

Establishing the Extent of Learners' Challenges in Comprehending and Assimilating the Basic Concepts of Chemical Formulae and Chemical Equations in General Chemistry

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Abstract: Chemical formulae and equations constitute the foundational symbolic language of chemistry, yet learners persistently demonstrate significant difficulties in their comprehension and application. This conceptual bottleneck has far-reaching implications for subsequent achievement in chemistry and related STEM disciplines. This study sought to empirically establish the extent, severity, and systemic nature of learners' challenges in comprehending and assimilating the basic concepts of chemical formulae and chemical equations in general chemistry. Situated within the pragmatic paradigm and operationalized through an embedded mixed methods design, the study employed a diagnostic assessment administered to fifty systematically selected Grade 11 learners. Descriptive statistics, benchmark-based performance categorization, and inferential hypothesis testing were triangulatively employed to determine both the existence and magnitude of learners' conceptual difficulties. The assessment instrument focused specifically on writing chemical formulae, interpreting subscripts and coefficients, applying valency principles, and balancing chemical equations. Results revealed a mean score of 23.52% (SD = 9.50), with 72% of learners falling within extremely poor to poor performance categories and none attaining the benchmark for good comprehension ($\geq 50\%$). A one-sample t-test confirmed that the observed mean was statistically significantly below the benchmark ($t = -19.72, p < .05$). Measures of dispersion indicated moderate variability (range = 35%) within an overall low-achievement band. The convergence of central tendency measures (mean = 23.52%, median = 22.00%, mode = 15.00%) confirmed cohort-wide conceptual fragility rather than isolated underachievement. The findings demonstrate that learners' difficulties are widespread, severe, and systemic, representing structural conceptual underdevelopment rather than episodic performance lapses. The study provides rigorous empirical grounding for pedagogical restructuring and targeted instructional scaffolding in foundational chemistry education, with implications extending to curriculum design, teacher professional development, and assessment practices.

Keywords: Diagnostic Assessment, Conceptual Assimilation, Chemical Formulae, Chemical Equations, Representational Competence, Chemistry Education.

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I. INTRODUCTION AND BACKGROUND

➤ *The Epistemological Significance of Chemical Symbolism*

Chemical formulae and chemical equations represent one of the most sophisticated symbolic systems in scientific discourse, functioning simultaneously as linguistic representations, mathematical expressions, and conceptual models that encode information about matter's composition,

structure, and transformations. This complexity is illuminated by Johnstone's (1982, 2000) seminal framework, which posits that chemistry operates across three interconnected levels: the macroscopic level of observable phenomena, the submicroscopic level of molecular and atomic entities, and the symbolic level of representational systems. Chemical formulae and equations occupy this symbolic level, serving as the critical bridge through which learners translate between

observable phenomena and particulate explanations, and this tripartite nature creates unique cognitive demands that distinguish chemistry from other scientific disciplines, rendering its symbolic language particularly challenging for novice learners.

Understanding chemical formulae and chemical equations is therefore fundamental to success in general chemistry, as these symbolic systems represent how matter is structured, combined, and conserved during chemical reactions. However, for many chemistry learners, these representations present significant cognitive challenges that extend well beyond mere memorization. Learners are simultaneously required to interpret subscripts as indicators of atomic ratios, coefficients as quantitative multipliers, valency relationships as electrostatic principles, and conservation principles as fundamental laws governing matter. This cognitive overload, compounded by the abstract nature of symbolic representation, frequently results in superficial procedural learning rather than deep conceptual understanding.

➤ *The Cognitive Demands of Symbolic Chemistry*

Contemporary cognitive science provides substantial insight into why chemical symbolism presents such formidable challenges. According to Sweller's (1988, 2010) Cognitive Load Theory, the intrinsic cognitive load of learning chemical formulae and equations is inherently high due to the element interactivity involved, learners must simultaneously process multiple interacting elements in form of subscripts, coefficients, valency, charge, state symbols, stoichiometric relationships that cannot be understood in isolation. When instructional approaches fail to manage this cognitive load through appropriate scaffolding and worked examples, learners experience cognitive overload, resulting in fragmented knowledge structures and procedural dependence.

Kozma and Russell (1997) and Stieff et al. (2021) demonstrate through their research on representational competence that novices in chemistry tend to process symbols at a surface level, focusing on procedural rules rather than developing deep mental models that connect symbols to underlying chemical principles. This surface processing manifests in characteristic error patterns, as learners may correctly balance equations through algorithmic manipulation while being unable to explain what the coefficients represent at the molecular level, or they may write correct formulae for simple compounds while failing to generalize to unfamiliar examples. Talanquer (2014) argues that this pattern indicates learners are operating at what might be termed a "rule-based" rather than "principle-based" level of understanding, where procedures are followed without comprehension of the underlying chemical logic.

➤ *The Zambian Context and Educational Significance*

The challenges of chemical symbolism are not confined to any particular educational context, but their manifestation and consequences are shaped by local conditions. In the Zambian educational system, chemistry is a core subject in the science curriculum, with significant implications for

career pathways in health sciences, engineering, environmental science, and technology. The Examinations Council of Zambia's comprehensive analysis of 2021-2023 Grade 12 and GCE examination results reveal persistent underperformance in items requiring the writing of chemical formulae and balancing of chemical equations. This weakness is often attributed to poor understanding of bonding, valency, and formula-writing rules, foundational concepts that are typically introduced in Grade 10 and form the basis for all subsequent chemistry learning.

Mumba and Chirwa (2022) identify multiple interrelated factors contributing to this situation: limited educational resources, inconsistent teacher expertise, particularly in rural and underserved areas, overcrowded classrooms, inadequate laboratory facilities for practical reinforcement, over-reliance on teacher-centered instructional approaches, insufficient continuous professional development for teachers, and limited exposure to remedial and practice-oriented activities. Additionally, low learner motivation, poor foundational knowledge from earlier grades, and insufficient instructional time for complex abstract concepts contribute to persistent misconceptions and errors. Without targeted intervention, these difficulties will continue to hinder chemistry achievement and weaken foundational scientific knowledge essential for national development.

➤ *Research Problem and Rationale*

While the existence of learner difficulties in chemical formulae and equations is widely acknowledged in both international literature and local examination data, there remains a significant gap in empirical evidence regarding the *extent* and *severity* of these challenges within specific educational contexts. As Cooper and Stieff (2021) note, many educational interventions are designed based on generalized assumptions about learner difficulties without systematic diagnostic assessment. This study addresses this gap by providing rigorous empirical evidence of the magnitude of the problem, thereby establishing a foundation for evidence-based pedagogical intervention.

The problem is conceptualized as operating at multiple levels, encompassing cognitive factors such as the inherent difficulty of symbolic representation, instructional factors relating to the effectiveness of teaching approaches, curricular factors concerning the sequencing and scaffolding of concepts, and systemic factors including resource availability, teacher preparation, and assessment practices. Understanding the relative contribution of these factors requires systematic investigation that moves beyond anecdotal observation to empirical verification. This study contributes to this understanding by establishing the baseline extent of learner difficulties, enabling subsequent research to identify causal factors and evaluate intervention effectiveness.

➤ *Purpose and Significance of the Study*

This study aimed to empirically establish the systemic nature and magnitude of learners' conceptual difficulties with chemical formulae and equations, relative to a

comprehension benchmark, and to generate evidence for instructional reform.

By employing diagnostic assessment and rigorous statistical analysis, the study provides empirical evidence that moves beyond generalized concern to quantifiable verification. This evidence has significance for multiple stakeholders: teachers, who require diagnostic information to inform their instruction; curriculum developers, who need evidence of learner difficulties to guide curriculum reform; teacher educators, who must prepare teachers to address these challenges; and policymakers, who require empirical justification for resource allocation and educational reform.

II. LITERATURE REVIEW

➤ *Theoretical Framework: Cognitive and Representational Perspectives*

The theoretical grounding of this study draws from three interconnected frameworks: Cognitive Load Theory (CLT), the Representational Competence Framework, and Johnstone's Tripartite Model of Chemistry Learning. These frameworks provide complementary lenses for understanding why learners struggle with chemical symbolism and how these struggles might be addressed.

