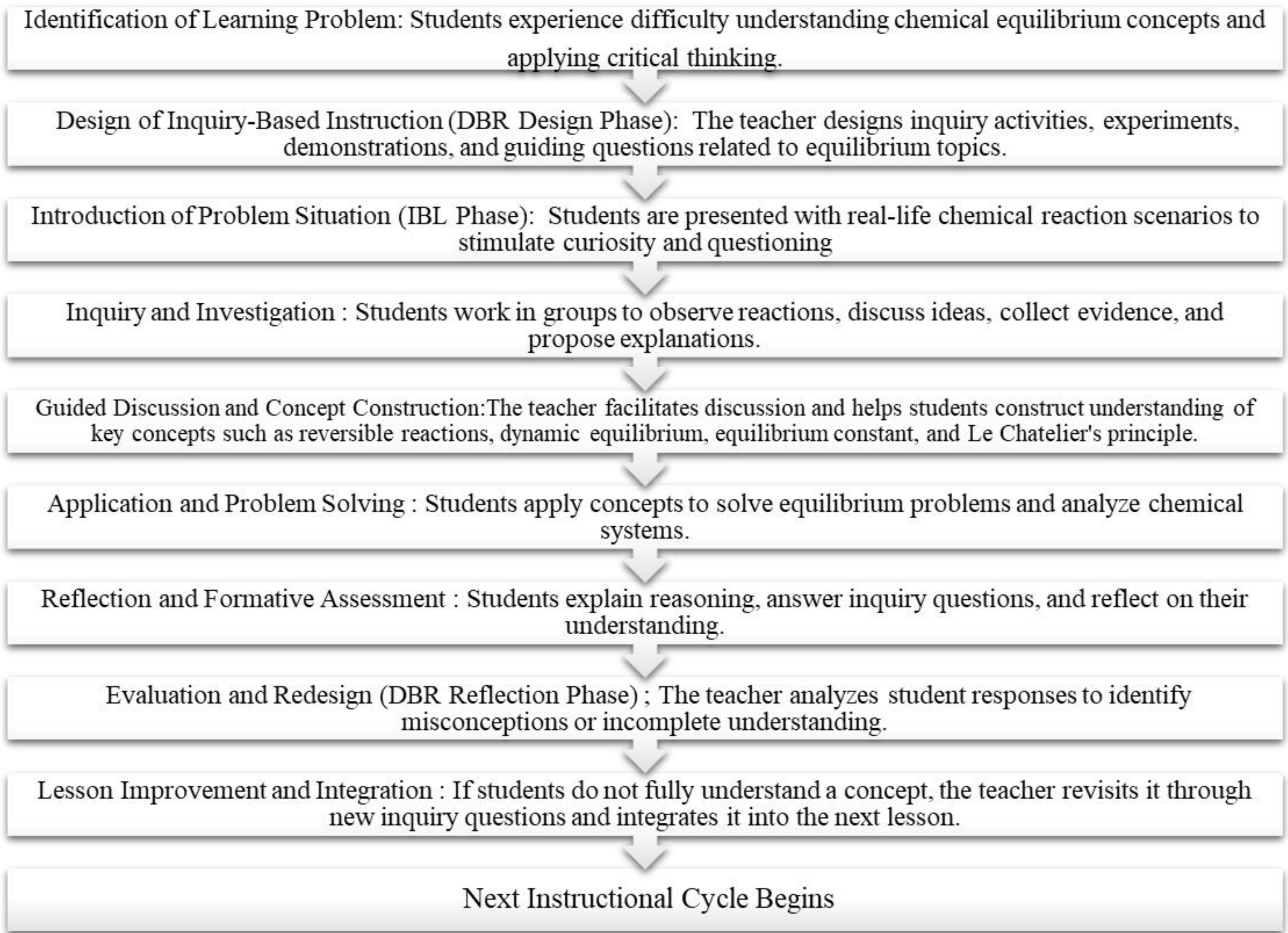


Figure 2: DBR-IBL intervention cycle for teaching chemical Equilibrium.

3.5.2 Description of Classroom Activity Sequence

The design-based research–inquiry-based learning (DBR–IBL) intervention was implemented over six weeks during the teaching of the chemical equilibrium unit. The intervention was carried out through a series of iterative DBR cycles involving planning, implementation, reflection, and refinement. Each lesson lasted 80 minutes and was designed to create an active learning environment where students could investigate chemical phenomena, discuss ideas, and develop their understanding of chemical equilibrium through inquiry.

A range of inquiry-based teaching strategies was used throughout the intervention to support student learning. These included guided questioning, prediction activities, small-group discussions, collaborative problem-solving tasks, practical investigations, concept clarification sessions, and reflection activities. The teacher's role was mainly to facilitate learning by asking questions that encouraged students to think critically and explain their ideas. Instead of providing direct answers, students were encouraged to explore concepts, discuss their reasoning with peers, and support their explanations using evidence from classroom activities and experiments.

The intervention began with activities designed to explore students' existing ideas about chemical equilibrium. Since chemical equilibrium is often considered an abstract topic, hands-on and visual activities were used to make the concept more meaningful. One of the first activities involved a water-transfer model. Students transferred water between two containers and observed how the system changed over time. This simple activity was used to help students visualize equilibrium as a dynamic process in which changes continue to occur even when the overall system appears unchanged.

As the lessons progressed, the water-transfer model was revisited through additional inquiry tasks. Students were asked to predict what would happen when changes were made to the system, such as increasing or decreasing the amount of water in one container. They discussed their predictions in groups before carrying out the activity. After making observations, students compared the outcomes with their predictions and shared their explanations with classmates. These discussions provided opportunities for students to examine their thinking, consider alternative viewpoints, and develop scientific explanations based on evidence.

To further strengthen understanding of chemical equilibrium, students participated in several inquiry-based experiments that connected classroom concepts with real-life situations. One activity involved a carbonated soft drink, which served as a familiar example for exploring equilibrium shifts. Students observed what happened when the bottle was opened and investigated how changes in pressure affected the equilibrium system. Before conducting the activity, they predicted what they expected to observe and explained their reasoning. Following the experiment, students discussed their observations and related them to Le Chatelier's Principle. The use of an everyday product helped students connect abstract chemical concepts with experiences from their daily lives.

Collaborative learning was an important feature of the intervention. Students worked in small groups to conduct investigations, discuss observations, compare explanations, and present their conclusions. Guided worksheets were used to structure each activity and support the inquiry process. These worksheets included tasks that required students to make predictions, record observations, analyze evidence, and explain their findings. When students encountered difficulties, the teacher provided additional guidance through questioning and discussion rather than direct instruction.

Reflection was integrated into every lesson. At the end of each session, students were given opportunities to think about what they had learned, identify ideas that were still unclear, and summarize key concepts in their own words. They were also encouraged to relate chemical equilibrium to familiar situations such as food preparation, soft-drink production, and fermentation processes. These reflection activities helped students make connections between scientific concepts and everyday experiences.

Throughout the six-week intervention, classroom observations, student feedback, and reflection notes were used to guide the ongoing refinement of the learning activities. Adjustments were made when necessary to improve the clarity of instructions, strengthen student engagement, and provide additional opportunities for inquiry and discussion. This continuous process of improvement ensured that the intervention remained responsive to students' learning needs while maintaining the core principles of design-based research and inquiry-based learning.

Overall, the DBR–IBL intervention provided students with repeated opportunities to investigate, discuss, reflect, and apply chemical equilibrium concepts in meaningful and familiar contexts. By engaging students in active inquiry and collaborative learning, the intervention was designed to support deeper conceptual understanding and encourage thoughtful scientific reasoning.

3.6 Data collection procedures

Data for this study were collected in several stages following the design-based research (DBR) process. Both quantitative and qualitative data were collected to examine the effectiveness of the design-based research inquiry-based learning (DBR–IBL) approach in improving students' critical thinking skills and conceptual understanding of chemical equilibrium.

The first stage was the preparation stage. During this stage, the researcher obtained permission from the school administration and the relevant education authorities to conduct the study. The purpose of the study and the research procedures were explained to the participating students. Data collection instruments, including the critical thinking test (CTT), chemical equilibrium diagnostic test, observation checklists (CEDT), and interview guides, were finalized. These instruments were reviewed by experts and piloted with a small group of students to ensure their clarity, validity, and reliability.

In the second stage, the process involved collecting baseline data. Before the implementation of the intervention, students completed a pre-test consisting of a critical thinking test and a multi-tier diagnostic test on chemical equilibrium. The purpose of the pre-test was to assess students' initial critical thinking skills and their prior understanding of chemical equilibrium concepts. The tests were administered during regular class time under the supervision of the researcher and the classroom teacher.

The third stage was the implementation of the DBR–IBL instructional approach. The intervention was carried out during the teaching of the chemical equilibrium unit over several weeks. During this period, inquiry-based learning activities developed through the DBR framework were implemented in the classroom. The researcher observed the lessons and recorded students' participation, questioning behaviors, collaborative interactions, and explanations of scientific ideas. Observation notes and fidelity checklists were used to ensure that the instructional approach was implemented as intended.

In addition to classroom observations, students' learning artifacts were collected throughout the intervention. These included worksheets, group reports, written explanations, design tasks, and problem-solving activities completed during the lessons. These materials provided evidence of the development of students' conceptual understanding and critical thinking skills. Short group reflection discussions were also conducted to capture students' emerging ideas, learning challenges, and reflections on the learning process.

The fourth stage involved post-intervention data collection. Following the completion of the instructional intervention, students completed the same critical thinking test and chemical equilibrium diagnostic test as post-tests. These assessments were used to determine changes in students' critical thinking skills and conceptual understanding of chemical equilibrium after participation in the DBR–IBL intervention.

The final stage consisted of semi-structured student interviews. Selected students participated in interviews designed to gain deeper insights into their learning experiences. Eight students were interviewed for a duration between 45 minutes and 60 minutes duration. The interviews focused on students' perceptions of the inquiry activities, challenges encountered during the intervention, and the ways in which the lessons contributed to their understanding of chemical equilibrium. With participants' consent, the interviews were audio-recorded and subsequently transcribed for analysis.

Throughout the research process, ethical guidelines were strictly followed. Students' identities were kept confidential, and all collected data were coded and securely stored. The use of multiple data sources, including tests, observations, student artifacts, and interviews, enhanced the credibility, reliability, and trustworthiness of the study findings through data triangulation.

3.7. Implementation of the DBR–IBL Intervention through Cycles and Phases

The intervention was implemented through a series of iterative design-based research (DBR) cycles that integrated the principles of inquiry-based learning (IBL) into the teaching of chemical equilibrium. Consistent with the DBR framework proposed by McKenney and Reeves (2024), the intervention involved repeated phases of analysis and exploration, design and construction, implementation, evaluation, and refinement. These cycles enabled instructional decisions to be continuously informed by classroom evidence and students' learning needs.

Cycle 1: Analysis and Exploration

The first cycle focused on identifying students' prior knowledge, learning difficulties, and misconceptions related to chemical equilibrium. Baseline information was collected through pre-test results, classroom discussions, and initial observations. Particular attention was given to students' understanding of reversible reactions, dynamic equilibrium, and factors affecting equilibrium systems. Information gathered during this phase informed the design of instructional activities intended to address identified misconceptions and support conceptual development.

Cycle 2: Design and Construction

Based on the findings from the analysis phase, a sequence of inquiry-based learning activities was developed. The instructional design incorporated multiple representations, contextualized examples, guided inquiry tasks, prediction activities, collaborative discussions, and practical investigations. Activities such as the water-transfer model were included to help students visualize the dynamic nature of equilibrium, while real-life examples were selected to connect abstract chemical concepts with familiar experiences. Guided worksheets and discussion prompts were also developed to support students' reasoning and reflection throughout the learning process.

Cycle 3: Implementation and Evaluation

The designed activities were implemented during the six-week chemical equilibrium unit. Students actively engaged in predicting outcomes, conducting investigations, discussing observations, and constructing explanations based on evidence. During implementation, classroom observations, student reflections, worksheets, and field notes were systematically collected to document students' participation, conceptual difficulties, and emerging understanding. These sources of evidence provided valuable insights into how students responded to the instructional activities and which aspects of the intervention required modification.

Cycle 4: Reflection and Refinement

At the end of each instructional cycle, data collected from observations, student feedback, learning artifacts, and reflective discussions were reviewed to evaluate the effectiveness of the intervention. Areas of conceptual difficulty were identified, and instructional activities were modified accordingly. Refinements included revising guiding questions, providing additional scaffolding for challenging concepts, incorporating further opportunities for discussion, and revisiting concepts that required clarification. These modifications informed subsequent lessons and contributed to the progressive improvement of the intervention throughout the study.

Through this iterative process, the DBR–IBL intervention remained responsive to students' learning experiences while maintaining alignment with the objectives of promoting conceptual understanding and critical thinking in chemical equilibrium. The cyclical nature of the intervention also provided opportunities to refine instructional strategies based on evidence gathered from authentic classroom practice.

Table 2: Summary of DBR–IBL Cycles.

Cycle	DBR Phase	Major Activities	Data Sources	Refinements Made
1	Analysis & Exploration	Pre-test, misconception identification	Pre-test, observation	Design of inquiry activities
2	Design & Construction	Water-transfer model, worksheets	Student responses	Improved guiding questions
3	Implementation & Evaluation	Inquiry experiments, discussions	Observations, reflections	Additional scaffolding
4	Reflection & Refinement	Lesson review and redesign	Feedback, field notes	Activity modifications

3.8. Data analysis technique

Quantitative data from the critical thinking and diagnostic tests were analyzed using descriptive statistics including mean and standard deviation. A paired-samples t-test was employed to determine whether there was a statistically significant difference between students' pre-test and post-test scores. Cohen's d effect size was calculated to determine the magnitude of the intervention effect.

Qualitative data obtained from classroom observations and interviews were analyzed using thematic analysis. To ensure analytical rigor, a systematic coding process was undertaken involving two independent raters who manually coded all interview transcripts and observational field notes were analyzed qualitatively. The qualitative data stream was analyzed using inductive reflexive thematic analysis as delineated by Braun and Clarke’s (2021) six-phase framework. This process was structured to systematically transition raw narrative data into interpreted analytical themes while maintaining a highly transparent audit trail.

Quantitative and qualitative findings were integrated during the interpretation phase to provide a comprehensive understanding of the effectiveness of the DBR–IBL intervention.

3.9 Ethical considerations

Ethical approval was obtained from relevant institutional authorities before the commencement of the study. Informed consent was obtained from students. Participation was voluntary, and participants were informed about their right to withdraw from the study at any time without any precondition. Confidentiality were maintained throughout the research process. Data collected were used solely for the present research purpose and stored securely.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Quantitative findings

This section presents the quantitative results of the study based on data collected through the critical thinking test (CTT) and the chemical equilibrium diagnostic Test (CEDT). These instruments were administered before and after the implementation of the design-based research–inquiry-based learning (DBR–IBL) intervention to assess changes in students' critical thinking skills and conceptual understanding of chemical equilibrium.

