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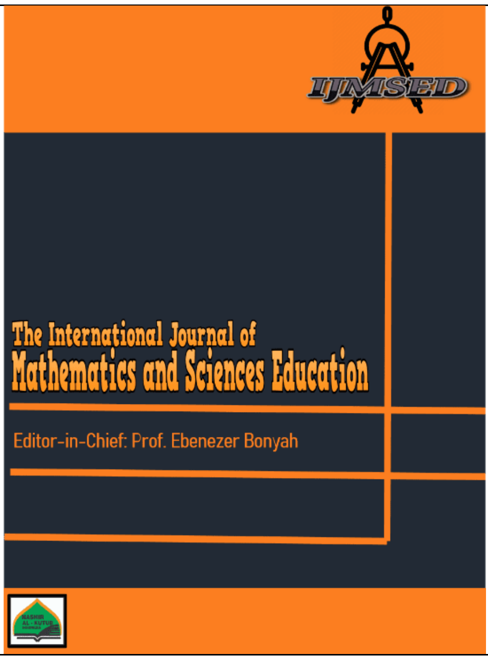

Students' conceptual, representational, and analytical difficulties in balancing chemical equations: A thematic analysis

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Students' conceptual, representational, and analytical difficulties in balancing chemical equations: A thematic analysis

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Balancing chemical equations (BCE) is foundational to chemistry learning, yet Nigerian secondary students persistently underperform on this skill. A companion quantitative survey drawn from the same population (Ogundiji, 2024) documented the prevalence of specific difficulties, for example that 96.56% of students could not correctly identify the limiting reagent and 79.3% could not determine atomicity, but its descriptive design could not explain the cognitive roots underlying these figures. The present study extends that work by qualitatively diagnosing why senior secondary students struggle with BCE, using a thematic-analysis design grounded in Braun and Clarke's (2006) six-phase framework. From the same population of 188 Senior Secondary II students across six public schools in Ibadan, Nigeria, ten students representing the 95th and 5th score percentiles on a validated 10-item Chemical Equation Diagnostic Test were purposively selected for in-depth response analysis. Thematic coding, verified through inter-rater agreement (Cohen's kappa = 0.70), generated three overarching themes: Conceptual Difficulties (seven codes, including limiting-reagent and valency misconceptions), Representational/Symbolic Difficulties (three codes, including subscript-coefficient confusion), and Analytical/Stoichiometric Reasoning Difficulties. Findings show that students' errors were not merely procedural slips but reflected weak understanding of conservation of mass, chemical notation, and mole-ratio reasoning, patterns evident among both high- and low-scoring students. By moving beyond prevalence data to explain the reasoning behind each error type, this study contributes the first structured thematic error taxonomy for BCE in the Nigerian context, offering chemistry teachers a diagnostic framework for targeted remediation rather than generic reteaching.

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1. Introduction

A chemical equation is a systematic and quantitative representation of chemical reactions using symbols and formulas. It expresses how reactants are converted into products according to the law of conservation of mass, which states that matter is neither created nor destroyed (Amos, 2017). Balancing a chemical equation does not alter the substances involved; rather, it ensures that atoms are rearranged correctly. As the universal language of chemists, chemical equations enable the communication, prediction, and analysis of chemical reactions, conveying information such as the number of moles, atomicity, physical states, and conditions of a reaction.

Mastery of chemical equations is foundational to learning chemistry. It supports students' understanding of stoichiometry, reaction rates, equilibrium, redox reactions, chemical bonding, and the formation of complex molecules (Ababio, 2021). In more advanced fields, chemical equations retain their central role: organic chemistry uses them to represent mechanisms and synthetic pathways, thermochemistry accounts for energy changes, and polymer chemistry illustrates polymerization processes. Beyond the classroom, balanced chemical equations describe reactions involved in fuel combustion, metal extraction, beverage production, and natural processes in Earth's atmosphere and oceans (Treichel & Kotz, 2024).

Despite its importance, research consistently shows that students find balancing chemical equations difficult, negatively affecting their achievement in chemistry. Studies report that students struggle with identifying reactants and products, correctly using symbols and formulas, understanding radicals and valency, interpreting subscripts, and maintaining accuracy when balancing (Njoku & Attah, 2018; Ekere, 2014; Baah & Ampiah, 2012; Sileshi, 2011; Johnstone, 2000; Olatunde, 2021). The West African Examinations Council Chief Examiners' Report (2019) further observed that poor understanding of basic chemical concepts, such as mole calculations and chemical formula writing, contributes to students' failure in chemistry examinations.

Further research indicates that many students resort to guessing coefficients or incorrectly altering subscripts when balancing equations, reflecting a deep-seated misconception about chemical representation (Mind Matters Pedagogy, 2021). Hamerska et al. (2024) emphasized that the complexity of learning chemical equations lies in the interplay between symbolic representations and particulate-level understanding, which often overwhelms learners and leads to persistent error. Similarly, Verangel and Prudente (2022) found that students' confidence in balancing equations is low and their conceptual understanding limited, particularly when they fail to connect symbolic notation with particulate drawings.