Cognitive Load Theory Sweller (1988, 2010) posits that working memory has limited capacity, and learning is optimized when instructional design manages cognitive load appropriately. The intrinsic cognitive load of chemical formulae arises from the high element interactivity involved; learners must simultaneously process multiple interacting elements. Extraneous cognitive load, which does not contribute to learning, can be reduced through well-designed instruction that eliminates unnecessary complexity and provides clear guidance. Germane cognitive load, which contributes to schema construction, can be enhanced through activities that promote deep processing and integration of new knowledge with existing schemas. In the context of chemical formulae and equations, effective instruction must therefore manage intrinsic load through progressive sequencing, reduce extraneous load through clear and consistent representations, and enhance germane load through activities that promote conceptual integration.

• *The Representational Competence Framework*

The representational competence framework proposed by Kozma and Russell (1997) and further developed by Stieff et al. (2021) emphasizes that expertise in chemistry requires the ability to translate between and among multiple representations, macroscopic phenomena, submicroscopic entities, and symbolic representations. Representational competence involves understanding what symbols represent, being able to generate appropriate representations, and being able to transform between representations. Novice learners typically demonstrate limited representational competence, treating symbols as objects to be manipulated rather than as representations of underlying chemical reality. Development of representational competence requires explicit instruction in the meaning of symbols and their relationship to other

representations, practice in translating between representations, and feedback that corrects misconceptions.

Johnstone's Tripartite Model (1982, 2000) provides a discipline-specific framework for understanding the unique challenges of chemistry learning. According to this model, chemistry operates at three levels: the macroscopic which represents observable phenomena that can be seen, touched, or smelled, the submicroscopic representing the molecular, atomic, and ionic entities that cannot be directly observed, and the symbolic representations such as formulae, equations, and diagrams. Effective chemistry learning requires the ability to move fluidly among these levels, translating between macroscopic observations and submicroscopic explanations through the symbolic language of chemistry. Difficulties arise when learners attempt to operate at one level without understanding its relationship to the others, or when they confuse representations across levels. The symbolic level is particularly challenging because it requires abstract thinking and the ability to manipulate representations that have no direct perceptual referents.

➤ *Empirical Studies on Learner Difficulties with Chemical Formulae and Equations*

A substantial body of empirical research has documented learner difficulties with chemical formulae and equations, though the *extent* and *severity* of these difficulties vary across contexts and methodological approaches.

• *International Perspectives:*

Yarroch (1985) conducted one of the early systematic studies of student difficulties with chemical equations, finding that students who could correctly balance equations often could not explain what the equations represented, a finding that has been replicated in subsequent research. This dissociation between procedural competence and conceptual understanding has become a central theme in chemistry education research. Subsequent studies have identified specific patterns of difficulty, including problems with subscripts and coefficients, confusion between macroscopic and symbolic representations, and failure to conserve atoms in chemical reactions. These specific challenges have been documented across multiple investigations, with Dori and Hameiri (2003) highlighting the difficulties learners encounter with subscripts and coefficients, Taber (2013) drawing attention to the persistent confusion between macroscopic and symbolic representational levels, and Gulacar et al. (2015) reporting on the widespread failure to conserve atoms when balancing chemical equations.

More recent research has used increasingly sophisticated diagnostic methods to characterize learner difficulties. Villafañe and Lewis (2022) developed and validated a diagnostic instrument specifically for chemical equation reasoning, identifying three distinct dimensions of understanding: symbolic interpretation, stoichiometric reasoning, and conceptual application. Their research revealed that learners often demonstrate competence in one dimension while struggling in others, suggesting that understanding of chemical equations is multidimensional and not reducible to a single skill. Knaus et al. (2022) used

representational analysis to explore student difficulties with balancing equations, finding that learners frequently rely on procedural algorithms without understanding the underlying conservation logic.

Hamerská et al. (2024) conducted a comprehensive investigation of procedural versus conceptual understanding in balancing chemical equations, finding that many students can successfully balance equations through pattern matching and algorithm application, but struggle to explain the chemical meaning of balanced equations or to apply balancing principles to novel contexts. This dissociation between procedural and conceptual understanding has significant implications for instruction, suggesting that teaching balancing procedures without developing conceptual understanding yields fragile knowledge that does not transfer to new situations.

- *Representational Competence and Spatial Reasoning*

Stieff et al. (2021) investigated the role of spatial reasoning in chemistry problem solving, finding that spatial ability predicts success in tasks requiring the coordination of multiple representations. Learners with strong spatial reasoning are better able to translate between symbolic and submicroscopic representations, suggesting that representational competence is partially dependent on general cognitive abilities. This finding has implications for instruction, suggesting that visual and spatial strategies may benefit learners with weaker spatial abilities.

- *Misconceptions and Alternative Conceptions:*

Research on misconceptions in chemistry has identified characteristic alternative conceptions that learners develop about chemical formulae and equations. Taber (2013) identified a range of common misconceptions, including confusion between subscripts and coefficients, failure to recognize that coefficients apply to all atoms in a formula, and the belief that equations represent recipes rather than conservation laws. These misconceptions are often resistant to traditional instruction and require explicit conceptual change strategies to address.

- *African Context Studies*

Limited research has been conducted on learner difficulties with chemical symbolism in African contexts, though available studies suggest similar patterns of difficulty compounded by resource constraints and instructional quality issues. Ogunniyi (2007) identified challenges in chemistry learning in sub-Saharan Africa, noting that limited laboratory resources, large class sizes, and teacher-centered instruction contribute to procedural learning without conceptual understanding. Mumba and Chirwa (2022) specifically examined challenges in Zambian chemistry education, identifying the mismatch between the abstract nature of chemical concepts and concrete instructional approaches as a significant factor.

- *Diagnostic Assessment in Chemistry Education*

Diagnostic assessment has emerged as a powerful approach for identifying learner difficulties and informing instruction. Unlike summative assessments, which measure

achievement at the end of instruction, or formative assessments, which provide ongoing feedback during instruction, diagnostic assessments are specifically designed to identify specific conceptual difficulties and misconceptions.

- *The Role of Diagnostic Assessment*

Gierl and Bulut (2022) provide a comprehensive overview of diagnostic classification models in educational assessment, demonstrating how these approaches can provide fine-grained information about learner understanding. In chemistry education, diagnostic assessments have been used to identify specific misconceptions, characterize patterns of difficulty, and evaluate the effectiveness of instructional interventions. Seery (2015) advocates for the integration of diagnostic assessment into chemistry instruction, arguing that such assessment is essential for moving beyond surface-level learning and addressing deep conceptual difficulties.

- *Design and Validation of Diagnostic Instruments*

The development of valid and reliable diagnostic instruments in chemistry requires careful attention to both content validity (the extent to which items represent the construct being measured) and cognitive validity (the extent to which items elicit the intended cognitive processes). Villafañe and Lewis (2022) demonstrate a rigorous approach to instrument development, using expert review, cognitive interviews, and statistical analysis to ensure that items measure what they claim to measure. Such rigor is essential for diagnostic instruments that will be used to characterize learner difficulties and guide instruction.

- *Benchmarking and Interpretation*

Establishing appropriate benchmarks for interpreting diagnostic assessment results is crucial for determining the extent of learner difficulties. Leighton (2021) discusses the use of cognitive diagnostic assessment to inform instruction, emphasizing the importance of interpreting assessment results in terms of specific cognitive processes rather than global scores. In this study, we establish a benchmark of 50% as the threshold for good comprehension, a criterion-referenced standard that provides a meaningful basis for interpretation.

- *Instructional Interventions for Chemical Formulae and Equations*

The literature on instructional interventions for chemical formulae and equations is extensive, with approaches ranging from conceptual change strategies to procedural scaffolding to representational competence development.

- *Conceptual Change Approaches*

Conceptual change theory (Posner et al., 1982) suggests that learning occurs when learners recognize that their existing conceptions are inadequate and construct new understandings. In chemistry education, conceptual change approaches have been used to address misconceptions about formulae and equations, though with mixed success. Taber (2013) argues that conceptual change in chemistry requires

explicit attention to the intuitive and implicit assumptions that underpin misconceptions.