The quantitative analysis focused on comparing students' pre-test and post-test performances to determine whether participation in the DBR–IBL intervention resulted in significant learning gains. The findings provided evidence regarding the effectiveness of the intervention in promoting deeper conceptual understanding and strengthening critical thinking skills among grade 11 chemistry students.

4.1.1 Reliability Statistics for the Research Instruments

To evaluate the internal consistency of the research instruments, Cronbach's alpha (α) coefficients were computed for each scale. According to standard psychometric benchmarks, an alpha value of 0.70 or higher represents acceptable reliability, while values above 0.80 indicate good internal consistency (George & Mallery, 2020). The Critical Thinking Test, designed to evaluate students' higher-order cognitive processing, evaluation, and analytical skills, achieved a Cronbach's alpha coefficient of 0.809 across 8 items. According to standard psychometric thresholds, an alpha value between 0.80 and 0.89 is interpreted as "Good" (George & Mallery, 2020).

In psychometrics, alpha coefficients are highly sensitive to scale length; shorter instruments naturally yield lower scores because there are fewer items to capture covariance. The fact that the critical thinking test maintained an alpha above 0.80 with only 8 items demonstrates a highly efficient instrument. Every single test question was strongly cohesive, precise, and targeted the exact same underlying critical thinking dimensions. This high sensitivity confirms that the dramatic shift in student analytical skills captured during the post-test was stable and genuine.

Table 3: reliability statistics test

Instrument	Purpose	Number of Items	Reliability Method	Reliability Coefficient (α)	Interpretation
Critical Thinking Test	To assess students' critical thinking skills in chemical equilibrium	8	Cronbach's Alpha	0.809	Good
Chemical Equilibrium Diagnostic Test	To assess students' conceptual understanding of chemical equilibrium	20	Cronbach's Alpha	0.803	Good

The chemical equilibrium diagnostic test was implemented to uncover and trace student misconceptions regarding complex chemical systems. This 20-item instrument achieved a Cronbach's alpha coefficient of 0.803, which also falls securely within the “Good” internal consistency classification.

While longer tests can sometimes mathematically inflate alpha coefficients through item redundancy, a score of 0.803 across 20 items indicates a balanced scale architecture. It demonstrates that the items were sufficiently distinct to avoid repetitive querying, yet cohesive enough to ensure low measurement error. This confirms that the test reliably tracked conceptual shifts. The sharp reduction in score variance observed after the intervention (SD = 3.48) can be confidently attributed to actual student mastery rather than erratic guessing or ambiguous item phrasing.

4.1.2 Descriptive Statistics of Pre-Test and Post-Test Scores

Table 4: Descriptive Statistics of Students' Achievement Scores (N = 30)

Descriptive Statistics									
	N	Minimum	Maximum	Mean	Std. Deviation	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistc	Statistic	Statistc	Std.Error	Statistc	Std.Eror
pre-test result	30	16.0	45.0	29.297	7.8393	.153	.427	-.963	.833
post-test result	30	36.0	50.0	42.633	3.4788	.432	.427	-.442	.833
Valid N (list wise)	30								

Descriptive statistics were calculated to compare student performance before and after the instructional intervention (N = 30). On the pre-test, students exhibited a moderate baseline level of performance, with a mean score of (29.30) (SD = 7.84) and scores ranging from (16.00) to (45.00). Following the intervention, the post-test scores demonstrated a substantial increase in the mean performance to (42.63) (SD = 3.48), with a compressed score range spanning from (36.00) to (50.00). The lower standard deviation on the post-test indicates that student scores became significantly more uniform, suggesting that the intervention effectively raised overall mastery while narrowing the achievement gap within the cohort.

To evaluate the assumption of normality required for parametric inferential statistics, skewness and kurtosis coefficients were analyzed for both testing periods. For the pre-test scores, skewness was (0.153) and kurtosis was (-0.963). For the post-test scores, skewness was evaluated at (0.432) alongside a kurtosis value of (-0.442). Because all values fell safely within the conventional psychometric thresholds of (± 1.0) for skewness and (± 2.0) for kurtosis (George & Mallery, 2020), the data met the criteria for normal distribution. Consequently, the use of a parametric paired-samples *t*-test was statistically justified.

4.1.3. Statistical significance test

A paired-samples *t*-test was conducted to determine whether a statistically significant difference existed between students' scores before and after the intervention (N = 30). The results indicated that post-test scores (M = 42.63), (SD = 3.48) were significantly higher than pre-test scores (M = 29.30), (SD = 7.84), $t(29) = -13.75$, $p < 0.001$. Furthermore, the analysis revealed an exceptionally large effect size, Cohen's $d = 2.51$, indicating a substantial practical improvement. These findings demonstrate that the instructional intervention led to a statistically significant and highly meaningful increase in student performance.

Table 5: paired samples t-Test results and effect size for pre-test and post-test scores (N = 30)

Assessment	M	SD	t	df	P	Cohen's d
Pre test	29.30	7.84	-13.75	29	<0.001	2.51
Post test	42.63	3.48				

4.1.4 Comparison of the effect size and magnitude of Pre-Test and Post-Test Scores

To evaluate the practical significance of the instructional intervention, the standardized mean difference was calculated using Cohen's d. According to standard psychometric conventions established by Cohen (1988), an effect size exceeding 0.80 is classified as large. The analysis revealed an exceptionally large effect size ($d = 2.51$), indicating that the post-test mean shifted upward by more than two and a half standard deviations relative to the baseline pre-test distribution. This magnitude confirms that the intervention exerted a profound and practically meaningful impact on student academic outcomes, far exceeding typical educational research benchmarks.

4.2. Implementation of the DBR–IBL Intervention through Cycles and Phases

4.2.1 Cycle One: Reversible Reactions and Dynamic Equilibrium

Analysis and Exploration Phase: The first cycle focused on introducing students to reversible reactions and dynamic equilibrium. At the beginning of the lesson, students were asked to discuss familiar examples from everyday life, such as water evaporation and condensation. Through classroom questioning and group discussions, students were encouraged to share their prior knowledge and explain how they believed chemical reactions occur.

The analysis phase revealed several misconceptions. Many students believed that chemical reactions proceed only in one direction and that equilibrium means a reaction has completely stopped. Some students also thought that equilibrium could only occur when equal amounts of reactants and products were present. These findings are consistent with previous studies that identified misconceptions about the dynamic nature of equilibrium among secondary school students (Taber, 2022).

The exploration activities allowed students to investigate these ideas through observation and discussion. Students were encouraged to ask questions, make predictions, and explain their thinking. Inquiry-based learning research suggests that identifying learners' prior conceptions is essential because meaningful learning occurs when students actively confront and revise their existing ideas (Pedaste et al., 2021).

Design and Construction Phase: Based on the misconceptions identified during the analysis and exploration phase, learning activities were designed to help students better understand reversible reactions and dynamic equilibrium. Since chemical equilibrium is an abstract concept that students cannot observe directly, a simple water-transfer model was used to make the idea more visible and easier to understand.

The activity used two transparent water jars and two cups of different sizes. The jars represented the reactants and products, while the cups represented the rates of the forward and reverse reactions. At the beginning of the activity, one jar contained more water than the other, representing a reaction where reactants are converted into products.

Students transferred water between the two jars at the same time using the two cups. As the activity continued, they carefully observed how the water levels changed. Initially, the amount of water in each jar changed noticeably. However, after some time, the water levels appeared to remain constant even though water was still being transferred between the jars.

Through observation and discussion, students realized that the movement of water had not stopped. Instead, water was moving from one jar to the other at the same rate. This helped students understand that chemical equilibrium does not mean a reaction stops. Rather, it is a dynamic state in which the forward and reverse reactions continue to occur at equal rates.

The activity also helped students distinguish between the amount of substances and the rate of reactions. Many students initially believed that equilibrium occurs only when the amounts of reactants and products become equal. By observing the water-transfer model, they learned that equilibrium can exist even when the amounts in the two jars are different, as long as the rates of transfer are equal. This is an important concept in chemical equilibrium and is often difficult for students to understand (Taber, 2022).

Students worked in groups to record observations, discuss their ideas, and explain what was happening in the model. The teacher guided the discussion by asking questions such as: "*Has the movement of water stopped?*", "*Why do the water levels remain constant?*", and "*How does this model represent a chemical reaction at equilibrium?*" These questions encouraged students to think critically and use evidence from their observations to support their explanations.

The use of the water-transfer model made the lesson more interactive and helped students connect an abstract chemistry concept with a real and observable process. Research has shown that hands-on inquiry activities and visual models can improve students' understanding of difficult scientific concepts because they allow learners to actively explore ideas and construct their own explanations (Pedaste et al., 2021). Similarly, Taber (2022) emphasized that concrete models can help students overcome common misconceptions about chemical equilibrium.

By the end of the activity, many students had changed their initial understanding of equilibrium. They were able to explain that equilibrium is a dynamic process where reactions continue to occur in both directions at equal rates, resulting in no overall change in the concentrations of reactants and products. This demonstrated a clear improvement in their conceptual understanding of reversible reactions and dynamic equilibrium.

Evaluation and Reflection Phase: At the end of the activity, students were given time to think about what they had learned and compare it with what they believed before the lesson. They discussed their observations in groups and shared their ideas with the class. The teacher asked questions such as:

"What happened to the water levels in the jars?", *"Did the water stop moving?"*, and *"How does this activity help us understand chemical equilibrium?"*

During these discussions, many students realized that some of their earlier ideas about equilibrium were incorrect. Before the activity, several students thought that equilibrium meant a reaction had stopped completely. After observing the water-transfer model, they understood that movement continued even when the water levels remained unchanged. This helped them recognize that chemical equilibrium is a dynamic process in which the forward and reverse reactions continue to occur at the same rate.

Students were then asked to answer short questions and explain their reasoning. Their responses showed that most of them could now explain that equilibrium depends on equal reaction rates rather than equal amounts of reactants and products. They also demonstrated a better understanding of the difference between the amount of a substance and the rate at which a reaction takes place.

Students reflected on how the activity supported their learning. Many explained that the water-transfer model made the concept easier to understand because they could see a real example of continuous movement. Some students mentioned that watching water move between the jars while the water levels remained almost constant helped them understand why equilibrium is described as a dynamic state rather than a static one.

The teacher also reflected on the lesson by reviewing students' responses, observing group discussions, and identifying areas that still needed further explanation. This helped determine whether the learning objectives had been achieved and provided useful information for planning the next lesson. Reflection is an important part of inquiry-based learning because it allows students to connect their observations with scientific concepts and develop a deeper understanding of what they have taught (Pedaste et al., 2021).

The activity helped many students replace their misconceptions with scientifically correct explanations and prepared them for the next lesson on the equilibrium constant. (McKenney& Reeves, 2024; Pedaste et al., 2021).

Cycle One yielded two important findings that shaped subsequent instructional design. First, the water-transfer model was demonstrably effective in addressing the static equilibrium misconception: post-discussion reflections showed that the majority of students revised their understanding from 'reactions stop at equilibrium' to 'forward and reverse reactions continue at equal rates.' This supports research showing that concrete analogical models can facilitate conceptual restructuring by making abstract dynamic processes observable (Taber, 2022). Second, the cycle revealed that students held a conflation between equal concentrations and equal reaction rates — a distinction that had not been addressed in the initial activity design. This finding informed Cycle Two's focus on the equilibrium constant, where rate-vs-concentration confusion was explicitly targeted through guided data analysis. The iterative decision to carry unresolved conceptual difficulties forward as design inputs for the next cycle exemplifies the DBR principle of continuous evidence-informed refinement (McKenney & Reeves, 2024).

4.2.2 Cycle Two: Understanding the Equilibrium Constant (Kc)

The second cycle focused on helping students understand the concept of the equilibrium constant (Kc). Findings from the first cycle showed that although students had developed a better understanding of reversible reactions and dynamic equilibrium, many still had difficulty understanding how equilibrium can be described quantitatively. Therefore, this cycle was designed to help students understand what the equilibrium constant means and how it relates to the position of equilibrium.

Analysis and Exploration Phase: The lesson began with questions designed to explore students' existing understanding of the equilibrium constant. Students were asked questions such as: *"What does the equilibrium constant tell us?", "What is the difference between equilibrium constant and reaction rate", and "Does equilibrium mean equal amounts of reactants and products?"*

The discussion revealed several misconceptions. Many students believed that a large equilibrium constant meant that a reaction occurs very quickly. Others thought that equilibrium can only be reached when equal amounts of reactants and products are present. Only a few students were able to explain that the equilibrium constant describes the relationship between reactants and products when equilibrium is established.

When students were presented with reactions having different Kc values, many interpreted a larger value as indicating a faster reaction. This showed that they were confusing reaction rate with equilibrium position. Similar misconceptions have been reported in previous studies, which found that students often struggle to distinguish between kinetic concepts and equilibrium concepts because both involve chemical reactions but describe different aspects of the process (Taber, 2022; Barke et al., 2022).

To explore these ideas further, students were given concentration data from several equilibrium systems and asked to discuss what the values suggested about the reactions. Working in groups, they compared different equilibrium situations and shared their interpretations. During these discussions, students began to realize that equilibrium does not require equal amounts of reactants and products. This finding is consistent with research showing that students often enter chemistry classrooms with alternative conceptions that need to be challenged through active learning experiences (Pedaste et al., 2021; OECD, 2023).

Design and Construction Phase: Based on the difficulties identified during the exploration phase, activities were designed to help students construct their understanding through inquiry and collaborative learning.

Students were organized into small groups and provided with equilibrium concentration data for several reversible reactions. Rather than giving students the equilibrium expression directly, they were encouraged to examine the data, identify patterns, and discuss possible explanations. This approach allowed students to discover important relationships themselves rather than simply memorizing formulas.

As students analyzed the data, they noticed that certain relationships between reactants and products remained constant even when the starting concentrations were different. The teacher guided the discussion by asking questions such as: *"What pattern do you observe?", "Why do you think this value remains constant?", and "What does a large Kc value tell us about the reaction?."*

Through discussion and evidence-based reasoning, students gradually developed the understanding that the equilibrium constant does not indicate how fast a reaction occurs. Instead, it shows whether reactants or products are favored at equilibrium. Students learned that large Kc values indicate greater product formation, while small Kc values indicate that reactants are favored.

During group work, students actively debated different explanations and supported their ideas using evidence from the data provided. Classroom observations showed that students became more engaged as the lesson progressed. Many students who were initially hesitant began contributing to discussions, asking questions, and explaining their reasoning to classmates. Research has shown that inquiry-based learning promotes deeper conceptual understanding because students actively construct knowledge through investigation, discussion, and reflection rather than passively receiving information (Pedaste et al., 2021; Furtak et al., 2023).

The collaborative nature of the activities also appeared to support critical thinking development. Students were required to analyze information, evaluate explanations, and justify conclusions using evidence. These are important components of critical thinking and scientific reasoning. Similar findings have been reported by recent studies indicating that inquiry-oriented learning environments improve students' ability to think critically and solve scientific problems (Hassan et al., 2023; UNESCO, 2023).