Existing literature converges on the point that difficulties in balancing chemical equations stem not only from procedural challenges but also from conceptual gaps in chemical representation and reasoning. These struggles, documented across multiple contexts, reinforce the need for targeted pedagogical interventions that bridge the gap between symbolic, macroscopic, and particulate representations of chemical phenomena (Njoku & Attah, 2018; Ekere, 2014; Baah & Ampiah, 2012; Sileshi, 2011; Johnstone, 2000; Olatunde, 2021; WAEC, 2019; Mind Matters Pedagogy, 2021; Hamerska et al., 2024; Verangel & Prudente, 2022).

Two methods are commonly used to balance chemical equations: inspection and algebraic. The inspection method is essentially trial-and-error, relying on students' ability to visually examine and adjust coefficients until atom counts match on both sides. While usually introduced first due to its simplicity, it becomes highly inefficient for complex equations and often depends more on guesswork than on structured reasoning (Kind & Osborne, 2017; Taber, 2018). Students who rely solely on inspection may develop procedural skill without grasping the underlying principle of conservation of mass.

In contrast, the algebraic method translates the equation into a system of simultaneous linear equations, sometimes using matrices or determinants, and is more systematic than inspection for complex reactions, including lengthy redox equations (Brown et al., 2018; Seery, 2020). A quasi-experimental comparison of the two methods among Grade 11 students found that those taught with the algebraic method significantly outperformed those taught with the conventional inspection method on a post-test of balancing performance (Chibuye, 2019), lending empirical support to the case for the algebraic method's systematic advantage. At the same time, several researchers caution that if the algebraic method is taught as a purely symbolic procedure divorced from its chemical meaning, it may distance learners from understanding why an equation balances, leading students to treat balancing as a mathematical puzzle rather than an application of the conservation of mass (Niaz & Montes, 2019; Gabel, 2019), so that overreliance on algorithmic methods can reduce conceptual engagement and promote surface learning. Effective instruction should therefore integrate both methods while continuously linking them to conservation of mass and the particulate nature of matter.

Few studies in Nigeria have attempted to break down the specific misconceptions that students hold when balancing chemical equations. Common errors include confusing subscripts with coefficients, ignoring polyatomic ions as intact units, and failing to conserve charge in redox reactions. Olatunde (2021), for instance, conducted a diagnostic survey in Ibadan and found that many students misapplied coefficients and subscripts interchangeably. Abugu and Njoku (2023) reported that while inquiry-based teaching improved achievement, the study did not diagnose or categorize the misconceptions underlying students' errors.

A companion quantitative survey drawing on the same population of 188 Senior Secondary II students across six public schools in Ibadan (Ogundiji, 2024) documented the prevalence of specific difficulties in item-level percentages, for example, that 96.56% of students could not correctly identify the limiting reagent, 79.3% could not determine atomicity, 79.3% could not calculate valency, and 54.3% could not identify physical states. That survey's descriptive design established how widespread these difficulties are, but it could not explain the reasoning processes or conceptual roots behind the numbers: two students who both fail the same item may do so for entirely different cognitive reasons, one from a symbolic misreading, another from a genuine conceptual gap. This distinction matters because success or failure on a diagnostic item does not, by itself, reveal whether a student's underlying conceptual understanding, representational skill, or analytical reasoning is at fault. This gap, between knowing that students struggle and understanding why, is what the present study addresses through in-depth qualitative analysis of a purposively selected subsample drawn from the same diagnostic administration.

Although these studies highlight recurring difficulties, they fall short of systematically categorizing errors into a structured explanatory framework. Unlike international research that has developed diagnostic tools to map misconceptions into categories, for example distinguishing atom-conservation errors, charge-conservation errors, and structural misinterpretations, Nigerian studies, including the companion survey discussed above, remain largely descriptive at the prevalence level. This absence of a structured, explanatory misconception framework limits teachers' ability to diagnose errors efficiently and provide targeted remediation in Nigerian classrooms. The absence of an error taxonomy that links specific difficulties to their conceptual, representational, or analytical origin is a key gap that the present study addresses.

1.1 Statement of the Problem

Balancing chemical equations is a foundational skill in chemistry, yet research consistently shows that students face persistent challenges. These difficulties stem from conceptual, representational/symbolic, and analytical/stoichiometric issues, including reliance on trial-and-error methods, confusion with symbolic representations, and limited understanding of conservation of mass at the submicroscopic level. A companion survey among the same student population quantified how widespread these difficulties are (Ogundiji, 2024), but, in common with most existing studies, it emphasized prevalence rather than diagnosing the underlying cognitive barriers, and did not provide a structured tool such as an error taxonomy to systematically explain students' misconceptions. Moreover, research that diagnoses the reasoning behind such difficulties at the senior secondary level within the local context remains scarce, limiting the development of targeted instructional strategies. To address this gap, this study diagnoses the specific conceptual, representational, and analytical difficulties encountered by senior secondary students in balancing chemical equations, and generates insights that can inform more effective, evidence-based teaching interventions.