- *Representational Competence Instruction*

Instruction specifically designed to develop representational competence has shown promising results. Kozma and Russell (1997) developed representational competence instruction that explicitly teaches learners to translate between macroscopic, submicroscopic, and symbolic representations, finding that such instruction improves both conceptual understanding and procedural performance. Stieff et al. (2021) demonstrated that instruction incorporating visual and spatial strategies can improve representational competence, particularly for learners with weaker spatial abilities.

- *Scaffolding and Cognitive Load Management*

Research informed by Cognitive Load Theory suggests that effective instruction in chemical formulae and equations requires careful management of cognitive load through progressive sequencing, worked examples, and scaffolding. Sevan and Talanquer (2022) argue that chemistry instruction should be designed to manage cognitive load by decomposing complex tasks and providing appropriate support, gradually fading support as learners develop understanding.

- *Peer Instruction and Collaborative Learning*

Collaborative learning approaches, including peer instruction and problem-based learning, have been shown to improve understanding of chemical symbolism. Cooper and Stieff (2021) found that peer discussion and explanation promote deeper processing and more robust understanding, particularly when learners are required to explain their reasoning to others.

➤ *Gaps in the Literature and Rationale for the Present Study*

Despite extensive research on learner difficulties with chemical formulae and equations, several significant gaps remain:

- *Methodological Limitations*

Much of the existing research relies on small sample sizes, convenience sampling, or qualitative methods that do not allow for quantification of the extent or severity of difficulties. This limits the generalizability of findings and their utility for informing policy and practice.

- *Contextual Specificity*

Research has primarily been conducted in developed country contexts, particularly the United States and Europe. The extent to which findings generalize to developing country contexts, with their different educational resources and instructional traditions, is unclear.

- *Benchmark-Based Assessment*

Few studies have used explicit benchmarks to characterize the severity of learner difficulties. Without such benchmarks, it is difficult to determine whether observed difficulties represent minor gaps or systemic problems requiring major intervention.

- *Integration of Multiple Analytical Approaches*

Most studies rely on a single methodological approach, either descriptive statistics or qualitative analysis, without the triangulation that would strengthen conclusions.

- *Systemic Rather than Individual Characterization*

Research has tended to focus on individual learner difficulties without characterizing the extent to which difficulties are widespread across cohorts. Understanding the systemic nature of difficulties is essential for designing appropriate interventions.

The present study addresses these gaps by employing rigorous methodological procedures, including systematic sampling, benchmark-based assessment, and multiple analytical approaches (descriptive statistics, frequency analysis, and hypothesis testing) to establish the extent and severity of learner difficulties in the Zambian context.

III. METHODOLOGY

➤ *Philosophical Paradigm*

The study was grounded in the pragmatic paradigm, which emphasizes methodological flexibility and problem-oriented inquiry. Pragmatism was deemed appropriate because the investigation sought to generate actionable evidence capable of informing instructional improvement. The integration of quantitative precision with qualitative contextual interpretation allowed the research to remain both empirically rigorous and educationally relevant. As Creswell and Plano Clark (2018) argue, pragmatism provides a philosophical foundation for mixed methods research, allowing researchers to draw on the strengths of multiple approaches while mitigating their respective limitations.

The pragmatic orientation of this study is reflected in its methodological choices: the use of quantitative diagnostic assessment to establish the extent of learner difficulties, combined with qualitative reflection to contextualize findings and inform recommendations. This integration serves the pragmatic goal of generating evidence that is both reliable and relevant to educational practice.

➤ *Research Design*

An Embedded Design (ED), as articulated by Creswell and Plano Clark (2018), was employed. Within this mixed methods framework, one dataset assumes primacy while the other plays a supportive role. In this phase of the broader inquiry, quantitative diagnostic data constituted the primary dataset, while qualitative reflections supported contextual interpretation. Both strands were collected concurrently, though statistical analysis drove the determination of extent.

The embedded design was selected because it allows for the collection of both quantitative and qualitative data while maintaining a clear focus on the primary research aim. The diagnostic assessment provided the quantitative data necessary to establish the extent of learner difficulties, while qualitative observations during test administration and subsequent reflection informed the interpretation of findings and the development of recommendations.

➤ *Sampling and Participants*

• *Target Population*

The target population consisted of Grade 11 learners enrolled in general chemistry courses at a selected secondary school in Zambia. Grade 11 was chosen as the focus because learners at this level have completed introductory chemistry (Grades 8-10) and are expected to have developed foundational understanding of chemical formulae and equations. Challenges at this level are particularly significant because they indicate that earlier instruction has not achieved its intended outcomes.

• *Sample Size Determination*

To ensure an appropriate level of precision and statistical reliability of the collected data, Yamane's (1967) formula was used to determine the sample size for the study. The formula is expressed as:

$$n = \frac{N}{1 + N(e)^2}$$

Where n represents the sample size, N represents the total population size, and e represents the margin of error (level of precision).

In this study, the total population (N) consisted of approximately 100 Grade 11 learners. A marginal error of 5% ($e = 0.05$) was considered appropriate, balancing precision against practical constraints. The sample size was calculated as follows:

$$n = \frac{100}{1 + 100(0.05)^2}$$

$$n = \frac{100}{1 + 100(0.0025)}$$

$$n = \frac{100}{1 + 0.25}$$

$$n = \frac{100}{1.25}$$

$$n = 80$$

However, due to the application of Yamane's formula with the revised calculation, the sample size was adjusted to 50 learners. This adjustment was made to accommodate the specifics of the accessible population and ensure effective management of the research process.

• *Sampling Procedure*

Systematic sampling was employed to select the 50 participants from the accessible population. Learners were listed alphabetically, and every second learner on the list was selected. This systematic approach ensured a representative sample while maintaining the feasibility of data collection and analysis. The sample comprised 25 male and 25 female

learners, reflecting the gender distribution of the target population.

• *Participant Characteristics*

All participants were enrolled in general chemistry courses and had completed the foundational units on atomic structure, bonding, and chemical formulae. The participants represented a range of academic abilities, from high-achieving to struggling learners, reflecting the diversity of the target population. Participants were informed of the purpose of the study and provided informed consent prior to participation.

➤ *Instrumentation*

• *Diagnostic Assessment Development*

A diagnostic test graded out of 100 marks was developed to assess learners' ability to write and interpret chemical formulae and balance chemical equations. The test was designed to measure both procedural competence (the ability to correctly write formulae and balance equations) and conceptual understanding (the ability to explain and apply principles). The test items were developed based on the following principles:

• *Alignment with Curriculum Objectives*

Items were aligned with the Grade 10 and Grade 11 chemistry curriculum objectives for chemical formulae and equations.

• *Cognitive Demand*

Items ranged from simple recall of formula-writing rules to complex application of principles to unfamiliar situations, allowing differentiation of learner understanding.

• *Multiple Dimensions*

Items assessed multiple dimensions of understanding, including interpretation of subscripts and coefficients, application of valency principles, and understanding of conservation of matter.

• *Content Validity*

Items were reviewed by experienced chemistry teachers and subject specialists to ensure content validity.

• *Test Content*

The diagnostic test comprised the following sections:

• *Writing Chemical Formulae (40 marks)*

Items requiring learners to write formulae for compounds given their names, and to write names for compounds given their formulae. This section assessed understanding of valency, charge balance, and formula construction.

• *Interpreting Subscripts and Coefficients (20 marks)*

Items requiring learners to interpret the meaning of subscripts and coefficients in chemical formulae and equations. This section assessed understanding of the quantitative relationships represented in symbolic notation.

- *Balancing Chemical Equations (40 marks)*

Items requiring learners to balance chemical equations and explain their reasoning. This section assessed both procedural competence and conceptual understanding of conservation principles.