Evaluation and Reflection Phase: At the end of the lesson, students completed individual exercises and reflection activities to evaluate their understanding of the equilibrium constant. They were asked to explain the meaning of Kc in their own words, interpret different equilibrium constant values, and describe how their understanding had changed during the lesson.

The responses showed a clear improvement in conceptual understanding. Most students correctly explained that the equilibrium constant describes the relative amounts of reactants and products present at equilibrium. They also recognized that equilibrium does not necessarily involve equal amounts of substances and that Kc provides information about the position of equilibrium rather than reaction speed.

During the reflection session, students openly discussed changes in their thinking.

One student (at group 4) explained:

“Before this lesson, I thought Kc showed how fast a reaction happens. Now I understand that it tells us whether products or reactants are favored when equilibrium is reached.”

Another student (group 2) stated:

“I used to think equilibrium meant equal amounts of reactants and products, but the activities helped me understand that equilibrium depends on the balance of reaction rates.”

These reflections suggest that many students successfully replaced their previous misconceptions with scientifically accepted explanations. Similar conceptual changes have been reported in chemistry education studies, where inquiry-based activities help students confront and revise incorrect ideas through evidence-based learning experiences (Taber, 2022; Barke et al., 2022).

The teacher's reflection also indicated significant progress in students' understanding. Compared with the first cycle, students demonstrated greater confidence when discussing equilibrium concepts and relied less on memorization. Their explanations became more detailed, and they were better able to justify their answers using scientific reasoning.

However, a few students continued to experience difficulty interpreting very large and very small Kc values. This finding agrees with previous studies showing that numerical interpretation of equilibrium concepts remains challenging for some learners even after instruction (Çalık&Ayas, 2021). As a result, additional examples and guided practice activities were incorporated into the next cycle.

Through exploration, discussion, data analysis, problem-solving, and reflection, students developed a deeper understanding of a concept that is often considered difficult in chemistry. The findings support previous research showing that inquiry-based learning can improve conceptual understanding, critical thinking, and long-term retention of scientific concepts (Furtak et al., 2023; Hassan et al., 2023; McKenney& Reeves, 2024; Pedaste et al., 2021).

4.2.3 Cycle Three: Le Chatelier's Principle and Factors Affecting Chemical Equilibrium

Analysis and Exploration Phase: The third cycle focused on Le Chatelier's Principle and the factors that affect chemical equilibrium. Before introducing new concepts, students were encouraged to revisit and reflect on the ideas developed during Cycle Two concerning equilibrium constants and the equilibrium state. The purpose was to determine whether students had fully understood that equilibrium is established when the rates of the forward and reverse reactions become equal and that the equilibrium constant expresses the relationship between reactants and products at equilibrium. To activate prior knowledge, students were presented with a series of questions:

1. What happens to a reaction when equilibrium is reached?

2. Do the reactants and products stop reacting at equilibrium?

3. Why do concentrations remain constant at equilibrium?

4. What does a large equilibrium constant indicate about a reaction?

5. Can an equilibrium system respond to changes imposed from outside the system?

6. If additional reactant is added to a system at equilibrium, what will happen and why?

Students discussed these questions in groups and shared their responses. Their answers revealed that although most students could explain the meaning of dynamic equilibrium, several still struggled to connect equilibrium constants with changes occurring in an equilibrium system. Some students correctly predicted the direction of equilibrium shifts but could not explain the molecular reasons behind those changes. Others relied on memorized rules without understanding how the system attempts to restore equilibrium. To further explore students' critical thinking, the teacher presented the following equilibrium reaction:

$$N_2 (g) + 3H_2 (g) \rightleftharpoons 2NH_3 (g)$$

Students were asked:

1. What would happen if more hydrogen gas were added?

2. What would happen if ammonia were removed from the system?

3. Why would the reaction shift in a particular direction?

4. How does the system restore equilibrium after the disturbance?

These questions encouraged students to recognize that equilibrium systems are dynamic and capable of responding to external changes. The exploration phase revealed that students needed deeper understanding of the relationship between equilibrium conditions and disturbances imposed on the system. Similar difficulties have been reported in chemistry education research, where students often memorize Le Chatelier's Principle without understanding the underlying particle-level processes (Taber, 2022).

Design and Construction Phase: during the exploration phase, learning activities were designed to help students develop a better understanding of Le Chatelier's Principle through observation, prediction, discussion, and experimentation. The activities were also intended to strengthen the concepts learned in Cycle Two, particularly the ideas of dynamic equilibrium and equilibrium constants.

At the beginning of the lesson, students were reminded of what they had learned in the previous cycle. The teacher asked questions such as:

1. What happens when a system reaches equilibrium?
2. Do reactions stop at equilibrium?
3. What does it mean when the forward and reverse reaction rates are equal?
4. What might happen if an equilibrium system is disturbed?

These questions helped students connect their previous learning with the new concept being introduced. To demonstrate Le Chatelier's Principle, a simple equilibrium experiment involving iron (III) chloride ($FeCl_3$) and potassium thiocyanate (KSCN) was carried out. When these solutions are mixed, they form a blood-red colored complex ion. This color change provided a clear visual representation of equilibrium and made it easier for students to observe changes in the system.

Before conducting the experiment, students were asked to predict what would happen if more reactants were added or if one of the substances in the system was removed. Students discussed their predictions in groups and explained the reasons for their answers.

First, additional iron (III) chloride solution was added to one test tube, while additional potassium thiocyanate solution was added to another. Students observed that the red color became darker in both cases. Through guided discussion, they concluded that adding more reactants caused the equilibrium to shift toward the product side, resulting in the formation of more red-colored complex ions.

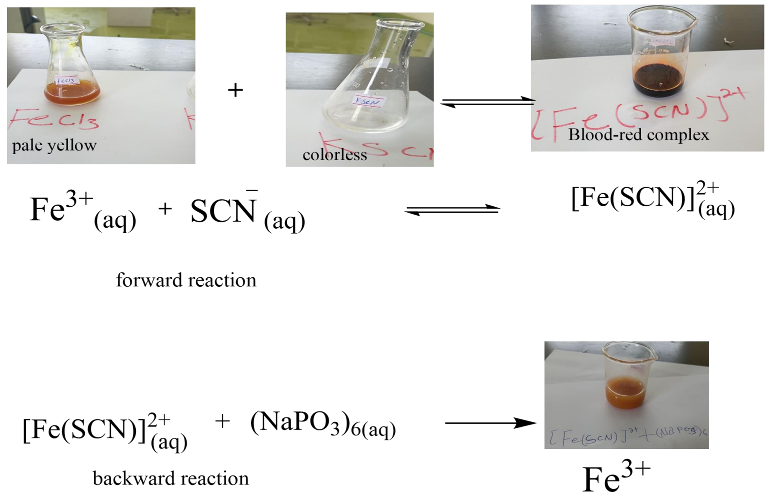


Figure 3: lab activities which demonstrate Le Chatelier's Principle.

The teacher then asked students:

1. Why did the red color become darker?
2. What does this tell us about the direction of the equilibrium shift?
3. How is the system responding to the added reactants?

These questions encouraged students to explain their observations using scientific reasoning rather than simply recalling memorized rules.

Next, sodium phosphate solution was added to the equilibrium mixture. Students observed that the red color gradually faded and the solution became lighter. After careful observation, students discussed possible explanations for this change.

Through questioning and group discussion, students realized that the phosphate ions removed some of the iron ions from the equilibrium system. As a result, the equilibrium shifted back toward the reactant side to replace the lost iron ions. This caused the concentration of the red-colored product to decrease, and the original yellowish color of the iron solution became visible again.

1. The teacher guided students using questions such as:
2. Why did the red color disappear?

3. Which substance was removed from the equilibrium system?
4. In which direction did the equilibrium shift?
5. How does this observation support Le Chatelier's Principle?

As students discussed these questions, they began to understand that an equilibrium system responds to a disturbance by shifting in a direction that reduces the effect of that disturbance. Rather than memorizing definitions, students were able to see the process happening in front of them and explain it using evidence from their observations.

The experiment generated considerable interest among students because they could directly observe the color changes associated with equilibrium shifts. Many students who previously found Le Chatelier's Principle difficult to understand reported that the activity helped them visualize how equilibrium systems respond to changes in concentration.

Throughout the activity, students worked collaboratively to make predictions, observe changes, discuss ideas, and develop explanations. The teacher acted as a facilitator by asking guiding questions and encouraging students to justify their answers using evidence. This approach helped students become active participants in the learning process and promoted deeper conceptual understanding.

The activity also reinforced the concepts learned in Cycle Two. Students were able to connect their understanding of dynamic equilibrium with the idea that equilibrium systems can respond to changes in concentration while still maintaining a balance between forward and reverse reactions. By the end of the lesson, most students could correctly explain how changes in concentration affect equilibrium position and could apply Le Chatelier's Principle to similar situations.

These findings support previous studies showing that inquiry-based laboratory activities help students understand abstract chemistry concepts by connecting theory with observable evidence (Pedaste et al., 2021; Furtak et al., 2023). The use of visual demonstrations and guided inquiry enabled students to develop a more meaningful understanding of chemical equilibrium and strengthened their critical thinking skills.

Evaluation and Reflection Phase: After completing the experiment and group discussions, students were given time to evaluate their understanding and reflect on what they had learned. The purpose of this phase was not only to assess their knowledge of Le Chatelier's Principle but also to encourage them to think critically about the evidence they had observed during the experiment.

Instead of asking students to recall definitions, the teacher used a few open-ended questions that required deeper thinking and scientific reasoning. The questions included:

1. Why do you think the equilibrium system responded when we added more reactants?
2. How the color did changes help you understand what was happening in the reaction?
3. If you were to disturb the system in a different way, what do you think would happen and why?
4. How does the system try to restore equilibrium after a change is introduced?
5. What evidence from the experiment supports your explanation?

Students first reflected individually and then discussed their ideas in groups. During the discussions, they were encouraged to justify their answers using observations from the experiment rather than relying on memorized rules. This approach helped students explain not only what happened but also why it happened.

Many students explained that adding iron (III) chloride or potassium thiocyanate increased the concentration of reactants, causing the system to produce more products. They supported their explanations by referring to the darker red color that appeared during the experiment. Similarly, students explained that the addition of sodium phosphate removed iron ions from the system, causing the equilibrium to shift in the opposite direction. They used the fading of the red color as evidence for their conclusions.

As the discussion continued, students began to compare different explanations and evaluate the reasoning of their classmates. Some students initially focused only on the color changes, while others connected the observations to the movement of the equilibrium position. Through questioning and discussion, students gradually developed more complete and scientifically accurate explanations. To encourage reflection on learning, students were asked one final question:

"How has your understanding of chemical equilibrium changed after this activity?"

Most students reported that they previously viewed Le Chatelier's Principle as a rule that had to be memorized. However, after observing the experiment and discussing the results, they understood that equilibrium systems respond to changes in predictable ways. Several students mentioned that seeing the color changes helped them connect theoretical ideas with real chemical processes.

Classroom observations during this phase showed that students were more confident in explaining scientific concepts and defending their ideas with evidence. They actively participated in discussions, listened to alternative viewpoints, and revised their explanations when necessary. These behaviors demonstrated the development of critical thinking skills, including analysis, reasoning, evaluation, and evidence-based decision-making.

The reflective discussions also helped students recognize how their thinking had changed throughout the learning process, reinforcing both conceptual understanding and critical thinking skills.

4.3 Students' Critical Thinking Skills and Conceptual Understanding Before and After the DBR–IBL Intervention

To evaluate the impact of the design-based research–inquiry-based learning (DBR–IBL) intervention, student performance was tracked across two primary domains: critical thinking skills and conceptual understanding of chemical equilibrium. The statistical profile comparing the baseline and post-intervention scores for the matched analytical sample (N = 30) is presented in Table 4 &Table 5.

Baseline Performance (Pre-Test Analysis)

Prior to the DBR–IBL intervention, students exhibited moderate baseline scores with an average mean of 29.30. The pre-test scores demonstrated a wide distribution, ranging from a minimum of 16.00 to a maximum of 45.00, resulting in a high standard deviation

(SD = 7.84). This high variance indicates a highly heterogeneous group with massive achievement gaps, confirming that students held varying degrees of baseline critical thinking skills and prominent conceptual bottlenecks regarding chemical equilibrium.

Post-Intervention Performance (Post-Test Analysis)

Following the implementation of the iterative DBR–IBL framework, student scores demonstrated a substantial upward shift. The post-test mean increased to 42.63, representing an absolute descriptive gain of 13.33 points. Furthermore, the performance floor rose dramatically, with the lowest score rising from 16.00 up to 36.00.

Concurrently, the standard deviation compressed by more than half, dropping to 3.48 with scores tightly clustered between 36.00 and 50.00. This contraction in variance proves that the student cohort became significantly more homogeneous in their mastery. The DBR–IBL intervention successfully pulled up lower-performing students and closed the initial classroom achievement gap without capping the growth of top performers.

Inferential Analysis and Statistical Significance

A parametric paired-samples t-test was executed to determine whether this 13.33-point mean increase was statistically genuine. The normality of the underlying data distribution was confirmed beforehand, as skewness (Pre = 0.153, Post = 0.432) and kurtosis (Pre = -0.963, Post = -0.442) metrics sat safely within acceptable psychometric boundaries (±1.0 for skewness; ±2.0 for kurtosis) (Table 4).

The paired-samples t-test confirmed that post-test scores were significantly higher than pre-test scores, $t(29) = -13.75$, $p < 0.001$. Because the p-value is well below the standard alpha threshold ($\alpha = 0.05$), the null hypothesis is confidently rejected. The results demonstrate that the observed learning gains are directly attributable to the intervention rather than random chance.

Practical Significance and Magnitude of Effect

To evaluate the real-world magnitude of the DBR–IBL intervention, the standardized mean difference was calculated using Cohen's d. According to classical psychometric conventions, an effect size exceeding 0.80 is classified as large.

The analysis revealed an exceptionally large effect size ($d = 2.51$), which indicates that the average student's performance shifted upward by more than two and a half standard deviations relative to the baseline distribution. This extreme magnitude confirms that the structured, inquiry-based scaffolding developed through the design-based research cycles exerted a profound, transformative practical impact on students' critical thinking capacities and conceptual clarity.

4.4 Integrated Qualitative Findings (Interview and Observational Data)

This study's qualitative component sought to deeply understand students' experiences and perceptions of learning chemical equilibrium using DBR-IBL approach. To capture the degrees of these experiences, data were collected from two primary sources: semi-structured interviews with purposively selected students. In addition, systematic classroom observations data were collected to triangulate the interview data findings. This deliberate combination of verbal accounts and observed behaviors provided a rich, triangulated perspective on the nature of students' engagement, cognitive processes, and affective experiences within each instructional environment.