- *Benchmarking Framework*

Learners' performance was classified into six benchmark categories:

Table 1 Bench-Mark Categories of Learner-Performance

Score Range	Category	Interpretation
0-9%	Extremely Poor	No evidence of comprehension
10-19%	Very Poor	Minimal comprehension
20-29%	Poor	Limited comprehension
30-39%	Fair	Partial comprehension
40-49%	Fairly Good	Adequate but incomplete comprehension
50-100%	Good	Acceptable comprehension

Source: Field Data, 2026

The benchmark of 50% for good comprehension was established based on educational standards in the Zambian context, where 50% is generally considered the minimum passing threshold. This criterion-referenced standard provides a meaningful basis for interpreting learner performance as indicating either adequate or inadequate understanding.

➤ *Data Collection Procedures*

Data collection was conducted over a two-week period at the participating school. The following procedures were followed:

- *Ethical Approval and Consent*

Ethical approval was obtained from the University of Zambia Research Ethics Committee. Permission was obtained from the school authorities, and informed consent was obtained from participants and their parents/guardians.

- *Test Administration*

The diagnostic assessment was administered in a standardized manner to all participants. The assessment was conducted in a single session of 90 minutes, with clear instructions provided at the beginning. Participants were informed that the assessment was for research purposes and would not affect their grades.

- *Qualitative Observation*

During test administration, the researcher observed learner behaviors and recorded observations of difficulties and strategies. These observations provided cohort interpretation of quantitative findings.

✓ **Data Collection and Recording:** Completed test papers were collected and scored according to a marking scheme. Scores were recorded and entered into a database for statistical analysis.

➤ *Credibility and Trustworthiness*

- *Reliability*

Reliability refers to the consistency and stability of a measurement instrument. In this investigation, reliability was supported through the structured design of the diagnostic

instrument, which was graded out of one hundred (100) percent and administered uniformly to fifty systematically selected learners. All learners completed the same assessment under comparable instructional conditions, thereby controlling for procedural variation.

The consistency of the performance pattern strengthens reliability; the mean (23.52%), median (22.00%), and mode (15.00%) converged within the same low-performance band. When measures of central tendency align closely, as they do in this dataset, they indicate statistical stability rather than erratic fluctuation. Furthermore, the moderate standard deviation (9.50) relative to the scale width suggests dispersion within a coherent low-achievement structure as opposed to random scoring anomalies. The absence of extreme outliers and the symmetrical clustering of scores reinforce the stability of measurement outcomes. Additionally, the one-sample t-test ($t = -19.72$) demonstrates that the observed deviation from the benchmark is not accidental. The magnitude of the recorded deviation, combined with the relatively small standard error ($s/\sqrt{n} \approx 1.343$), indicates measurement precision. Altogether, these statistical properties support the reliability of the results.

- *Internal Validity*

Internal validity refers to the degree to which the findings accurately reflect the phenomenon under investigation without interference from confounding variables. In this study, internal validity was strengthened by the alignment between the research aim, the diagnostic instrument, and the statistical procedures employed. The benchmark of fifty (50) percent was clearly pre-defined as the acceptable threshold for comprehension. The hypotheses were logically structured to test whether the observed mean significantly fell below this benchmark. The use of a one-tailed one-sample t-test directly addressed the stated objective of determining whether learners' understanding was deficient relative to an established criterion.

Because the diagnostic test focused specifically on writing chemical formulae and balancing chemical equations, and not on peripheral chemistry topics, the measured outcomes can reasonably be attributed to learners' conceptual understanding of symbolic chemistry. The rejection of the

null hypothesis was based on a statistically robust difference between the sample mean (23.52%) and the benchmark (50%), with a calculated t-value far exceeding the critical value ($-19.72 < -1.677$). This large statistical gap reduces the likelihood of the findings being attributed to sampling error. The coherence between descriptive statistics, benchmark distribution (seventy-two percent [72%] in extremely poor to poor categories), and inferential testing enhances internal validity because multiple analytical lenses converge on the same conclusion: the problem is systemic and severe.

- *Construct Validity*

Construct validity concerns whether the instrument truly measures the conceptual construct it claims to measure. In this case, the construct under investigation was learners' comprehension and assimilation of the basic concepts underlying chemical formulae and chemical equations. The diagnostic assessment required learners to write, interpret, and balance chemical representations. These tasks inherently demand understanding of subscripts, coefficients, valency relationships, and conservation principles of elements and compounds. Because the assessment directly operationalized these representational skills in learners, the instrument demonstrated strong alignment between theoretical construct and measurable task.

The complete absence of scores above forty percent (40%) further suggests that learners were not merely failing isolated computational items but were struggling with the conceptual core of symbolic chemistry. The clustering of results in the lower benchmark categories supports the interpretation that the instrument successfully captured genuine conceptual deficiency rather than superficial procedural lapses. The integration of benchmarking, central tendency analysis, dispersion statistics, and hypothesis testing provides triangulated confirmation that the construct being measured, conceptual assimilation of symbolic chemistry, was authentically assessed in this study.

- *Triangulation*

Triangulation of multiple analytical approaches (descriptive statistics, frequency analysis, and hypothesis testing) strengthens the credibility of findings by converging on consistent conclusions from different methodological perspectives. This convergence reduces the likelihood that findings are artifacts of a single analytical approach and increases confidence in their validity.

➤ *Statistical Procedures*

- *Data Analysis Plan*

The data analysis was designed to answer the research question: "What is the extent of learners' challenges in comprehending and assimilating the basic concepts of chemical formulae and chemical equations?" The following analytical procedures were employed:

- *Descriptive Statistics*

Measures of central tendency (mean, median, mode) and dispersion (standard deviation, range) were calculated to

summarize the overall performance profile and characterize the distribution of scores.

- *Frequency Distribution Analysis*

Learners were categorized into benchmark categories based on their scores, allowing characterization of the distribution of performance across levels of understanding.

- *Hypothesis Testing*

A one-sample t-test was conducted to determine whether the observed mean performance was significantly below the acceptable benchmark of 50%. This inferential procedure allowed determination of whether the observed deficit was statistically significant or could be attributed to sampling error.

- *Hypothesis Formulation*

The hypotheses were formulated as follows:

- ✓ Null Hypothesis (H_0): There is no significant problem in learners' understanding of chemical formulae and chemical equations; the mean score is equal to or greater than the benchmark score of 50%.

$$H_0: \mu \geq 50$$

- ✓ *Alternative Hypothesis (H_1)*

There is a significant problem in learners' understanding of chemical formulae and chemical equations; the mean score is less than the benchmark score of 50%.

$$H_1: \mu < 50$$

This was a one-tailed test, since the interest was specifically in determining whether learners performed below the benchmark.

- ✓ Test Statistic Selection: A one-sample t-test was used because:

The sample size was 50 ($n \geq 30$),

The population standard deviation was unknown,

The sample mean was compared to a predefined benchmark value.

The test statistic for a one-sample t-test is given by:

$$t = \frac{\bar{x} - \mu_0}{s/\sqrt{n}}$$

Where:

$\bar{x}$ = sample mean,

μ_0 = benchmark mean,

s = sample standard deviation,

n = sample size.

- *Significance Level and Decision Rule*

A significance level of $\alpha = 0.05$ was chosen, consistent with educational research conventions. At $\alpha = 0.05$ and degrees of freedom ($df = n-1 = 49$), the critical t-value for a one-tailed test is approximately $t_{\text{critical}} = -1.677$. The decision rule was: reject the null hypothesis if the calculated t-value is less than the critical t-value ($t < -1.677$).

Table 2 Measures of Central Tendency

Measure of central tendency table		
N	Valid	50
	Missing	0
	Mean	23.520
	Median	22.000
	Mode	15.0 ^a
	Sum	1176.0
	Range	35.00

Source: Field Data, 2026

- *Interpretation of Central Tendency Measures*

The mean score of 23.52% falls within the "Poor" category (20-29%), indicating limited comprehension. The median score of 22.00% is slightly lower than the mean, suggesting a slight negative skew (more scores at the lower end of the distribution). The modal score of 15.00% falls within the "Very Poor" category (10-19%), indicating that the most frequent performance level was characterized by minimal comprehension.

The convergence of mean (23.52%), median (22.00%), and mode (15.00%) within a narrow low-performance band indicates relatively symmetrical distribution centered on poor performance. The closeness of mean and median confirms the absence of extreme outliers depressing the average. The modal score of 15% demonstrates that the most frequent performance level lies within the very poor category. The

IV. RESULTS

➤ *Overall Learner Performance Profile*

The diagnostic test results provided a comprehensive picture of learner performance across the cohort. Table 1 presents the measures of central tendency for the overall performance.

aggregate sum of scores (1176) across fifty learners reinforces collective underachievement; the weakness is systemic rather than individual.

When central tendency measures converge at low-performance levels, educational data science literature interprets such patterns as structural conceptual insufficiency rather than heterogeneous learning gaps (Leighton, 2021). The dataset reflects precisely this structural weakness. The alignment of mean, median, and mode confirms uniform low-level conceptual performance; the weakness is cohort-wide and deeply embedded.

➤ *Performance Bench-marking*

The benchmark-based categorization of learner performance provided detailed insight into the distribution of understanding across the cohort. Table 2 presents the frequency distribution of learners by performance category.

Table 3 Frequency Distribution by Performance Category

Frequency Table			
Range	N	%	Interpretation
0-9	2	4.0%	Extremely poor
10-19	18	36.0%	Very poor
20-29	16	32.0%	Poor
30-39	11	22.0%	Fair
40-49	3	6.0%	Fairly good
50-100	0	0.0%	Good

Source: Field Data, 2026

- *Interpretation of Benchmark Distribution*

The benchmark-based categorization provides unequivocal empirical evidence of systemic conceptual deficiency. Learners' scores ranged from a minimum of 5% to a maximum of 40%, yielding a range of 35 percentage points. No learner attained 50% or above, and none exceeded 40%. This upper-bound limitation indicates generalized conceptual weakness rather than isolated underachievement.

Seventy-two percent (72%) of learners fell within the extremely poor to poor categories (0-29%), demonstrating that the majority of the cohort had limited to minimal comprehension. An additional 22% fell within the fair category (30-39%), indicating partial comprehension. Only 6% reached the fairly good category (40-49%), though even these learners demonstrated incomplete understanding. The complete absence of any learner attaining the benchmark for good comprehension ($\geq 50\%$) confirms that foundational

symbolic competence in chemical formulae and equations has not been well-internalized.

The clustering of scores within the lower bands indicates that learners are not merely struggling with advanced stoichiometric reasoning; they are failing to assimilate elementary representational constructs such as subscripts, valency relationships, coefficient interpretation, and conservation principles. The ceiling performance of 40% reinforces the conclusion that even the highest-performing learners demonstrate only partial procedural familiarity without deep conceptual grounding.

According to Sevian and Talanquer (2022), this pattern aligns with contemporary chemistry education scholarship asserting that representational competence remains one of the most persistent barriers to meaningful conceptual understanding. Learners appear to manipulate symbols

superficially without translating them into molecular-level meaning. Cooper and Stieff (2021) further argue that failure to coordinate macroscopic, submicroscopic, and symbolic representations produces fragmented cognitive schemas. The present findings empirically substantiate this fragmentation within this cohort.

Performance benchmarking establishes that learners' challenges are widespread, severe, and systemic. The difficulty is foundational, not peripheral. Conceptual underdevelopment at the symbolic core of chemistry is evident across the cohort.

➤ Hypothesis Testing Results

The one-sample t-test statistically confirmed the descriptive findings regarding the extent of learners' challenges. Table 3 presents the results of the hypothesis test.

Table 4 One-Sample t-Test Results

Parameter	Value
Sample Mean	23.52
Benchmark Mean	50
Difference	-26.48
Standard Deviation	9.5
Standard Error	1.343
Calculated t-value	-19.72
Critical t-value ($\alpha = .05$, $df = 49$)	-1.677
Decision	Reject H_0
Significance	$p < .05$

Source: Field Data, 2026

• Substitution and Calculation

The test statistic was calculated as follows:

$$t = \frac{23.52 - 50}{9.50/\sqrt{50}}$$

$$t = \frac{-26.48}{9.50/7.071}$$

$$t = \frac{-26.48}{1.343}$$

$$t = -19.72$$

• Interpretation of Hypothesis Test

The calculated t-value ($t = -19.72$) is far less than the critical t-value ($t_{\text{critical}} = -1.677$), resulting in decisive rejection of the null hypothesis at $\alpha = .05$. This indicates that the mean performance of learners in writing chemical formulae and balancing chemical equations is statistically significantly lower than the benchmark score of 50%.

The probability that such a deviation occurred by chance is negligible ($p < .05$). The difference between the observed mean (23.52%) and the benchmark (50%) is not marginal; it is profound. The deficit represents a 26.48 percentage point gap, meaning that learners are performing at less than half of the acceptable benchmark. This statistically

significant deviation has substantial educational significance, indicating systemic conceptual failure rather than minor performance variation.

The magnitude of the t-statistic (-19.72) substantially exceeds the critical threshold, indicating a very large effect size. This inferential result demonstrates both the *existence* and the *magnitude* of the conceptual deficit. The deficit is statistically significant and educationally consequential.

According to Gierl and Bulut (2022), educational measurement scholarship emphasizes that inferential analysis in diagnostic contexts must inform instructional re-design rather than function merely as statistical validation. In this case, statistical evidence strengthens the argument that structured intervention is imperatively needed to mitigate this weakness.

Hypothesis testing confirms that learners' understanding of chemical formulae and equations is significantly below the acceptable benchmark. The problem is empirically verified and statistically robust.

➤ Measures of Dispersion

The measures of dispersion provided additional insight into the variability of learner performance. Table 4 presents the key dispersion statistics.

Table 5 Measures of Dispersion

Statistic	Value
Standard Deviation	9.5
Range	35
Minimum Score	5
Maximum Score	40
Variance	90.25

Source: Field Data, 2026

• *Interpretation of Dispersion Measures*

The standard deviation ($s = 9.50$) reflects moderate variability within an overall low-achievement band. The range of 35 percentage points (from 5% to 40%) indicates some variation in procedural familiarity, yet no learner approaches conceptual mastery. Dispersion exists, but it operates within a uniformly weak performance structure.

The variance of 90.25 indicates that scores are spread across a range of approximately 9.5 percentage points from the mean. This moderate variability suggests that while there are differences in performance across the cohort, these differences are relatively modest in educational terms, the range of performance extends from extremely poor to fairly good, but not to acceptable comprehension.

Moderate dispersion combined with low central tendency suggests uneven procedural exposure without

conceptual integration. Learners differ in degree, not in category. The absence of high-end dispersion reinforces systemic limitation. Talanquer (2023) notes that moderate variability within low mean performance typically signals partial symbolic manipulation unsupported by coherent mental models. The present findings align with this interpretation.

Dispersion analysis confirms moderate variation within a fundamentally weak conceptual framework. The problem remains systemic rather than isolated.

➤ *Summary of Statistical Findings*

The convergence of benchmark distribution, inferential statistics, central tendency measures, and dispersion analysis demonstrates structural conceptual underdevelopment in chemical formulae and equations. Table 5 summarizes the key statistical findings.

Table 6 Summary of Key Statistical Findings

Analysis Approach	Finding	Interpretation
Central Tendency	Mean = 23.52%, Median = 22.00%, Mode = 15.00%	Poor to very poor understanding across cohort
Performance Distribution	72% in extremely poor to poor categories; 0% in good category	Systemic deficiency; no acceptable comprehension
Hypothesis Testing	$t = -19.72, p < .05$, reject H_0	Statistically significant deficit below benchmark
Dispersion	SD = 9.50, Range = 35.00%	Moderate variability within low-achievement band

Source: Field Data, 2026

Each analytical approach converges on the same conclusion: learners experience profound, systemic, and statistically verified challenges in comprehending and assimilating the basic concepts of chemical formulae and chemical equations. The deficit is structural. It is measurable. It is severe.

V. DISCUSSION

➤ *The Nature and Extent of the Conceptual Deficit*

The findings of this study demonstrate unequivocally that learners' difficulties with chemical formulae and equations are not episodic or marginal but represent a systemic conceptual deficit affecting the majority of learners. With a mean score of 23.52% and 72% of learners falling within the extremely poor to poor performance categories, the study provides empirical confirmation of what has been widely observed but not systematically quantified: learners in the Zambian secondary education system are failing to develop foundational understanding of chemical symbolism.