The qualitative analysis resulted in five main themes emerged from the reflexive thematic analysis, which captured the cognitive restructuring, behavioral adaptations, and personal evaluations of the student cohort throughout the intervention: (1) improved understanding of chemical equilibrium, (2) improvement in critical thinking skills, (3) active participation and engagement, (4) lived experiences of students with the engagement and participation in the DBR-IBR approach, and (5) challenges faced during the intervention. Each theme is detailed below with rich interpretive commentary, direct quotations from participants, and supporting classroom observations to contextualize and deepen the qualitative narrative.

Theme 1: Improved Understanding of Chemical Equilibrium

The integration of narrative reflections and behavioral tracking demonstrated a profound shift in students' conceptual frameworks, proving that the DBR–IBL approach effectively facilitated conceptual change. For example, one participant expressed an improved understanding of chemical equilibrium concept. He noted that:

"Before these lessons, I thought equilibrium meant that the reaction stopped. Now I understand that the forward and reverse reactions continue, but they occur at the same rate." (S5)

This excerpt demonstrates a clear transition from a faulty *"static"* mental model to an accurate dynamic equilibrium understanding. This cognitive shift was visually confirmed by classroom observations during the final design cycles, where the observer records noted 'students actively manipulating simulation paths to demonstrate continuous, simultaneous forward and reverse reactions to their peers'. Both data sources highlighted that the hands-on tracking of dynamic rates forced students to visualize microscopic particle movements running continuously at mathematically equal velocities, replacing their baseline assumption that balanced states represent a complete physical freeze.

Likewise, another student reiterated that the employed approach to teaching the dynamic equilibrium was helpful to see the pattern-based thinking regarding when and how the dynamic equilibrium is established. Her view echoed like this:

"Yes. I thought equilibrium meant equal amounts of reactants and products. Now I know that this is not always true...and I was oblivious to this kinds of thinking, for I believe that equilibrium I meant to be equal amount of reactants and products. As such the concept of dynamic equilibrium had become much clearer afterwards."(S5)

Students routinely carry the intuitive misconception that equilibrium demands an identical chemical mass or product concentration on both sides of an equation. Triangulating this interview response with classroom observations reveal that during early laboratory tasks, multiple groups hesitated and re-checked their calculations when their measured product quantities did not perfectly equal their reactant quantities.

However, by the middle of the intervention, field notes showed groups confidently recording unequal concentrations while explicitly stating aloud that the system was balanced. The laboratory layouts successfully uncoupled the concept of rate uniformity from spatial quantity, helping students overcome cognitive conflict and establish a sophisticated grasp of concentration ratios. Regarding this line of thinking, one participant highlighted his ideas as follows:

"I now understand that equilibrium can change when conditions such as pressure, concentration, or temperature change... The soft drink experiment helped me see how pressure affects equilibrium. Before, I memorized the principle, but now I understand how it works in real situations." (S6)

This statement indicated that the intervention leads to achieve a contextualized way of understanding about Le Chatelier's Principle by shifting it from a dry, rote-memorized definition into an adaptable framework. This is strongly supported by observation logs recorded during the carbonated beverage experiment, which noted high levels of focused activity where students stood up, closely tracked the rate of gas bubble generation upon pressure release, and immediately referenced their Le Chatelier's guide sheets to trace the direction of the equilibrium shift. The behavioral data confirms that observing an everyday phenomenon in real time allowed learners to successfully link macroscopic visual changes to microscopic ones, thereby fostering their ability to connect real-life phenomena with general chemical concepts.

Theme 2: Improvement in Critical Thinking Skills

The qualitative synthesis verified that the iterative design cycles forced a transition from superficial heuristic processing to rigorous evidence-based reasoning and higher-order critical thinking skills.

Some students were of the opinion that the employed DBR-IBL approach to learning the factors affecting equilibrium promoted their capability to provided evidence-based reasoning during the learning process. For example, one participant reiterated the following:

"During the soft drink experiment, we were asked to explain why bubbles formed when the bottle was opened. At first, I was not sure of the answer. I thought it was just because air entered the bottle. After discussing with my group and looking at what happened in the experiment, I understood that the pressure changed and affected the equilibrium." (S1)

This quote displays the trajectory of a student abandoning an initial superficial hypothesis ("air entering the bottle") in favor of evidence-based reasoning. This cognitive transition is physically illustrated by observer notes from the beginning of this experiment, which highlighted that 'individual students initially blurted out superficial answers without consulting their data, but were quickly corrected by group members who pointed directly to their recorded data tables to force a reconsideration'. The physical behavior of using data tables during arguments highlights how the peer-led environment operationalized critical thinking, forcing individual learners to reject baseline assumptions and replace them with valid thermodynamic explanations.

Despite this, some students found that the practical teaching approach was demanding in terms of articulating the chemical concepts during the investigative process. This is evident during the expressions of her opinion in this aspect, which is presented as follows:

"The difficult part was explaining the reason behind the observation. We had to think about the chemistry, not only what we saw... I used the evidence from the experiment and what we learned about Le Chatelier's Principle." (S1)

Challenge identified by the student moving past raw sensory data to explain underlying chemistry is visually corroborated by classroom logs revealing that 'some students spent a significant portion of their lab time engaged in prediction and justification phases'. Observers noted that students routinely drew molecular-level diagrams on whiteboards to *"see"* the invisible chemical shifts that explained their physical observations. The instructional scaffolding successfully trained students to treat physical markers (like bubbling) as clues to decode invisible chemical transformations, moving them away from superficial descriptions toward structural chemical analysis.

Some students demonstrated that their involvement in DBR-IBL was beneficial for offering opportunities to evaluate their own ideas in the lens of their colleague's way explanation of particular topics. This is event in the following excerpt expressed by one participant:

"In one activity, we had to predict what would happen when the concentration of a reactant increased. Different students had different answers, so we had to discuss and decide which explanation made the most sense... Before, I usually accepted the first answer. During these lessons, I learned to compare different ideas and choose the one supported by evidence."(S2)

This reflection confirms a direct upgrade in the student's cognitive processing through an analysis of explanations. This finding highlights that providing chances for students to think deeply while working collaboratively and letting them do interactive tasks that help evaluate each other might be the reason for their enhanced learning in the factors that affect the directions of equilibrium meaningfully. This upgrade was further complemented by the observation note findings that the observer documented multiple instances of productive peer debate, including an exchange where a group spent over five minutes debating concentration shifts, with students actively cross-referencing conflicting predictions against their empirical laboratory findings before writing down a final group consensus. The observed behavioral pattern validates the student's interview statement: the cooperative environment systematically broke the habit of rushing to a passive consensus, and rather replacing it with a rigorous process of weighing conflicting ideas against empirical benchmarks.

Some participants liked the chance offered to ask sound questions pays off in terms of promoting their critical thinking skills. On participant said:

"The teacher frequently asked us to explain our answers. This helped me think more carefully and give reasons for my ideas."(S1)

The recurring demand for justification altered the students' internal cognitive pacing, thereby increasing their critical thinking skills. Similarly, field notes finding revealed a distinct teaching pattern: whenever a group gave a quick or one-word answer, the instructor immediately responded with Socratic prompts such as, "*What is your evidence for that?*" or "*How does Le Chatelier's Principle support this view?*" The instructor's consistent behavioral positioning acted as an external cognitive regulator, training students to slow down, review their own logic, and systematically verify their claims before presenting them, all of which are helpful for improve students' critical thinking skills.

Theme 3: Active Participation and Engagement

The DBR–IBL environment triggered a marked increase in student agency and collective motivation, shifting the classroom dynamic into a collaborative learning model.

Some participants were of the opinion that the employed approach was crucial for leading them to be responsive learners, and at the same time to appreciate the benefits of working in social groups. A participant who shared this idea reiterated that:

"Before, the teacher explained most of the content. In these lessons, we had to investigate and find answers ourselves... I participated more because I had a role in the group activities and discussions." (S3)

This response highlights a major shift in accountability within the classroom. Observers documented this transition through a striking change in classroom physical dynamics: traditional teacher-fronted lectures were replaced by a decentralized layout where the teacher moved around the room as a facilitator, while students took physical ownership of lab materials, timing devices, and recording sheets. The decentralization recorded in field notes directly mirrors the student's reported sense of elevated accountability, confirming that reducing passive lecture time successfully transformed students from passive consumers of information into active stakeholders who felt personally responsible for their group's investigative outcomes.

With regard to the benefits of the interactive lab activities provided during the investigative process, one participant reflected that chances offered to discuss scientific ideas with colleagues is supportive to promote his ability to explain chemical concepts with ease. He noted like this:

"It helped me understand the lesson better because I could see what was happening and talk about it with others. Sometimes my classmates explained ideas in a way that was easier for me to understand." (S3)

This excerpt underscores the immense value of collaborative learning. This collaborative scaffold was caught in real time by observers who frequently recorded students leaning in toward each other, using informal language, hand gestures, and everyday analogies to explain complex concentration graphs to struggling peers. Small-group settings served as local translation hubs, where observed student-to-student gestures and informal explanations bridged conceptual gaps that formal instructional terminology could not.

Theme 4: Lived Experiences of Students with Engagement and Participation in the DBR-IBL approach

The overarching consensus regarding the DBR–IBL intervention was highly favorable, with students viewing it as a valuable framework that links conceptual theory with real-world practice.

This is apparent in some students who demonstrated that learning chemistry through this practical based and process-oriented inquiry has the potential to pave the way to associate real-world scenarios with scientific concepts. One participant opined her perspectives like this:

"I enjoyed the experiments and group discussions because they made the lessons more interesting... I learned how to think about a problem and explain my answer rather than just memorizing information."(S7)

This feedback shows a clear rejection of traditional learning approaches. This high interest level is corroborated by classroom observers who noted zero signs of off-task behavior (such as phone distraction or side conversations) during experimental cycles; instead, students remained consistently engaged in handling equipment, debating steps, and drafting scientific conclusions. The total absence of off-task behavior validates the student's statement and proves that students value true conceptual understanding over short-term test memorization when given a highly engaging, active learning environment.

Theme 5: Challenges Faced During the Intervention

Despite the high quantitative gains, the transition into an open-ended inquiry environment created clear initial friction and cognitive discomfort for students.

While the DBR-IBL approach is applauded by most of the participants, some students clearly showed what they encountered challenges related to making the abstract chemical concepts accessible to grasp.

One participant highlighted that adapting to the employed approach is difficult and it is particularly demanding until exposed to sufficient lab activities are performed. He said Like this:

"At first, I was not confident when sharing my ideas... My classmates encouraged me, and I became more comfortable speaking during discussions." (S7)

Because students were accustomed to low-stakes rote memorization, they experienced initial stress when asked to articulate and defend their scientific reasoning out loud. This anxiety was tracked in field notes from the first week of the intervention, which noted that several students sat silently during group work, avoided eye contact during presentations, or spoke in low, hesitant voices. However, by the third week, observers recorded these same students actively volunteering to present their group's whiteboard models. Combining these observations with the interview data reveals that a supportive peer group acts as a crucial safety net, helping students overcome communication anxiety and progressively build academic confidence.

Another participant expressed similar ideas to the ideas of the above participant. She reiterated like this:

"Sometimes it was difficult to explain my thinking, especially at the beginning... The more we practiced, the easier it became to explain and defend our ideas." (S8)

The student highlights a common hurdle: the challenge of translating an intuitive thought process into a structured, clear explanation. This friction was documented by observers who noted initial pauses, fragmented sentences, and prolonged debates within groups when students were first forced to write down their step-by-step reasoning. Both the behavioral data and the transcript confirm that articulating scientific arguments is a learned skill that requires continuous practice and reinforcement to become comfortable.

4.5 Discussion of Findings

This study examined the effect of a design-based research–inquiry-based learning (DBR–IBL) intervention on grade 11 students' conceptual understanding of chemical equilibrium and their critical thinking skills. The quantitative findings revealed substantial learning gains following the intervention, with students' mean scores increasing from 29.30 in the pre-test to 42.63 in the post-test and yielding a very large effect size (d = 2.51). These findings suggest that the intervention was effective in supporting students' learning of chemical equilibrium, a topic that has consistently been identified as one of the most conceptually difficult areas in secondary chemistry education (Kousathana & Tsaparlis, 2002; Bain & Towns, 2016; Saputra & Parbuntari, 2025).

The positive learning outcomes observed in this study are consistent with a growing body of research indicating that inquiry-based science instruction improves students' conceptual understanding by engaging them actively in the process of knowledge construction (Furtak et al., 2012; Lazonder & Harmsen, 2016; Jegstad, 2024). Previous studies have shown that inquiry-oriented learning environments provide opportunities for learners to investigate scientific phenomena, generate explanations, test ideas, and use evidence to support claims. The present study supports these findings by demonstrating that students who participated in inquiry-based equilibrium activities developed a more sophisticated understanding of equilibrium concepts. However, unlike many previous studies that focused primarily on measuring learning outcomes, the current study also examined how iterative design refinements and classroom-based inquiry experiences contributed to conceptual development. This provides a more detailed understanding of the mechanisms through which inquiry-based learning can support chemistry learning in authentic classroom settings.

A particularly important finding concerns students' conceptual change regarding chemical equilibrium. Prior to the intervention, many students held misconceptions commonly documented in chemistry education literature. For example, students viewed equilibrium as a state in which reactions stop completely or assumed that equal concentrations of reactants and products must be present at equilibrium. Such misconceptions have been reported across different educational contexts and continue to present significant barriers to meaningful learning (Hackling & Garnett, 1985; Bain & Towns, 2016; Saputra & Parbuntari, 2025). Following the intervention, students demonstrated a more scientifically accurate understanding of equilibrium as a dynamic process in which forward and reverse reactions occur simultaneously at equal rates.

This finding aligns with conceptual change theories, which suggest that learners revise their existing conceptions when they encounter experiences that challenge their prior understanding and provide more plausible scientific explanations (Posner et al., 1982; Vosniadou, 2019). While previous studies have shown that inquiry-based approaches can reduce misconceptions in chemistry (Çalik et al., 2015; Saputra & Parbuntari, 2025), the present study extends this knowledge by demonstrating how carefully designed inquiry activities, supported by iterative DBR cycles, can facilitate conceptual reconstruction in the context of chemical equilibrium. Thus, the contribution of this study lies not only in confirming the effectiveness of inquiry-based instruction but also in illustrating how design-based refinements can strengthen conceptual change processes in real classroom environments.

The hands-on activities incorporated into the intervention appear to have played a critical role in supporting students' understanding. Activities such as the water-transfer model and soft-drink experiment enabled students to visualize aspects of equilibrium that are otherwise difficult to observe directly. Research in chemistry education has consistently shown that students struggle to connect macroscopic observations with microscopic and symbolic representations of chemical phenomena (Johnstone, 1991; Talanquer, 2011). The findings of this study suggest that inquiry activities that bridge these representational levels can support students in developing more coherent conceptual frameworks. In this respect, the study reinforces existing evidence regarding the value of concrete models and experiential learning in chemistry education while providing an example of how such activities can be integrated within a DBR informed instructional design.