The severity of the deficit is underscored by the complete absence of learners reaching the benchmark for good comprehension ($\geq 50\%$). This finding is particularly concerning given that participants were Grade 11 learners who had completed two years of chemistry instruction. It suggests that current instructional approaches are not achieving their intended outcomes, and that the difficulties learners experience are not being adequately addressed through the regular curriculum.

The convergence of central tendency measures (mean = 23.52%, median = 22.00%, mode = 15.00%) at low-performance levels indicates that the deficit is not limited to a subset of struggling learners but characterizes the cohort as a whole. This pattern is consistent with what Leighton (2021) describes as "structural conceptual insufficiency", a systemic failure in knowledge acquisition that affects an entire cohort rather than isolated individuals. The implication is that individual remediation alone will not be sufficient; systemic pedagogical restructuring is required.

The moderate variability within the low-achievement band ($SD = 9.50$, range = 35%) suggests that while there are differences in performance across the cohort, these differences are relatively small in educational terms. Even the highest-performing learners (maximum score = 40%) demonstrated only partial understanding, with significant gaps in conceptual knowledge. This finding challenges any assumption that the problem is simply one of a few struggling learners; it affects the entire cohort.

➤ *Theoretical Interpretation of Findings*

The findings align closely with the theoretical frameworks that guided this study, providing empirical support for their explanatory power.

- *Cognitive Load Theory (Sweller, 1988, 2010)*

The uniformly low performance suggests that the intrinsic cognitive load of chemical symbolism exceeds learners' cognitive processing capacity, and that current instructional approaches are not effectively managing this load. Learners appear to be experiencing cognitive overload when confronted with the multiple interacting elements of chemical formulae and equations, resulting in fragmented knowledge structures and procedural dependence. The absence of learners reaching acceptable comprehension suggests that the instructional approach is failing to build coherent schemas that would allow efficient processing of chemical information.

- *Representational Competence Framework (Kozma and Russell, 1997)*

The findings indicate that learners have not developed representational competence—the ability to translate between macroscopic, submicroscopic, and symbolic representations. Learners appear to be processing symbols at a surface level, focusing on procedural rules without connecting these symbols to underlying chemical principles. This surface processing is consistent with the low scores on items requiring interpretation of subscripts and coefficients, which demand understanding of the quantitative relationships represented in symbolic notation.

- *Johnstone's Tripartite Model (1982, 2000)*

The findings suggest that learners are attempting to operate at the symbolic level without adequate grounding in macroscopic phenomena or submicroscopic explanations. The symbolic representations of chemical formulae and equations are being learned as isolated manipulations rather than as representations of chemical reality. This approach leads to procedural learning without conceptual understanding, manifested in the dissociation between procedural competence such as following rules for formula writing and conceptual understanding explaining the meaning of symbols in chemical terms.

➤ *Comparison with International Research*

The findings of this study are consistent with international research documenting learner difficulties with chemical symbolism, though the severity of the deficit in this context is notable. Yaroch's (1985) finding that learners can balance equations without understanding what the equations

represent is replicated in this study, with learners demonstrating procedural familiarity without conceptual understanding. The concentration of scores in the lower performance categories suggests that the difficulties documented in international research are even more pronounced in the Zambian context.

The research on misconceptions in chemistry (Taber, 2013) provides a framework for understanding the specific errors learners make in writing formulae and balancing equations. The low scores on items requiring application of valency principles suggest that learners hold alternative conceptions about valency and chemical bonding that interfere with correct formula construction. The difficulties with coefficients and conservation principles indicate a failure to grasp the quantitative logic of chemical equations.

Research on representational competence (Stieff et al., 2021; Villafañe & Lewis, 2022) provides insight into why learners struggle with symbolic manipulation. The low scores on items requiring interpretation of chemical symbols suggest that learners have not developed the ability to coordinate multiple representations, a key component of representational competence. The absence of learners reaching acceptable comprehension indicates that this representational deficit is widespread and systemic.

➤ *Implications for Teaching and Learning*

The pedagogical implications of these findings are both profound and urgently practical, offering a clear roadmap for transforming chemistry instruction to address the systemic conceptual deficit identified in this study. Foremost among these implications is the critical need for scaffolding and cognitive load-management, as the evidence strongly suggests that current instructional approaches overwhelm learners by presenting too much information simultaneously; consequently, teaching chemical formulae and equations must be carefully sequenced to introduce concepts progressively, with subscripts taught as indicators of atomic ratio before coefficients are introduced as quantitative multipliers, valency relationships understood as electrostatic principles before being applied to formula construction, and the conservation of matter experientially demonstrated before symbolic encoding is even attempted. Additionally, the findings necessitate instruction specifically designed to cultivate representational competence, requiring that learners be explicitly taught to translate between macroscopic phenomena, submicroscopic explanations, and symbolic representations through multiple strategies, including modeling of symbolic representations, practice in generating representations, and explicit discussion of the relationships between different representational levels, so that instruction moves decisively beyond procedural rehearsal toward deliberate conceptual cultivation. Closely related to this is the underscored importance of diagnostic and formative assessment, given the severity of the deficit documented in this study; teachers must therefore be equipped with robust tools to identify specific learner difficulties and misconceptions, while formative assessment should be embedded continuously throughout instruction to provide ongoing feedback on conceptual mastery and guide targeted

remediation where gaps persist. Crucially, the persistence of learner difficulties points to the necessity of conceptual change approaches, as simple repetition of correct procedures is unlikely to prove effective; instead, learners must be confronted with the inadequacy of their existing conceptions and supported in constructing new understandings through explicit challenges to their misconceptions. Finally, the findings strongly indicate that passive, teacher-centered instruction is insufficient for developing meaningful conceptual understanding, and that learners must be actively engaged in constructing knowledge through collaborative problem-solving, peer explanation, and structured discussion, with model-based problem solving, peer dialogues, and guided construction of chemical representations emphasized to foster deeper engagement and more robust learning outcomes. Taken together, these implications argue for a comprehensive reorientation of chemistry pedagogy, one that is sequenced, representational, diagnostic, conceptually challenging, and collaboratively active, if foundational learning is to move beyond superficial symbol manipulation toward genuine conceptual mastery.

➤ *Systemic Implications*

The findings suggest that the problem extends beyond individual classrooms and requires systemic intervention at multiple levels.

- *Curriculum Design*

The severity of the deficit suggests that the curriculum may need to be reconsidered. The progression of concepts may need to be slowed to allow for deeper mastery of foundational understanding. Additional instructional time may need to be allocated to chemical formulae and equations, given their foundational importance. Curriculum sequencing must manage cognitive load by introducing representational layers progressively, decomposing complexity before reintegrating symbolic systems.

- *Teacher Professional Development*

The findings underscore the need for teacher professional development in pedagogical content knowledge for chemistry. Teachers must understand not only the chemistry content but also how learners typically develop understanding of this content, what misconceptions they tend to hold, and what instructional strategies are effective in addressing these difficulties. Teacher professional development should prioritize pedagogical content knowledge in representational chemistry, ensuring that educators are equipped to scaffold learners' conceptual growth.

- *Resource Provision*

The findings suggest that adequate resources, including laboratory facilities, models, and manipulatives, are essential for developing representational competence. Learners need concrete experiences with chemical phenomena to ground their understanding of symbolic representations. Resource allocation should prioritize the development of laboratory facilities and the provision of instructional materials that support representational learning.

- *Assessment Practices*

The findings have implications for assessment practices at both classroom and national levels. Assessment should move beyond summative judgment to include diagnostic and formative components that identify learner difficulties and guide instruction. Cognitive diagnostic approaches should be used to map learners' conceptual trajectories and identify specific difficulties requiring intervention.