The study also revealed improvements in students' critical thinking skills. Interview and observation data showed that students increasingly engaged in interpreting evidence, evaluating alternative explanations, justifying conclusions, and defending claims using experimental observations. These findings are consistent with research suggesting that inquiry-based science instruction supports the development of higher-order thinking skills by engaging students in authentic scientific practices (Osborne, 2014; García-Carmona, 2023). The findings also align with contemporary views of scientific literacy, which emphasize evidence-based reasoning, argumentation, and critical evaluation as essential competencies for science learners (OECD, 2023).

Although previous studies have reported positive relationships between inquiry learning and critical thinking development, much of this work has focused on general science education contexts (Abrami et al., 2015; García-Carmona, 2023). The present study contributes to this literature by providing empirical evidence from chemistry education, specifically within the challenging topic of chemical equilibrium. The findings suggest that inquiry activities that require students to explain observations, compare interpretations, and justify conclusions can simultaneously promote conceptual understanding and critical thinking. This highlights the potential of inquiry-based chemistry instruction to support multiple educational goals rather than focusing solely on content acquisition.

Another notable finding concerns student engagement and participation. Students described the intervention as more interactive, enjoyable, and intellectually stimulating than their previous learning experiences. They particularly valued opportunities to conduct experiments, discuss ideas collaboratively, and discover explanations through investigation. These findings support previous research demonstrating that inquiry-based learning promotes greater motivation, engagement, and ownership of learning than traditional teacher-centered approaches (National Research Council, 2000; Lazonder & Harmsen, 2016; Jegstad, 2024). Increased engagement may partly explain the substantial learning gains observed in this study, as students who are cognitively and emotionally invested in learning activities are more likely to engage in productive learning behaviors.

At the same time, the findings indicate that students initially experienced challenges when adapting to inquiry-based learning. Many were reluctant to articulate their ideas, justify their reasoning, or participate in scientific discussions. Similar challenges have been reported in studies where students transition from teacher-centered instruction to inquiry-oriented learning environments (Hmelo-Silver et al., 2007; Furtak et al., 2012). However, these difficulties gradually diminished as students gained experience with inquiry processes and received support from the teacher and their peers. This finding underscores the importance of scaffolding in inquiry-based learning and supports research suggesting that guidance remains essential for successful inquiry implementation (Lazonder & Harmsen, 2016).

The iterative nature of the DBR approach also appears to have contributed significantly to the intervention's success. Through continuous observation, reflection, and refinement, instructional activities were adapted to address students' emerging learning needs. This finding is consistent with DBR literature, which emphasizes the value of iterative cycles for developing contextually relevant and theoretically informed educational innovations (Anderson & Shattuck, 2012; Halawa et al., 2024). While many studies evaluate the effectiveness of inquiry-based interventions after implementation, fewer studies examine how ongoing refinement during implementation contributes to improved learning outcomes. The present study therefore adds to the growing body of DBR research by illustrating how iterative adaptation can enhance the effectiveness of inquiry-based chemistry instruction.

The integration of quantitative and qualitative findings provides a comprehensive understanding of both the outcomes and processes of learning. Quantitative data demonstrated substantial achievement gains, while qualitative evidence revealed how students developed conceptual understanding, confidence, scientific reasoning, and engagement through participation in inquiry activities. The convergence of these findings strengthens the credibility of the results and provides a richer account of how learning occurred.

Overall, this study contributes to the science education literature in three important ways. First, it provides further evidence that inquiry-based learning can support conceptual understanding and critical thinking in chemistry education. Second, it extends existing research by demonstrating how the integration of Design-Based Research and Inquiry-Based Learning can facilitate conceptual change in a complex chemistry topic such as chemical equilibrium. Third, it offers context-specific evidence from a secondary school setting, illustrating how iterative instructional design, hands-on inquiry experiences, and teacher scaffolding can work together to support meaningful science learning. While the findings are limited to the context in which the intervention was implemented, they provide useful insights for researchers and practitioners seeking to improve the teaching and learning of challenging chemistry concepts.

While the findings of this study are encouraging and internally consistent, several limitations must be acknowledged to ensure appropriate interpretation. First, the study was conducted in a single public secondary school in Injibara City using a purposive, intact-class sample of 30 students. The absence of a randomly assigned comparison group means that the observed learning gains cannot be attributed solely to the intervention with the confidence afforded by experimental designs; other contextual factors, including the researcher's presence, the heightened attention given to participating students, and the specific characteristics of this classroom and teacher, may have contributed to outcomes. Second, the six-week intervention period did not allow for assessment of the retention or transferability of learning gains over time. Future research employing delayed post-tests would be necessary to establish whether the conceptual changes observed are durable. Third, the study focused exclusively on chemical equilibrium at the Grade 11 level; it remains an open question whether the DBR–IBL approach produces comparable results in other chemistry topics, at other grade levels, or in educational contexts outside Ethiopia.

4.6 Critical Thinking Development Through the Lens of Facione's Framework

Facione's (2011) model of critical thinking identifies six core intellectual dispositions: interpretation, analysis, evaluation, inference, explanation, and self-regulation. The qualitative evidence generated in this study maps coherently onto these dispositions, providing a structured basis for interpreting the observed CT development.

Interpretation was evidenced by students' growing ability to read concentration data and graph patterns meaningfully — for example, recognizing that constant post-equilibrium concentrations indicate rate equality rather than reaction cessation. Analysis was demonstrated through students' identification of causal relationships in experimental observations, such as linking the darkening of the $FeCl_3$/KSCN system to the equilibrium shift induced by increased reactant concentration. Evaluation emerged in peer discussions where students compared competing explanations and assessed which was best supported by empirical evidence — a behavior documented in field notes across all three cycles. Inference was visible in students' ability to predict equilibrium shifts for novel reaction conditions using Le Chatelier's Principle as a generalized reasoning tool. Explanation was practiced through the structured requirements of guided worksheets, reflective discussions, and the teacher's Socratic questioning pattern. Self-regulation the metacognitive dimension of CT was evidenced by students' mid-activity revisions of their predictions when observation contradicted their initial reasoning.

Taken together, this pattern of CT development is consistent with the findings of Arifin et al. (2025), whose meta-analysis identified inquiry-based science instruction as a significant predictor of CT growth, and with Sutiani et al.'s (2021) study in secondary chemistry classrooms. The contribution of the present study is to demonstrate that these CT gains are achievable within a specifically designed DBR–IBL framework applied to the challenging content area of chemical equilibrium.

CHAPTER FIVE: CONCULUSSIONS AND IMPLICATIONS

5.1 Conclusions

The findings of this study demonstrate that the design-based research–inquiry-based learning (DBR–IBL) intervention had a positive and meaningful impact on Grade 11 students’ conceptual understanding of chemical equilibrium and critical thinking skills. The quantitative results showed a significant improvement in students’ achievement after participating in the intervention. The increase in post-test scores and the large effect size indicate that the intervention was successful in helping students develop a stronger understanding of chemical equilibrium concepts. These findings suggest that learning environments that actively engage students in inquiry, discussion, and investigation can support deeper understanding of complex chemistry concepts.

The qualitative findings further strengthened the quantitative results by providing insight into how students experienced the intervention. Students reported that the inquiry activities, experiments, and collaborative discussions helped them understand concepts that they had previously found difficult. In particular, many students explained that they had initially believed that chemical equilibrium meant a reaction had stopped completely or that reactants and products must be present in equal amounts. Through the DBR–IBL activities, students were able to recognize equilibrium as a dynamic process and develop a more scientifically accurate understanding of equilibrium systems.

The study also revealed that the intervention contributed to the development of students’ critical thinking skills. Students described how they were encouraged to analyze observations, evaluate different explanations, justify their responses, and support their conclusions with evidence. Classroom observations similarly showed that students became increasingly confident in expressing their ideas, asking questions, and participating in scientific discussions. These findings indicate that the DBR–IBL approach not only enhanced conceptual understanding but also promoted important higher-order thinking skills that are essential for science learning.

Another important finding was the positive influence of the intervention on student engagement and participation. Students described the learning activities as interesting, interactive, and different from their usual classroom experiences. The opportunity to investigate scientific phenomena, work collaboratively with peers, and construct explanations independently increased their motivation and involvement in the learning process. As students became more familiar with inquiry-based learning, they also became more confident in sharing their ideas and solving unfamiliar chemistry problems.

Overall, the findings highlight the value of combining Design-Based Research with Inquiry-Based Learning in chemistry education. The iterative process of designing, implementing, evaluating, and refining instructional activities enabled the intervention to respond to students' learning needs while promoting meaningful learning experiences. The study therefore concludes that the DBR–IBL approach is an effective instructional strategy for improving conceptual understanding, addressing misconceptions, developing critical thinking skills, and increasing student engagement in learning chemical equilibrium.

However, it is important to acknowledge that the study was conducted with a relatively small sample of students from a single secondary school and focused only on the topic of chemical equilibrium over a six-week intervention period. Therefore, although the findings are encouraging, they should be interpreted within the context of the study and may not be generalized to all educational settings without further research.

The present study makes three original contributions to the field of Chemistry Education Research. First, it extends the existing IBL literature by embedding inquiry-based chemical equilibrium instruction within a systematic DBR framework — an integration that has rarely been examined empirically in secondary chemistry settings, and which has not previously been investigated in the Ethiopian educational context. This integration addresses a recognized gap between the theoretical promise of inquiry-based chemistry instruction and its inconsistent implementation quality, by providing a principled design mechanism for continuous instructional refinement.

Second, the study produces context-sensitive design knowledge: not merely evidence that DBR–IBL 'works,' but insight into how and why it works in a specific classroom setting, including identification of the specific misconceptions targeted in each design cycle, the pedagogical moves that proved most effective in eliciting conceptual change, and the scaffolding strategies that enabled students to engage productively in evidence-based reasoning despite initial reluctance.

Third, the study contributes to empirical scholarship on critical thinking development in chemistry education by applying Facione's (2011) framework as an analytical lens for interpreting qualitative evidence an approach that enables more precise and replicable characterization of CT growth than has been typical in the secondary chemistry literature. These contributions position the study as a meaningful addition to both the international CER literature and the emerging body of chemistry education research in Sub-Saharan Africa.

5.2 Implications of the Study

5.2.1 Implications for Chemistry Teachers

Teachers should consider transitioning from lecture-based delivery toward guided inquiry environments for teaching chemical equilibrium. The present study demonstrates that structured IBL activities including water-transfer models, guided experiments, and reflective discussions can be implemented within existing curriculum constraints. Professional development programs should support teachers in facilitating inquiry rather than transmitting information.

5.2.2 Implications for Curriculum Developers

The findings suggest that secondary chemistry curricula should be designed to create space for iterative, inquiry-based engagement with abstract concepts such as chemical equilibrium. Curriculum frameworks should specify not only content coverage but also the pedagogical approaches through which conceptually demanding topics are to be taught, given that the mode of instruction significantly affects the depth of learning achieved.

5.2.3 Implications for School Leaders and Teacher Educators

School leaders should support the structural conditions that enable inquiry-based teaching including adequate laboratory resources, flexible scheduling, and a school culture that values student participation and productive struggle. Teacher educators should incorporate DBR–IBL principles into pre-service and in-service chemistry teacher training programs.

5.2.4 Implications for Educational Policymakers

National educational policies in Ethiopia that prioritize active learning should be accompanied by targeted investment in classroom resources, teacher training, and formative assessment tools that make inquiry-based teaching practically viable in public secondary schools. The present study's intervention was implemented with minimal additional resources, suggesting that effective inquiry instruction is achievable within existing resource constraints with appropriate design support.

5.3 Recommendations for Future Research

Based on the findings and limitations of this study, the following directions are recommended for future research:

(1) Topic Extension: Future studies should apply the DBR–IBL approach to other conceptually challenging secondary chemistry topics, including chemical kinetics, acids and bases, electrochemistry, and organic chemistry, to examine whether the approach generates comparable gains in conceptual understanding and critical thinking across different content domains.

(2) Comparative Studies: Future research should employ quasi-experimental or experimental designs with matched comparison groups to enable more confident causal attribution of learning outcomes to the DBR–IBL intervention, rather than pre-post designs alone.

(3) Longitudinal Investigation: Studies with delayed post-test designs (e.g., 3–6 months following the intervention) are needed to investigate whether the conceptual changes and critical thinking gains observed in this study are durable over time, or whether they require ongoing inquiry-based reinforcement to be maintained.

(4) Multi-Site and Multi-Context Studies: Future DBR–IBL research should be conducted across multiple schools in different regions of Ethiopia — including urban, peri-urban,

and rural settings and across different East African educational systems to examine the generalizability and contextual sensitivity of the approach.

(5) Teacher Professional Development: Future research should examine how DBR–IBL principles can be integrated into sustained teacher professional development programs, and whether teachers who receive training in inquiry facilitation and iterative design thinking implement more effective chemistry instruction over time.

(6) Student Subgroup Analysis: Future studies with larger samples should investigate whether the DBR–IBL approach produces equitable learning gains across gender, prior achievement level, and socioeconomic background dimensions of educational equity that the present study was not powered to examine.

References

Adauyah, R., &Aznam, N. (2024). Guided Inquiry Learning Model in Chemistry Education: A Systematic Review. *JournalPenelitianPendidikan IPA*, *10*(3), 77–87. https://doi.org/10.29303/jppipa.v10i3.6373

Aditomo, A., &Klieme, E. (2020). Forms of inquiry-based science instruction and their relations with learning outcomes: evidence from high and low-performing education systems. *International Journal of Science Education*, *42*(4), 504–525. https://doi.org/10.1080/09500693.2020.1716093

Alarcon, D., Talavera-Mendoza, F., Paucar, F., Caceres, K., and Viza, R. (2023). Science and inquiry-based teaching and learning: a systematic review. Frontiers in Education, 8.

Alsaleh, N. J. (2020). Teaching critical thinking skills: Literature review. *Turkish Online Journal of Educational Technology-TOJET*, *19*(1), 21-39.

Annisa, D., &Rohaeti, E. (2018). *The effect of inquiry-based learning on students' understanding of the chemical equilibrium concept*. 080004. https://doi.org/10.1063/1.5062823

Antonio, R. P., &Prudente, M. S. (2024). Effects of Inquiry-Based Approaches on Students' Higher-Order Thinking Skills in Science: A Meta-Analysis. *International Journal of Education in Mathematics, Science and Technology*, *12*(1), 251-281.

Arifin, Z., Sukarmin, S., Saputro, S., & Kamari, A. (2025). The effect of inquiry-based learning on students'critical thinking skills in science education: A systematic review and meta-analysis. *Eurasia Journal of Mathematics, Science and Technology Education*, *21*(3), em2592.https://doi.org/10.29333/ejmste/15988

Aung, K., & Rashid, N. (2025). Challenges, innovations, and the role of design-based research in advancing nursing education: a review. *Nursing Communications*. https://doi.org/10.53388/in2025008

Bain, K., & Towns, M. H. (2016). A review of research on the teaching and learning of chemical equilibrium. Chemistry Education Research and Practice, 17(2), 246–262. https://doi.org/10.1039/C5RP00176A

Barke, H.-D., Hazari, A., &Yitbarek, S. (2022). *Misconceptions in chemistry: Addressing perceptions in chemical education* (2nd Ed.). Springer. https://doi.org/10.1007/978-3-030-98765-4

Barthmann, K., Schrüfer, G., & Eckstein, V. (2025). Design-Based Research - A Research Format for Educational Research. *Vietnam Journal of Education*. https://doi.org/10.52296/vje.2025.438

Bergquist, W., &Heikkinen, H. (1990). Student ideas regarding chemical equilibrium: What written test answers do not reveal. *Journal of Chemical Education*, *67*(12), 1000. https://doi.org/10.1021/ed067p1000

Bilgin, I. (2003). The effects of cooperative learning on students' understanding of chemical equilibrium. *Journal of Chemical Education*, 80(7), 832–837.

Bunce D. M. and Robinson W. R. (1997), Research in chemical education: the third branch of our profession, J. Chem. Educ., 74(9), 1076–1079

Cochrane, T., Galvin, K., Glasser, S., Osborne, M., Buskes, G., &Rajagopal, V. (2024). Exploring Design-Based Research as a framework for addressing pedagogical problems faced by higher education. *ASCILITE Publications*. https://doi.org/10.14742/apubs.2024.1335

Cohen, J. (1988). Statistical power analysis for the behavioral sciences (2nd ed.). Lawrence Erlbaum Associates.

Cooper, M. M. (2018). Chemistry education research—from personal empiricism to evidence, theory, and informed practice. *Chemical Reviews*, 118(12), 6053–6087.

Di, R., Sawangboon, T., &Chano, J. (2025). Enhancing innovative thinking through a theory-based instructional model in design education to support Sustainable Development Goals (SDGs). *ASEAN Journal of Educational Research and Technology*, *4*(3), 311-332.

Dibner, K. A., & Snow, C. E. (Eds.). (2016). Science literacy: Concepts, contexts, and consequences.

Dunn, J., &Ramnarain, U. (2025). The use of mobile technology in abductive inquiry-based teaching and learning of chemical bonding. *Chemistry Education Research and Practice, 26*(2), 445–458.

Duschl, R. (2008). Science education in three-part harmony: Balancing conceptual, epistemic, and social learning goals. Review of Research in Education, 32:268–291.

Ford, C., McNally, D., & Ford, K. (2017). Using Design-Based Research in Higher Education Innovation. , 21, 50-67. https://doi.org/10.24059/olj.v21i3.1232

Freeman, S., Eddy, S. L., McDonough, M., Smith, M. K., Okoroafor, N., Jordt, H., &Wenderoth, M. P. (2014). Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences*, 111(23), 8410–8415.

Furtak, E. M., Seidel, T., Iverson, H., & Briggs, D. C. (2023). Experimental and quasi-experimental studies of inquiry-based science teaching: A meta-analysis. *Review of Educational Research, 93*(2), 245–284. https://doi.org/10.3102/00346543221112345

García-Carmona, A. (2023). Scientific thinking and critical thinking in science education: Two distinct but symbiotically related intellectual processes. *Science & Education, 33*(1), 1–29.

George, D., &Mallery, P. (2020). IBM SPSS Statistics 26 step by step: A simple guide and reference (16th ed.). Routledge.

Hair, J. F., Black, W. C., Babin, B. J., & Anderson, R. E. (2019). Multivariate data analysis (8th ed.). Cengage Learning EMEA.

Halawa, S., Lin, T. C., & Hsu, Y. S. (2024). Exploring instructional design in K–12 STEM education: A systematic literature review. *International Journal of STEM Education, 11*(43), 1–25.

Herron J. D. and Nurrenbern S. C., (1999), Chemical education research: improving chemistry learning, J. Chem. Educ., 76(10), 1353–1361

Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2007). Scaffolding and achievement in problem-based and inquiry learning: A response to Kirschner, Sweller, and Clark (2006). Educational Psychologist, 42(2), 99–107. https://doi.org/10.1080/00461520701263368

Hoadley, C., & Campos, F. (2022). Design-based research: What it is and why it matters to studying online learning. *Educational Psychologist*, 57, 207 - 220. https://doi.org/10.1080/00461520.2022.2079128

Jegstad, K. M. (2024). Inquiry-based chemistry education: A systematic review. *Studies in Science Education, 60*(2), 251–313.

Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. Journal of Computer Assisted Learning, 7(2), 75–83. https://doi.org/10.1111/j.1365-2729.1991.tb00230.x

Juniar, A., &AmparodmanSianipar, I. (2022). The influence of guided inquiry learning models on science process skills and student learning outcomes on chemical equilibrium material. *JurnalPendidikan Kimia*, *14*(2), 79–84. https://doi.org/10.24114/jpkim.v14i2.34553

Kotsis, K. T. (2025). Inquiry-based learning in science: Mathematical reasoning's support of critical thinking. Journal of Research in Mathematics, Science, and Technology Education, 2(1):60–72.

Kousathana, M., & Tsaparlis, G. (2002). Students' errors in solving numerical chemical equilibrium problems. Chemistry Education Research and Practice, 3(1), 5–17. https://doi.org/10.1039/B1RP90023J

Lazenby, K. (2023). Progress and challenges in chemistry education research. *Chemistry Education Research and Practice*, 24(2), 285–301.

Lazonder, A. W., & Harmsen, R. (2016). Meta-analysis of inquiry-based learning: Effects of guidance. Review of Educational Research, 86(3), 681–718. https://doi.org/10.3102/0034654315627366

Lederman, N. G., Zeidler, D. L., & Lederman, J. S. (2023). *Handbook of Research on Science Education*. Routledge. https://doi.org/10.4324/9780367855758

Liu, C., Zowghi, D., Kearney, M., and Bano, M. (2021). Inquiry-based mobile learning in secondary school science education: A systematic review. Journal of Computer Assisted Learning, 37(1):1–23.

Liu, O. L., Frankel, L., &Roohr, K. C. (2014). Assessing critical thinking in higher education: Current state and directions for next-generation assessment. *ETS Research Report Series*, *2014*(1), 1-23.

Luvanga, B. (2023). Inquiry-Based Learning in Tanzania: Chemistry Teachers' Knowledge and Perceptions. *Contemporary Issues in Education: Linking Research and Practice*, 331–349. https://doi.org/10.37759/ICE01.2023.18

McKenney, S., & Reeves, T. C. (2024). *Conducting educational design research* (3rd Ed.). Routledge. https://doi.org/10.4324/9781003268287

Morris, D. L. (2025). Rethinking Science Education Practices: Shifting from Investigation-Centric to Comprehensive Inquiry-Based Instruction. *Education Sciences*, *15*(1), 73. https://doi.org/10.3390/educsci15010073.

National Educational Assessment and Examinations Agency. (2022). 2021-2022 annual report on national examinations. Ministry of Education, Ethiopia.

Obczovsky, M., Bernsteiner, A., Haagen-Schützenhöfer, C., &Schubatzky, T. (2024). Systematizing Decisions in Design-Based Research: From Theory to Design. *Science Education*. https://doi.org/10.1002/sce.21915

OECD. (2023). PISA 2022 Results (Volume I): The State of Learning and Equity in Education. OECD Publishing. https://doi.org/10.1787/53f23881-en

Ogegbo, A., Upahi, J., Ramnarain, U., and Wu, H. (2025). A systematic review on assessment in inquiry-based science education. International Journal of Research in STEM Education.

Olofin, S. O., Ogunjobi, A. O., Falemu, F. A., Akinwumi, I. O., &Olumilua, B. (2023). Science education as a tool for achieving socio-economic development in

Nigeria. *International Journal of Development and Economic Sustainability*, *11*(4), 33-44.

Organization for Economic Co-operation and Development (OECD). (2023). *PISA 2022 results (Volume I): The state of learning and equity in education*. OECD Publishing. https://doi.org/10.1787/53f23881-en

Osborne, J. (2014). Teaching scientific practices: Meeting the challenge of change. Journal of Science Teacher Education, 25(2), 177–196. https://doi.org/10.1007/s10972-014-9384-1

Osborne, J. (2023). Science, scientific literacy, and science education. In *Handbook of research on science education* (pp. 785-816). Routledge.

Pedaste, M., Mäeots, M., Siiman, L. A., de Jong, T., van Riesen, S. A. N., Kamp, E. T., Manoli, C. C., Zacharia, Z. C., &Tsourlidaki, E. (2015). Phases of inquiry-based learning: Definitions and the inquiry cycle. *Educational Research Review*, *14*, 47–61. https://doi.org/10.1016/j.edurev.2015.02.003

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. Science Education, 66(2), 211–227. https://doi.org/10.1002/sce.3730660207

Rahmawati, Y., Zulhipri, Z., Hartanto, O., Falani, I., &Iriyadi, D. (2022). Students' conceptual understanding in chemistry learning using PhET interactive simulations. *Journal of Technology and Science Education*, *12*(2), 303. https://doi.org/10.3926/jotse.1597

Saputra, A., &Parbuntari, H. (2025). Development of a five-tier diagnostic test of misconceptions on chemical equilibrium material. *BIOCHEPHY: Journal of Science Education, 5*(1), 163–174.

Scott, E., Wenderoth, M., & Doherty, J. (2020). Design-Based Research: A Methodology to Extend and Enrich Biology Education Research. *CBE Life Sciences Education*, 19. https://doi.org/10.1187/cbe.19-11-0245

Suparman, S., Widodo, A., &Sopandi, W. (2024). Research trends on students' misconceptions in chemical equilibrium. *Journal of Chemical Education*, 101(2), 456–468.

Sutiani, A., Situmorang, M., &Silalahi, A. (2021). Implementation of an Inquiry Learning Model with Science Literacy to Improve Student Critical Thinking Skills. *International Journal of Instruction*, *14*(2), 117–138. https://doi.org/10.29333/iji.2021.1428a

Taber, K. S. (2022). *Teaching and learning chemistry in higher education and secondary schools: A guide to contemporary practice*. Springer. https://doi.org/10.1007/978-3-030-98761-6

Taber, K. S. (2022). *Teaching and learning chemistry in school: A guide to understanding chemical concepts and misconceptions*. Springer Nature. https://doi.org/10.1007/978-3-030-99834-5

Talanquer, V. (2011). Macro, submicro, and symbolic: The many faces of the chemistry "triplet". International Journal of Science Education, 33(2), 179–195. https://doi.org/10.1080/09500690903386435

Tanryale, M. H., Astija, Kundera, I. N., Nurchamidah, &Hamsah, M. (2025). Implementing of Inquiry Model Based on Technology to Increase Scientific Literacy and Critical Thinking. *JurnalPendidikan Dan Pengajaran*, *58*(2), 304–315. https://doi.org/10.23887/jpp.v58i2.92019

Tinoca, L., Piedade, J., Santos, S., Pedro, A., & Gomes, S. (2022). Design-Based Research in the Educational Field: A Systematic Literature Review. *Education Sciences*. https://doi.org/10.3390/educsci12060410

Treagust, D. F., Chandrasegaran, A. L., Crowley, S., Ong, W.-L., Chang, T.-S., &Cheong, I.-P.-A. (2011). Evaluating students' understanding of chemical equilibrium using a two-tier diagnostic instrument. Research in Science & Technological Education, 29(3), 297–315.

Urdanivia Alarcon, D. A., Talavera-Mendoza, F., RucanoPaucar, F. H., Cayani Caceres, K. S., &MachacaViza, R. (2023). Science and inquiry-based teaching and learning:

a systematic review. *Frontiers in Education*, *8*. https://doi.org/10.3389/feduc.2023.1170487

Vaezi, H., Moonaghi, H., &Golbaf, R. (2019). Design-Based Research: Definition, Characteristics, Application and Challenges. *Journal of Education in Black Sea Region*. https://doi.org/10.31578/jebs.v5i1.185

Vilela, M., Morais, C., &Paiva, J. C. (2025). Inquiry-Based Science Education in High Chemistry: Enhancing Oral and Written Communication Skills through Authentic and Problem-Based Learning Activities. *Education Sciences*, *15*(3), 334. https://doi.org/10.3390/educsci15030334

Vosniadou, S. (2019). The development of students' understanding of science. In K. Sawyer (Ed.), The Cambridge handbook of the learning sciences (2nd ed., pp. 318–334). Cambridge University Press.

Wale, B. D., &Bishaw, K. S. (2020). Effects of using inquiry-based learning on EFL students' critical thinking skills. *Asian-Pacific Journal of Second and Foreign Language Education*, *5*(1), 9. https://doi.org/10.1186/s40862-020-00090-2

Xu, J., Abdullah, Z., &Samah, N. A. (2024). Views of design students on improvements in critical thinking through PBL in China's HyFlex environment. International Journal of Online Pedagogy and Course Design, 14(1), 1–17.

Yadav, A. R., & Singh, C. K. (2026). An Exploration of Teaching Strategies That Promote Problem-Solving and Higher-Order Thinking Skills. *International Journal of Engineering Science & Humanities*, *16*(1), 100-109.

Zhao, Y., & Zheng, Y. (2026). Effects of elaborative and metacognitive feedback on students' science achievement, epistemological beliefs, and inquiry behaviors in simulation-based science inquiry learning. Interactive Learning Environments, 1–19. https://doi.org/10.1080/10494820.2026.2638487

Appendices

One : pre-test instrument for chemical equilibrium unit

Critical Thinking Test Questions

Topic: Chemical Equilibrium (Grade 11)

Instructions to Students

Answer all questions carefully.

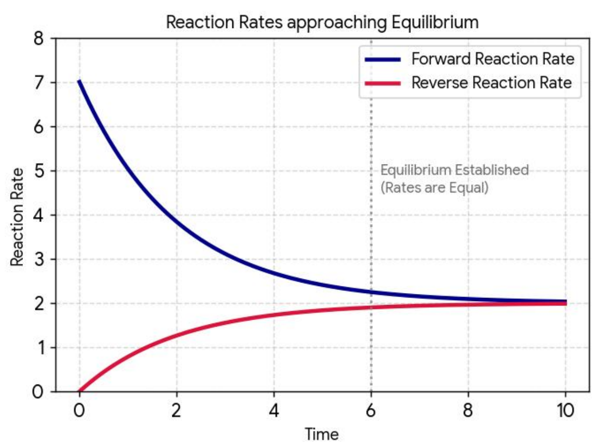
Show your reasoning and explain your answers clearly.

Use chemical concepts to justify your responses.

Part I: Understanding the Concept of Equilibrium (7.5 Marks)

Problem1. In a closed container the following reaction takes place:

$N_2 (g) + 3H_2 (g) \rightleftharpoons 2NH_3 (g)$



a) Explain what is meant by chemical equilibrium in this reaction.

b) What happens to the rate of the forward reaction and the reverse reaction when equilibrium is reached?