➤ *Limitations and Future Research Directions*

While this study provides rigorous empirical evidence of the extent of learner difficulties, it is nevertheless important to acknowledge several methodological constraints that temper the scope of its conclusions. One such constraint concerns the sample itself, which consisted of only 50 learners drawn from a single school in Zambia, thereby limiting the generalizability of findings to broader populations and educational contexts, and pointing to the clear need for future investigations that incorporate larger, more diverse samples across multiple schools and regions. Furthermore, the study's reliance on a cross-sectional design, assessing learners at just one point in time, precludes any understanding of how conceptual understanding evolves or deteriorates over the course of instruction, suggesting that longitudinal research would be invaluable for tracing the developmental trajectory of difficulties and pinpointing when they first emerge. Beyond these design considerations, the investigation deliberately concentrated on establishing the magnitude of the problem rather than probing its underlying causes, meaning that the specific cognitive, instructional, and curricular factors responsible for these deficits remain largely unexplored and ripe for systematic inquiry. Likewise, the assessment tool, while demonstrating acceptable content validity and reliability, may not fully capture the multidimensional nature of conceptual understanding, as it cannot access the nuanced reasoning processes that learners employ; future work incorporating qualitative methods such as interviews and think-aloud protocols would therefore provide richer, more textured insights into the nature of student thinking. Notwithstanding these methodological constraints, the study's findings establish a crucial empirical baseline that can now support intervention research, and it is precisely this groundwork that should guide future investigations into the effectiveness of targeted instructional strategies designed to remediate the specific difficulties identified. Ultimately, these limitations do not diminish the study's contributions but rather illuminate a clear and compelling agenda for subsequent research, ensuring that each constraint becomes an opportunity for deeper exploration and more effective educational reform.

➤ *Conclusion of Discussion*

The findings of this study demonstrate unequivocally that learners experience profound, systemic, and statistically verified challenges in comprehending and assimilating the basic concepts of chemical formulae and chemical equations. The severity of the deficit, with 72% of learners in extremely poor to poor categories and none reaching acceptable comprehension, indicates that current instructional approaches are failing to achieve their intended outcomes.

The deficit is structural, arising from multiple interconnected factors: the inherent cognitive complexity of chemical symbolism, inadequate instructional approaches, curriculum sequencing issues, and systemic constraints. Addressing this deficit requires comprehensive pedagogical transformation rather than incremental instructional adjustment. The transition must be from procedural rehearsal toward deliberate cultivation of representational competence.

Without deliberate, research-informed instructional transformation, symbolic chemistry will continue to function as a cognitive bottleneck in science learning. Foundational reconstruction is not optional; it is educationally imperative.

VI. CONCLUSION AND RECOMMENDATIONS

➤ *Summary of Key Findings*

At the centre of this investigation lies the empirical verification that learners experience profound, systemic, and statistically significant challenges in grasping the foundational concepts of chemical formulae and equations. Moreover, the convergence of descriptive statistics, benchmark-based performance categorization, inferential testing, and dispersion analysis yields coherent and mutually reinforcing evidence of a structural conceptual deficiency that cannot be dismissed as random or isolated. Perhaps most alarmingly, the mean score of 23.52%, positioned far below the acceptable benchmark of 50%, combined with the complete absence of any learner attaining good comprehension, underscores just how critically underdeveloped symbolic competence in chemistry has become. Beyond this stark measure of severity, the alignment of the mean, median, and mode within uniformly low-performance bands confirms that this fragility affects the entire cohort rather than a select subset, pointing unequivocally to a systemic rather than an idiosyncratic problem. Statistically, the one-sample t-test result ($t = -19.72$, $p < .05$) provides rigorous verification that the observed deficit is not an artifact of sampling fluctuation but rather a substantive and measurable educational crisis demanding immediate attention. Interestingly, while moderate dispersion exists within this uniformly low-achievement band, the variation remains relatively modest in educational terms, suggesting that even the highest-performing learners exhibit only incomplete understanding. Crucially, the findings reveal that students manipulate chemical symbols procedurally without internalizing their representational meaning, as subscripts, coefficients, valency relationships, and conservation principles fail to be assimilated into coherent conceptual systems, with symbolic chemistry instead functioning as a cognitive bottleneck that constrains higher-order reasoning and stoichiometric understanding. Ultimately, this study transcends mere descriptive concern by providing quantitative verification that not only confirms the existence of the problem but also establishes its full magnitude; the deficit is structural, statistically robust, and educationally consequential, and without deliberate, research-informed instructional transformation, foundational chemistry learning will remain irrevocably compromised.

➤ *Theoretical Contributions*

This study makes several significant and nuanced contributions to the theoretical understanding of chemistry learning difficulties. Initially, this investigation moves well beyond anecdotal observation by providing rigorous empirical evidence that quantifies both the extent and the severity of student challenges, thereby establishing a crucial baseline for future research and instructional interventions. Beyond this foundational quantification, the strength of the findings is greatly enhanced through the triangulation of evidence, as the convergence of descriptive statistics, benchmark categorization, and hypothesis testing provides compelling confirmation of a systemic conceptual deficiency. Furthermore, the research offers vital contextual specificity by generating data from a developing country, which significantly extends the generalizability of findings beyond the Western contexts that typically dominate the literature on science education. The study's theoretical contribution is also profound, as it successfully demonstrates the explanatory power of integrating cognitive, representational, and pedagogical frameworks to create a more holistic understanding of why learners struggle. Finally, the work highlights a critical diagnostic application, showcasing the utility of targeted assessment tools not only for identifying widespread learning gaps but also for providing a concrete evidence base to guide meaningful instructional reform.

➤ *Recommendations*

Based on the findings of this study, several recommendations are offered for chemistry teachers to address the systemic conceptual deficits identified. Central to this approach is the employment of modeling strategies that concretely represent abstract chemical concepts, as instruction should integrate visual, symbolic, and manipulable models that allow learners to explore the relationships between atoms, molecules, and reactions, thereby linking symbolic representations to tangible understanding and supporting learners in internalizing the meaning of subscripts, coefficients, and valency. Building on this foundation, teachers should structure learning progressively, starting from foundational representational understanding before advancing to more complex problem-solving tasks, as this progressive sequencing manages cognitive load and enables learners to build coherent knowledge schemas. To complement these strategies, diagnostic and formative assessments should be embedded throughout instruction, providing continuous feedback on learners' conceptual mastery and guiding targeted remediation where gaps persist. Furthermore, collaborative and interactive approaches, such as model-based problem solving, peer discussions, and guided construction of chemical representations, should be emphasized to engage learners actively and foster deeper understanding. Teachers are also encouraged to employ structured analogies and physical-symbolic mappings that help learners bridge the gap between abstract formulae and the underlying chemical logic, allowing them to construct and manipulate chemical representations in ways that mirror real-world molecular interactions. Integrating such approaches not only strengthens conceptual understanding but also aligns with competence-based principles by cultivating learners' ability

to apply knowledge meaningfully and accurately in diverse contexts, ultimately transforming chemistry instruction from passive reception to active conceptual construction.

Based on the findings of this study, several recommendations are offered for various stakeholders to address the systemic conceptual deficits identified. For teacher education programs, the preparation of chemistry teachers must prioritize pedagogical content knowledge, ensuring that educators understand not only the content itself but also how learners typically develop understanding of chemical symbolism and where difficulties commonly arise. Teacher education should also develop teachers' skills in diagnostic assessment, enabling them to identify specific learner difficulties and design appropriate interventions tailored to individual and group needs. Importantly, teacher education programs should model the instructional approaches recommended for chemistry instruction, including modeling strategies, collaborative learning, and progressive scaffolding, so that prospective teachers experience these approaches firsthand and can implement them effectively in their own classrooms. Ongoing professional development must be provided to practicing teachers to update their knowledge and skills in response to new research findings and changing educational contexts, ensuring that professional growth continues throughout teachers' careers.

For curriculum developers, the curriculum should be reviewed to ensure that concepts are introduced in an appropriate sequence that manages cognitive load and builds foundational understanding before introducing complexity, as the current findings suggest that learners are overwhelmed by the simultaneous demands of multiple symbolic conventions. Additional instructional time may need to be allocated to chemical formulae and equations, given their foundational importance to success in general chemistry and the severity of learner difficulties documented in this study. The curriculum should explicitly address representational competence, ensuring that learners are taught to coordinate macroscopic, submicroscopic, and symbolic representations through structured learning experiences that connect these levels meaningfully. Furthermore, the curriculum should include diagnostic components that help teachers identify learner difficulties and design targeted interventions, embedding assessment tools within the curriculum framework to support responsive teaching.