Problem2. A student says:

"*When a reaction reaches equilibrium, the reaction stops.*''

Do you agree or disagree with this statement?

Explain your answer using scientific reasoning.

<u>Part II: Application of Le Chatelier's Principle (7.5 Marks)</u>

Problem3. Consider the equilibrium reaction:

$CO_{(g)} + H_2O\ (g) \rightleftharpoons CO_2\ (g) + H_2\ (g)$

Predict what will happen to the equilibrium position when:

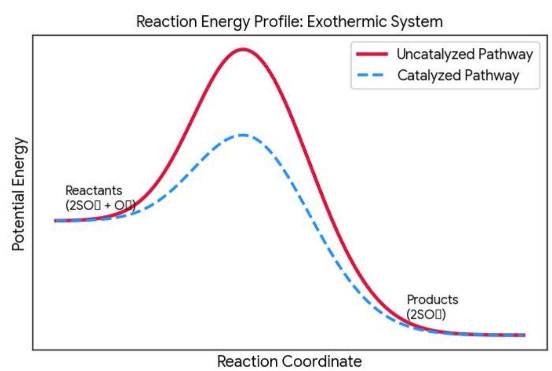
a) More CO gas is added.

b) Some H_2 gas is removed from the system.

c) The pressure of the system increases.

Problem4. The following reaction is at equilibrium:

$2SO_2\ (g) + O_2\ (g) \rightleftharpoons 2SO_3\ (g)$



Explain what will happen if:

a) The temperature increases.

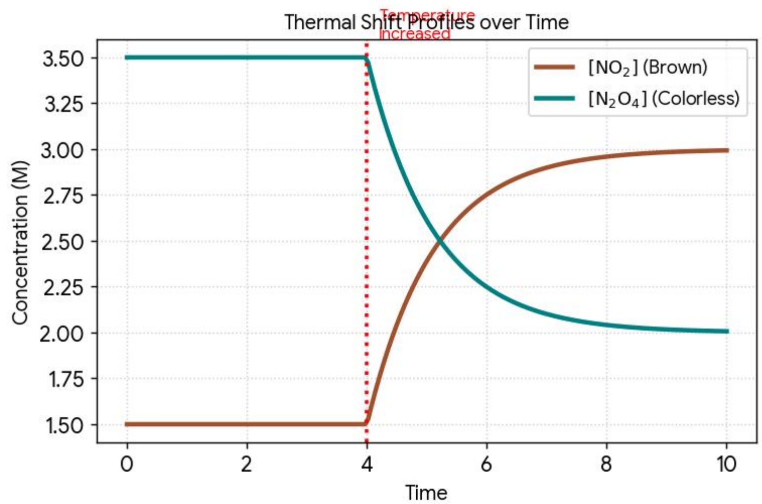
b) A catalyst is added.

Provide justification for your answer.

Part III: Interpretation of Experimental Observations (7.5 Marks)

Problem5. The following equilibrium reaction occurs in a closed container:

$2NO_2 (g) \rightleftharpoons N_2O_4 (g)$



The gas NO_2 is brown, while N_2O_4 is colorless.

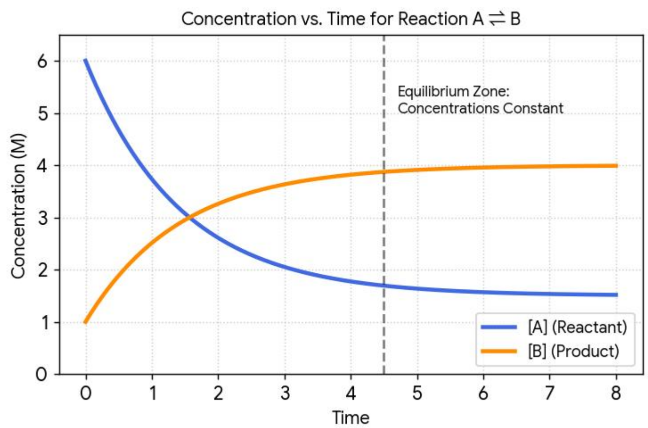
During an experiment the temperature is increased and the brown color becomes darker.

a) What does this observation suggest about the direction of the equilibrium shift?

b) Based on the observation, determine whether the forward reaction is endothermic or exothermic. Explain your reasoning.

Problem 6. A graph shows the concentration of substances A and B over time for the reaction:

$A \rightleftharpoons B$



At the beginning, the concentration of A decreases while the concentration of B increases. After some time, both concentrations become constant.

a) .What does the constant concentration indicate about the reaction?

b). Does the reaction stop when equilibrium is reached? Explain.

Part IV: Evaluation and Scientific Argument (7.5 Marks)

Problem 7. The Haber process is used to produce ammonia in industry.

N_2 (g) + $3H_2$ (g) $\rightleftharpoons$ $2NH_3$ (g)

Industrial chemists use high pressure and moderate temperature.

Explain why these conditions are used to increase ammonia production.

Problem8. A student claims:

"If the equilibrium constant (Kc) is greater than 1, the reaction will go to completion."

Evaluate this statement and explain whether it is correct or incorrect.

Multi-tier diagnostic multiple choice questions for the chemical equilibrium unit

Instructions:

For each question**:**

- Time: 1hr
- Total item: 20
- Choose the correct answer (Tier 1)
- Indicate your confidence in your answer (Tier 2)
- Choose the reason that best explains your answer (Tier 3)
- Indicate your confidence in your reason (Tier 4)
- Confidence Levels:

C = Certain , **NC** = Not Certain

Section A: Multiple Choice Questions (20 marks)

Problem 1 **(Tier 1). When additional reactant is added to a system at equilibrium, the equilibrium will:**

Shift toward the products
B. Shift toward the reactants
C. Remain unchanged
D. Stop the reaction

Confidence in Answer (Tier 2): C ☐ NC ☐

Reason (tier 3)

A. A system at equilibrium responds to disturbances by reducing their effect.
B. Adding more particles always slows the forward reaction.
C. Equilibrium means reactants cannot change into products.
D. Increasing concentration decreases reaction speed.

Confidence in Reason (Tier 4): C ☐ NC ☐

Problem 2 **(Tier 1). What is the effect of a catalyst on equilibrium?**

It shifts equilibrium toward products

B. It shifts equilibrium toward reactants

C. It does not change equilibrium position

D. It increases equilibrium constant

Confidence level in answer (Tier 2): C ☐ NC ☐

Reason (tier 3):

A. A catalyst lowers activation energy for both forward and reverse reactions.

B. Catalysts increase product concentration.

C. Catalysts remove reactant molecules.

D. Catalysts increase the equilibrium constant.

Confidence level in Reason (Tier 4): C ☐ NC ☐

Problem 3 **(tier 1). Increasing pressure in a gaseous equilibrium favors:**

A. The side with more gas molecules

B. The side with fewer gas molecules

C. The liquid side

D. The solid side

Confidence level in answer (Tier 2): C ☐ NC ☐

Reason (Tier 3)

A. The system tends to reduce the effect of increased pressure.

B. Pressure increases the equilibrium constant.

C. Gas molecules are not affected by pressure.

D. Pressure increases only the forward reaction rate.

Confidence level in Reason (Tier 4): C ☐ NC ☐

Problem 4 (Tier 1). For an exothermic reaction, increasing temperature will:

A. Shift equilibrium to the right

B. Shift equilibrium to the left

C. Not affect equilibrium

D. Stop the reaction

Confidence level in answer (Tier 2): C ☐ NC ☐

Reason (tier 3)

A. Heat can be treated as part of the reaction when considering equilibrium.

B. Temperature only increases reaction speed.

C. Increasing temperature removes products.

D. Heat behaves like a catalyst.

Confidence level in Reason (Tier 4): C ☐ NC ☐

Problem 5 (Tier 1). Chemical equilibrium is called dynamic because:

A. The reaction stops

B. Only forward reaction occurs

C. Forward and reverse reactions occur simultaneously

D. Products replace all reactants

Confidence level in answer (Tier 2): C ☐ NC ☐

Reason (tier 3)

A. Reactant and product molecules continue reacting even when concentrations remain constant.

B. Molecules stop moving at equilibrium.

C. Only products react after equilibrium.

D. All reactants disappear.

Confidence level in Reason (Tier 4): C ☐ NC ☐

Problem 6 (Tier 1). Which factor always changes the equilibrium constant?

A. Pressure

B. Temperature

C. Concentration

D. Catalyst

Confidence level in answer (Tier 2): C ☐ NC ☐

Reason (tier 3)

A. Temperature changes the energy balance of the reaction.

B. Pressure determines reaction speed.

C. Catalysts determine equilibrium position.

D. Concentration affects equilibrium constant.

Confidence level in Reason (Tier 4): C ☐ NC ☐

Problem 7 (Tier 1). A reaction shifts to the right when heat is added. The reaction **is:**

A. Exothermic

B. Endothermic

C. Neutral

D. Catalyzed

Confidence level in answer (Tier 2): C ☐ NC ☐

Reason (Tier 3)

A. Heat can behave as a reactant or product depending on the reaction type.

B. Heat increases equilibrium constant only for exothermic reactions.

C. Heating always favors product formation.

D. Heat removes reactants.

Confidence level in Reason (Tier 4): C ☐ NC ☐

Problem 8 (Tier 1). Removing a product from a system at equilibrium will:

A. Shift equilibrium toward products

B. Shift equilibrium toward reactants

C. Stop the reaction

D. Have no effect

Confidence level in answer (Tier 2): C ☐ NC ☐

Reason (tier 3)

A. The system tends to restore balance after a disturbance.

B. Products cannot reform once removed.

C. Removing products slows the forward reaction permanently.

D. Removing products decreases equilibrium constant.

Confidence level in reason (Tier 4): C ☐ NC ☐

Problem9 **(Tier 1). Pressure change has no effect when:**

A. Only gases are present

B. Equal numbers of gas molecules exist on both sides

C. Liquids are present

D. Solids are present

Confidence level in answer (Tier 2): C ☐ NC ☐

Reason (tier 3)

A. Pressure influence depends on the change in total gas particles.

B. Liquids determine gas pressure.

C. Solids control equilibrium shifts.

D. Pressure only changes reaction speed.

Confidence level in reason (Tier 4): C ☐ NC ☐

Problem 10 **(Tier 1). At equilibrium:**

A. Concentrations are always equal

B. Reaction stops

C. Forward and reverse reaction rates are equal

D. Products completely dominate

Confidence level in answer (Tier 2): C ☐ NC ☐

Reason (tier 3)

A. Equal reaction rates keep concentrations constant.

B. Reactions stop at equilibrium.

C. Products become stable and stop reacting.

D. Reactants disappear completely.

Confidence level in reason (Tier 4): C ☐ NC ☐

Problem 11(Tier 1). Which statement best describes the equilibrium constant (K) of a reaction?

A. It changes with concentration

B. It changes with temperature

C. It changes with catalyst

D. It changes with pressure

Confidence level in answer (Tier 2): C ☐ NC ☐

Reason (tier 3)

A. The value of the equilibrium constant depends on the energy relationship between reactants and products.

B. Adding substances always changes the equilibrium constant.

C. Catalysts determine the value of equilibrium constants.

D. Pressure always controls equilibrium constants.

Confidence in Reason (Tier 4): C ☐ NC ☐

Problem 12 (Tier 1). In the Haber process:

$N_2 (g) + 3H_2 (g) \rightleftharpoons 2NH_3 (g)$

Increasing pressure will:

A. Increase ammonia formation

B. Decrease ammonia formation

C. Have no effect

D. Stop the reaction

Confidence level in answer (Tier 2): C ☐ NC ☐

Reason (tier 3)

A. Changes in pressure may favor the side that occupies less volume.

B. Pressure increases reaction speed only.

C. Pressure affects only solids and liquids.

D. Pressure removes nitrogen from the reaction.

Confidence level in reason (Tier 4): C ☐ NC ☐

Problem 13 (Tier 1). If the concentration of a reactant decreases, the equilibrium will:

A. Shift toward products

B. Shift toward reactants

C. Remain unchanged

D. Stop completely

Confidence level in answer (Tier 2): C ☐ NC ☐

Reason (tier 3)

A. A system at equilibrium tends to counteract disturbances imposed on it.

B. Removing substances increases equilibrium constant.

C. Equilibrium systems cannot respond to concentration changes.

D. Concentration changes stop reactions.

Confidence level in reason (Tier 4): C ☐ NC ☐

Problem 14 (Tier 1). For the reaction

$$2SO_2\ (g) + O_2\ (g) \rightleftharpoons 2SO_3\ (g)$$

Increasing pressure will favor:

A. Formation of SO_2

B. Formation of SO_3

C. Decomposition of SO_3

D. No change

Confidence level in answer (Tier 2): C ☐ NC ☐

Reason (tier 3)

A. Systems under higher pressure tend to reduce the number of gas particles.

B. Pressure increases equilibrium constant.

C. Pressure only changes temperature.

D. Pressure affects liquids but not gases.

Confidence level in reason (Tier 4): C ☐ NC ☐

Problem 15 (Tier 1). When a catalyst is added to a reaction at equilibrium:

A. Product concentration increases permanently

B. Reactant concentration increases

C. Equilibrium position remains unchanged

D. Reaction stops

Confidence level in answer (Tier 2): C ☐ NC ☐

Reason (tier 3)

A. Catalysts provide an alternative reaction pathway.

B. Catalysts increase equilibrium constant.

C. Catalysts convert reactants directly into products.

D. Catalysts remove activation energy completely.

Confidence level in reason (Tier 4): C ☐ NC ☐

Problem 16 (Tier 1). The reaction quotient Q is used to:

A. Determine whether a reaction is at equilibrium

B. Determine reaction rate

C. Calculate activation energy

D. Measure temperature changes

Confidence level in answer (Tier 2): C ☐ NC ☐

Reason (tier 3)

A. Comparing reaction conditions with equilibrium conditions indicates the direction a reaction may proceed.

B. Reaction quotient determines catalyst activity.

C. Reaction quotient measures reaction speed.

D. Reaction quotient determines temperature effects.

Confidence level in reason (Tier 4): C ☐ NC ☐

Problem 17 (Tier 1). If $Q < K$, the reaction will:

A. Proceed toward products

B. Proceed toward reactants

C. Remain unchanged

D. Stop

Confidence level in answer (Tier 2): C ☐ NC ☐

Reason (tier 3)

A. The system may adjust until the reaction quotient becomes equal to the equilibrium constant.

B. Reactions stop when Q is smaller than K.

C. Reaction quotient always equals equilibrium constant.

D. Catalysts determine the direction of reactions.

Confidence level in reason (Tier 4): C ☐ NC ☐

Problem 18 (Tier 1). Which change increases the rate of both forward and reverse reactions without affecting equilibrium position?