For policymakers, resources should be allocated to support the development of laboratory facilities, instructional materials, and teacher professional development in chemistry education, as the systemic nature of the difficulties identified requires systemic investment. Research on chemistry education, particularly in developing country contexts, should be supported to provide evidence for policy and practice, ensuring that decisions are grounded in empirical findings rather than anecdotal observation. Assessment practices should be reviewed to ensure that they assess conceptual understanding as well as procedural competence, and that they provide diagnostic information to inform instruction rather than merely assigning summative grades.

Given the systemic nature of the difficulties identified, systemic reform is required that addresses curriculum, instruction, assessment, and teacher development in an integrated manner, as isolated changes are unlikely to produce sustained improvement.

This study provides a foundation for future research in several areas that merit systematic investigation. Studies should investigate the specific causal factors contributing to learner difficulties, including cognitive factors related to the inherent difficulty of symbolic representation, instructional factors relating to teaching approaches, curricular factors concerning sequencing and scaffolding, and systemic factors such as resource availability and teacher preparation. There is need to investigate the effectiveness of specific instructional strategies in addressing the difficulties identified, including modeling strategies, conceptual change approaches, and representational competence instruction, to establish evidence-based practices for chemistry teaching. Longitudinal studies in science education should examine how understanding of chemical symbolism develops over time and identify critical points at which difficulties emerge, providing insight into the developmental trajectory of conceptual understanding. Studies should compare difficulties across contexts such as different schools, regions, and countries to identify contextual factors that influence learning and to establish the generalizability of findings. There is need to, through structured research, develop and validate diagnostic instruments for chemistry learning in developing country contexts, ensuring that teachers have access to culturally appropriate and contextually relevant assessment tools. Finally, research should investigate the effectiveness of professional development programs in improving chemistry teaching and learner competences, establishing what forms of teacher education are most effective in addressing the systemic difficulties identified in this study.

➤ *Concluding Remarks*

This investigation has demonstrated that learners' difficulties in comprehending and assimilating the basic concepts of chemical formulae and chemical equations are not minor or episodic but represent a profound, systemic, and statistically verified deficit. The convergence of evidence from multiple analytical approaches, descriptive statistics, benchmark categorization, and hypothesis testing, provides compelling evidence that current instructional approaches are failing to achieve their intended outcomes.

The deficit is structural, arising from multiple interconnected factors: the inherent cognitive complexity of chemical symbolism, inadequate instructional approaches, curriculum sequencing issues, and systemic constraints. Addressing this deficit requires comprehensive pedagogical transformation that moves from procedural rehearsal toward deliberate cultivation of representational competence.

The findings have significant implications for teaching, curriculum development, teacher education, and educational policy. They provide empirical justification for targeted intervention and systemic reform. Without such reform,

symbolic chemistry will continue to function as a cognitive bottleneck in science learning, constraining learners' ability to progress in chemistry and related STEM fields.

Foundational reconstruction is not optional; it is educationally imperative. The evidence from this study provides a rigorous basis for the pedagogical restructuring needed to ensure that all learners develop the representational competence essential for meaningful participation in chemistry and the broader scientific enterprise.

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APPENDIX XV: APPROVAL OF STUDY



THE UNIVERSITY OF ZAMBIA DIRECTORATE OF RESEARCH AND DEVELOPMENT

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APPROVAL OF STUDY

IORG No. 0005376
HSSREC IRB No. 00006464
REF NO. HSSREC-2025-SEP-074

31st October 2025

Mr Sikawala Nzala
The University of Zambia
P.O. Box 32379
LUSAKA

Dear Mr Nzala,

RE: “CHEMICAL-HOOK - VALENCY METONYMIC MODELLING’S EFFICACY IN SCAFFOLDING LEARNER COMPREHENSION AND CONCEPTUAL ASSIMILATION OF CHEMICAL FORMULAE AND EQUATIONS IN CHEMISTRY”

Reference is made to your submission of the protocol captioned above. The HSSREC resolved to approve this study and your participation as Principal Investigator for a period of one year.

REVIEW TYPE	ORDINARY REVIEW	APPROVAL NO. HSSREC: 2025-SEP-074
Approval and Expiry Date	Approval Date: 31 st October, 2025	Expiry Date: 30 th October, 2026
Protocol Version and Date	Version - Nil.	30 th October, 2026
Information Sheet, Consent Forms and Dates	☐English.	To be provided
Consent form ID and Date	Version - Nil	To be provided
Recruitment Materials	Nil	Nil
Other Study Documents	Questionnaire.	
Number of Participants Approved for Study		

Specific conditions will apply to this approval. As Principal Investigator, it is your responsibility to ensure that the contents of this letter are adhered to. If these are not adhered to, the approval may be suspended. Should the study be suspended, study sponsors and other regulatory authorities will be informed.

➤ *Conditions of Approval*

- No participant may be involved in any study procedure prior to the study approval or after the expiration date.
- All unanticipated or Serious Adverse Events (SAEs) must be reported to HSSREC within 5 days.
- All protocol modifications must be approved by HSSREC prior to implementation unless they are intended to reduce risk (but must still be reported for approval). Modifications will include any change of investigator/s or site address.
- All protocol deviations must be reported to HSSREC within 5 working days.

- All recruitment materials must be approved by HSSREC prior to being used.
- Principal investigators are responsible for initiating Continuing Review proceedings. HSSREC will only approve a study for a period of 12 months.
- It is the responsibility of the PI to renew his/her ethics approval through a renewal application to HSSREC.
- Where the PI desires to extend the study after expiry of the study period, documents for study extension must be received by HSSREC at least 30 days before the expiry date. This is for the purpose of facilitating the review process. Documents received within 30 days after expiry will be labelled “late submissions” and will incur a penalty fee of K500.00. No study shall be renewed whose documents are submitted for renewal 30 days after expiry of the certificate.
- Every 6 (six) months a progress report form supplied by The University of Zambia Humanities and Social Sciences Research Ethics Committee as an IRB must be filled in and submitted to us. There is a penalty of K500.00 for failure to submit the report.
- When closing a project, the PI is responsible for notifying, in writing or using the Research Ethics and Management Online (REMO), both HSSREC and the National Health Research Authority (NHRA) when ethics certification is no longer required for a project.
- In order to close an approved study, a Closing Report must be submitted in writing or through the REMO system. A Closing Report should be filed when data collection has ended and the study team will no longer be using human participants or animals or secondary data or have any direct or indirect contact with the research participants or animals for the study.
- Filing a closing report (rather than just letting your approval lapse) is important as it assists HSSREC in efficiently tracking and reporting on projects. Note that some funding agencies and sponsors require a notice of closure from the IRB which had approved the study and can only be generated after the Closing Report has been filed.
- A reprint of this letter shall be done at a fee.
- All protocol modifications must be approved by HSSREC by way of an application for
- an amendment prior to implementation unless they are intended to reduce risk (but must still be reported for approval). Modifications will include any change of investigator/s or site address or methodology and methods. Many modifications entail minimal risk adjustments to a protocol and/or consent form and can be made on an Expedited basis (via the IRB Chair). Some examples are: format changes, correcting spelling errors, adding key personnel, minor changes to questionnaires, recruiting and changes, and so forth. Other, more substantive changes, especially those that may alter the risk-benefit ratio, may require Full Board review. In all cases, except where noted above regarding subject safety, any changes to any protocol document or procedure must first be approved by HSSREC before they can be implemented.

Should you have any questions regarding anything indicated in this letter, please do not hesitate to get in touch with us at the above indicated address.

On behalf of HSSREC, we would like to wish you all the success as you carry out your study.

Yours faithfully,



DR. J. I. Ziwa

CHAIRPERSON THE UNIVERSITY OF ZAMBIA HUMANITIES AND SOCIAL SCIENCES RESEARCH ETHICS COMMITTEE – IRB cc: Director, Research and Development Assistant Director, Research Support and Grants Manager, Research Administration and Support Ethics and Affiliation Officer