A. Increasing pressure

B. Adding catalyst

C. Increasing concentration

D. Increasing temperature

Confidence level in answer (Tier 2): C ☐ NC ☐

Reason (tier 3)

A. Some substances can reduce activation energy of reactions.

B. Reaction rate determines equilibrium constant.

C. Concentration determines equilibrium constant.

D. Pressure determines reaction speed only.

Confidence level in reason (Tier 4): C ☐ NC ☐

Problem 19 (Tier 1). In a system at equilibrium, concentrations of reactants and products:

A. Continue changing rapidly

B. Remain constant over time

C. Become equal

D. Become zero

Confidence level in answer (Tier 2): C ☐ NC ☐

Reason (tire 3)

A. Equal reaction rates keep concentrations stable even though reactions continue.

B. Reactions stop completely at equilibrium.

C. Products become more stable than reactants.

D. Reactants disappear completely.

Confidence level in reason (Tier 4): C ☐ NC ☐

Problem 20 (Tier 1). Which condition would most likely shift equilibrium toward reactants?

A. Increasing product concentration

B. Removing products

C. Adding catalyst

D. Increasing pressure

Confidence level in answer (Tier 2): C ☐ NC ☐

Preseason (tier 3)

A. A system may respond to disturbances by opposing them.

B. Catalysts determine equilibrium position.

C. Pressure always favors products.

D. Products cannot influence equilibrium.

Confidence level in reason (Tier 4): C ☐ NC ☐

Pre-test and post-test results

No	Name Of Students	Pre-Test Result Out Of 50	Post- Test Result Out Of 50
1.	S1	45	50
2.	S2	21.5	43
3.	S3	20	41
4.	S4	16	38.5
5.	S5	42	48
6.	S6	34	45.5
7.	S7	28	40.5
8.	S8	37	46
9.	S9	33	41
10.	S10	35.5	43
11.	S11	22	39.5
12.	S12	24	40
13.	S13	32.5	44
14.	S14	30.5	42
15.	S15	25	43.5
16.	S16	29	39
17.	S17	26	41
18.	S18	24	40
19.	S19	22	44
20.	S20	18	36
21.	S21	19.9	39

22.	S22	19	38.5
23.	S23	25.5	41.5
24.	S24	38	47
25.	S25	41	49
26.	S26	36	43
27.	S27	31.5	40
28.	S28	37.5	45
29.	S29	29.5	42.5
30.	S30	36	48

C. Semi-structured interview Questions

Theme 1: Critical Thinking Development

1. Can you tell me about a time during the chemical equilibrium lessons when you had to think carefully before answering a question or solving a problem?

i. What made the task challenging?

ii. How did you decide on your answer?

1 (Critical Thinking)

1.

?

- ?
- ?

2. How did the activities in the lessons help you explain your ideas, justify your answers, or evaluate different explanations?

i. Can you give a specific example?

2.

?

3. ?

Theme 2: Inquiry-Based Learning Experience

3. How did conducting investigations, asking questions, and discussing ideas with your classmates affect the way you learned chemical equilibrium?

i. Which learning activity helped you the most? Why?

3.

?

- ? ?

4. Compared with your previous chemistry lessons, what was different about learning through the DB–IBL approach?

i. How did these differences influence your participation and learning?

4. DB – IBL

?

- ?

Theme 3: Conceptual Understanding

5. How has your understanding of chemical equilibrium changed after participating in the DB–IBL lessons?

i. Were there any ideas that you misunderstood before but understand better now?

5. DBR – IBL ?

- ?

6. Which concept in chemical equilibrium became clearer to you through the activities and experiments?

i. What specifically helped you understand that concept?

6. -

?

- ?

Theme 4: Reflection on Learning

7. What aspects of the DB–IBL lessons did you enjoy the most, and why?

i. How did those experiences help you learn?

7. DB – IBL ? ?

- ?

8. Did you face any difficulties while carrying out the inquiry activities or experiments?

i. How did you overcome those difficulties?

8. ?

- ?

9. Do you think these lessons improved your ability to solve new chemistry problems or explain scientific ideas? Why or why not?

i. Can you share an example?

9.

?

- ?

10. If you were given the opportunity to learn other chemistry topics using this approach, what would you suggest keeping or improving?

i. Why do you think those changes would be helpful?

10.

?

-

D. Sample Interview Transcripts

Theme 1: Critical Thinking Development

Researcher: Can you tell me about a time during the chemical equilibrium lessons when you had to think carefully before answering a question or solving a problem?

S1: During the soft drink experiment, we were asked to explain why bubbles formed when the bottle was opened. At first, I was not sure of the answer. I thought it was just because air entered the bottle. After discussing with my group and looking at what happened in the experiment, I understood that the pressure changed and affected the equilibrium.

Researcher: What made the task challenging?

S1: The difficult part was explaining the reason behind the observation. We had to think about the chemistry, not only what we saw.

Researcher: How did you decide on your answer?

S1: I used the evidence from the experiment and what we learned about Le Chatelier's Principle.

Researcher: How did the lesson activities help you explain your ideas?

S1: The teacher always asked us to explain our answers. This helped me think more carefully and give reasons for my ideas.

Researcher: Can you describe a situation where you had to think critically during the lessons?

S2: In one activity, we had to predict what would happen when the concentration of a reactant increased. Different students had different answers, so we had to discuss and decide which explanation made the most sense.

Researcher: How did you reach your conclusion?

S2: We compared our ideas and checked them against the results of the experiment.

Researcher: Did the activities help you evaluate different explanations?

S2: Yes. Before, I usually accepted the first answer. During these lessons, I learned to compare different ideas and choose the one supported by evidence.

Theme 2: Inquiry-Based Learning Experience

Researcher: How did conducting investigations and discussing ideas with classmates affect your learning?

S3: It helped me understand the lesson better because I could see what was happening and talk about it with others. Sometimes my classmates explained ideas in a way that was easier for me to understand.

Researcher: Which learning activity helped you the most?

S3: The experiments helped me most because they showed how the concepts worked in real situations.

Researcher: How was this different from your previous chemistry lessons?

S3: Before, the teacher explained most of the content. In these lessons, we had to investigate and find answers ourselves.

Researcher: How did this affect your participation?

S3: I participated more because I had a role in the group activities and discussions.

Researcher: How did the inquiry activities influence your learning?

S4: The activities made learning more interesting. Instead of only listening, we were involved in solving problems and discussing ideas.

Researcher: Which activity helped you most?

S4: Group discussions helped me most because we learned from each other.

Researcher: What was different about the DB–IBL lessons?

S4: We asked more questions and worked together to find answers.

Researcher: How did this affect your learning?

S4: It helped me understand the concepts more clearly and remember them better.

Theme 3: Conceptual Understanding

Researcher: How has your understanding of chemical equilibrium changed after participating in the DB–IBL lessons?

S5: Before these lessons, I thought equilibrium meant that the reaction stopped. Now I understand that the forward and reverse reactions continue, but they occur at the same rate.

Researcher: Were there any ideas you misunderstood before?

S5: Yes. I thought equilibrium meant equal amounts of reactants and products. Now I know that this is not always true.

Researcher: Which concept became clearer through the activities?

S5: Dynamic equilibrium became much clearer.

Researcher: What helped you understand it?

S5: The experiments and class discussions helped me connect the theory with what I observed.

Researcher: How has your understanding of chemical equilibrium changed?

S6: I now understand that equilibrium can change when conditions such as pressure, concentration, or temperature change.

Researcher: Which concept became clearer to you?

S6: Le Chatelier's Principle became easier to understand.

Researcher: What helped you understand it?

S6: The soft drink experiment helped me see how pressure affects equilibrium.

Researcher: Did the activities correct any misconceptions?

S6: Yes. Before, I memorized the principle, but now I understand how it works in real situations.

Theme 4: Reflection on Learning

Researcher: What aspects of the DB–IBL lessons did you enjoy most?

S7: I enjoyed the experiments and group discussions because they made the lessons more interesting.

Researcher: How did these experiences help you learn?

S7: They helped me understand difficult concepts through observation and discussion.

Researcher: Did you face any difficulties?

S7: At first, I was not confident when sharing my ideas.

Researcher: How did you overcome those difficulties?

S7: My classmates encouraged me, and I became more comfortable speaking during discussions.

Researcher: Do you think these lessons improved your ability to solve chemistry problems?

S7: Yes. I learned how to think about a problem and explain my answer rather than just memorizing information.

Researcher: What did you enjoy most about the lessons?

S8: I liked discovering answers through experiments and investigations.

Researcher: Did you experience any challenges?

S8: Sometimes it was difficult to explain my thinking, especially at the beginning.

Researcher: How did you overcome those challenges?

S8: The more we practiced, the easier it became to explain and defend our ideas.

Researcher: If this approach were used in other chemistry topics, what would you suggest?

S8: I would like to see more experiments because they help students understand concepts more easily.

Researcher: Why would that be helpful?

S8: Experiments make learning more active and help students connect theory with practical.

E. Finalized Qualitative Codebook

Code	Description	Example Evidence
Evidence-Based Reasoning	Students used observations, experimental findings, or scientific concepts to support their answers and explanations.	Students referred to experimental results and Le Chatelier's Principle when explaining their conclusions.
Analysis of Explanations	Students considered, compared, and evaluated different explanations before deciding on the most appropriate one.	During group discussions, students explored alternative explanations before reaching a conclusion.
Prediction and Justification	Students predicted what might happen in a situation and explained the reasoning behind their predictions.	Students predicted shifts in equilibrium and provided scientific reasons for their responses.
Collaborative Learning	Students learned through interaction with peers, including discussion, cooperation, and sharing ideas.	Students reported that group discussions helped them better understand difficult concepts.
Active Participation	Students became more engaged in classroom activities, discussions, and investigations.	Students described contributing ideas and taking part actively during inquiry-based activities.
Dynamic Equilibrium	Students understood that forward and reverse	Students demonstrated a clearer understanding by

Understanding	reactions continue simultaneously at equal rates in equilibrium.	correcting earlier misconceptions about equilibrium.
Conceptual Change	Students replaced incorrect prior ideas with scientifically accepted explanations.	Students explained how their understanding of equilibrium concepts had changed during the lessons.
Understanding Le Chatelier's Principle	Students understood how changes in concentration, pressure, or temperature affect a system at equilibrium.	Students used experimental observations to explain equilibrium shifts according to Le Chatelier's Principle.
Increased Confidence	Students showed greater confidence in expressing, explaining, and defending their ideas.	Students reported feeling more comfortable participating in discussions and sharing their opinions.
Initial Learning Challenges	Students experienced difficulties when first adapting to inquiry-based learning activities.	Students mentioned struggling initially with explaining their ideas or participating in discussions.
Improved Problem-Solving Ability	Students developed stronger skills in analyzing situations and solving unfamiliar chemistry problems.	Students described relying more on reasoning and understanding rather than memorization.
Positive Perception of DB–IBL	Students expressed positive views about the inquiry-based learning approach and its benefits.	Students suggested that the approach should be used in other chemistry topics because it supported their learning.

Theme Definitions

Theme	Definition
Critical Thinking Development	How students improved their ability to think critically by analyzing information, evaluating different explanations, using evidence, and justifying their conclusions when solving chemical equilibrium problems.
Inquiry-Based Learning Experience	Students' experiences of learning through asking questions, carrying out investigations and experiments, working with peers, and actively participating in the DBR–IBL activities.
Conceptual Understanding	The ways in which students' understanding of chemical equilibrium changed, including overcoming misconceptions and developing more accurate scientific explanations.
Reflection on Learning	Students' views about their learning experiences, including their confidence, challenges faced, development of problem-solving skills, and suggestions for improving the learning process.

Illustrative Quotations by Theme

Theme	Participant	Illustrative Quotation
Critical Thinking Development	S1	"Before answering, I had to think about the evidence from the experiment and explain why the equilibrium changed. This helped me think more carefully instead of just guessing the answer."
Inquiry-Based Learning Experience	S3	"The experiments and group discussions helped me learn better because I could observe what was happening and share ideas with my classmates."
Conceptual Understanding	S5	"Before these lessons, I thought equilibrium meant the reaction stopped completely. Now I understand that the forward and reverse reactions continue at the same rate even though no visible change is observed."
Reflection on Learning	S7	"At first, I was not confident to share my ideas, but through the activities and discussions I became more comfortable and confident in explaining my answers."

Table 1: paired samples t-Test results and effect size for pre-test and post-test scores (N = 30)

Assessment	M	SD	t	df	P	Cohen's d
Pre test	29.30	7.84	13.75	29	<.001	2.51
Post test	42.63	3.48				

Table2: Descriptive Statistics results

Descriptive Statistics									
	N	Minimum	Maximum	Mean	Std. Deviation	Skewness		Kurtosis	
	Statistc	Statistic	Statistic	Statistic	Statistic	Statistic	Std.Error	Statistic	Std. Error
pre-test result	30	16.0	45.0	29.297	7.8393	.153	.427	-.963	.833
post-test result	30	36.0	50.0	42.633	3.4788	.432	.427	-.442	.833
Valid N (listwise)	30								

Table 3. Validity and Reliability statistics of Critical Thinking Tests andChemical Equilibrium Diagnostic Test Instruments.

Instrument	Purpose	Number of Items	Reliability Method	Reliability Coefficient (α)	Interpretation
Critical Thinking Test	To assess students' critical thinking skills in chemical equilibrium	8	Cronbach's Alpha	0.809	Good
Chemical Equilibrium Diagnostic Test	To assess students' conceptual understanding of chemical equilibrium	20	Cronbach's Alpha	0.803	Good

F. Classroom Observation Checklist

Purpose: To evaluate the development of students' conceptual clarity, evidence-based reasoning, and critical thinking skills during the intervention cycles.

Observer Name:___________________

Date of Observation:_________________

Grade/Section:11th__________________________

No.	Observation Item	Yes	No	Comments
Conceptual Understanding				
1	Students explain the idea of reversible reactions in their own words.	✓		
2	Students recognize that chemical equilibrium is a dynamic process where reactions continue to occur.	✓		
3	Students understand that equilibrium does not mean the reaction has stopped.	✓		
4	Students explain that reactants and products do not need to be equal in amount at equilibrium.	✓		
5	Students correctly use equilibrium concepts during discussions and activities.	✓		
6	Students relate classroom activities or experiments to chemical equilibrium concepts.	✓		
7	Students predict and explain changes in equilibrium using Le Chatelier's principle.	✓		
Critical Thinking Skills				
8	Students ask thoughtful questions during the lesson.	✓		
9	Students make predictions before conducting an activity or investigation.	✓		
10	Students provide reasons or evidence to	✓		

	support their answers.		
11	Students analyze observations and explain what they mean.	✓	
12	Students compare different ideas before reaching a conclusion.	✓	
13	Students justify their explanations using scientific reasoning.	✓	
14	Students change or refine their ideas when new evidence is presented.	✓	
15	Students draw conclusions based on evidence gathered during activities.	✓	
Participation and Collaboration			
16	Students actively participate in group discussions.	✓	
17	Students share ideas and listen to the opinions of others.	✓	
18	Students work cooperatively to solve problems and complete tasks.	✓	
19	Students reflect on what they have learned at the end of the lesson.	✓	

Yes = Observed , *No* = Not Observed