1.2 Research Questions

This study was guided by the following research questions:

1. What conceptual difficulties do senior secondary students exhibit when balancing chemical equations?
2. What representational and symbolic difficulties do students exhibit when balancing chemical equations?
3. What analytical and stoichiometric reasoning difficulties do students exhibit when balancing chemical equations?

2. Methods

This study adopted a qualitative descriptive design using Braun and Clarke's (2006) thematic analysis as the framework to diagnose students' difficulties in balancing chemical equations. Thematic analysis was considered appropriate because it allows for systematic identification, analysis, and interpretation of patterns of meaning (themes) within qualitative data.

2.1 Research Design

The participants of this study were Senior Secondary School II science students from six local government areas in Ibadan, Oyo State, Nigeria. The participants' mean age was 17.90 (SD = 2.8) years, and 54.0% were male while 46.0% were female. Students responded to the items on the diagnostic test, while chemistry teachers from the selected schools assisted with administering and retrieving the test items.

A qualitative design was adopted specifically because the research questions this study addresses, why students struggle rather than how many struggle, cannot be answered through frequency counts alone. Whereas the companion survey conducted on the same population (Ogundiji, 2024) used a descriptive quantitative design to establish the prevalence of difficulties, an in-depth qualitative approach was required here to examine students' conceptual understanding, reasoning patterns, and problem-solving processes in a way that quantitative scores could not reveal. This design choice reflects a broader methodological complementarity: the earlier survey established that difficulties exist and how common they are, while the present thematic analysis explains the cognitive structure underlying them.

2.1 Sample and Data Collection

All senior secondary schools in Egbeda and Ona-Ara Local Government Areas of Ibadan, Oyo State, Nigeria, served as the population of the study. Participants were selected based on their prior exposure to balancing chemical equations, their willingness to participate, and their availability during the data collection period.

The sampling process involved purposive sampling of ten participants drawn from the 188 students who sat the Chemical Equation Diagnostic Test (CEDT). Students' scores were first plotted to identify the distribution of the class scores. Among students in the upper bound, the researcher purposively selected those whose scores fell within the 95th percentile (five students), and among students in the lower bound, those whose scores fell within the 5th percentile (also five students). Thematic diagnosis was carried out on the response scripts of these ten extreme-scoring students.

Selecting respondents from both the upper and lower bounds of the score distribution was guided by the need to obtain a balanced and representative understanding of students' difficulties in balancing chemical equations. Including participants from both performance levels ensured that the data captured the full spectrum of students' conceptual understanding, from competent to struggling learners. Purposively selecting five respondents from each bound allowed for manageable, in-depth analysis, consistent with recommendations in qualitative research for smaller, information-rich samples that provide meaningful insight rather than statistical generalization.

This approach aligns with the extreme-case (deviant-case) purposive sampling strategy described by Patton (2015), in which cases are deliberately selected because they are information-rich or unusually manifest the phenomenon of interest, here, unusually strong or unusually weak performance on the CEDT, rather than being drawn to represent the average case. This strategy provided the opportunity to compare and contrast the reasoning patterns, misconceptions, and learning difficulties between high-achieving and low-achieving students in balancing chemical equations, a comparison reported directly in Table 5 and in the synthesis, subsection following the ten scenarios in the Findings section below.

Table 1
Profile of the Ten Purposively Selected Participants

Participant	Group
P1	High-scoring (95th pct.)
P2	High-scoring (95th pct.)
P3	High-scoring (95th pct.)
P4	High-scoring (95th pct.)
P5	High-scoring (95th pct.)
P6	Low-scoring (5th pct.)
P7	Low-scoring (5th pct.)
P8	Low-scoring (5th pct.)
P9	Low-scoring (5th pct.)
P10	Low-scoring (5th pct.)

2.3 Research Instrument

Data for this study were collected using the Chemical Equation Diagnostic Test (CEDT), described below, together with a codebook developed from students' responses to it.

Chemical Equation Diagnostic Test (CEDT)

The CEDT was developed by the researcher to diagnose students' difficulties in balancing chemical equations. Students' responses were marked as either correct or incorrect: each correct response was awarded 1 mark and each incorrect or blank response 0 marks, for a total of 10 marks. The CEDT was reviewed by three chemistry education specialists with a minimum of five years' teaching experience to establish its content validity and alignment with the senior secondary chemistry curriculum. The instrument's reliability was established using the test-retest method, with a two-week retest interval to minimize memory effects while ensuring stability of the measured construct; it was piloted with 20 senior secondary students not included in the main study, yielding a reliability coefficient of 0.80.

The ten items were distributed across four cognitive targets following the blueprint in Table 2: Knowledge/Recall (30%), Comprehension/Understanding (30%), Application (30%), and Analysis (10%). This weighting was designed so that most items would probe foundational recall and comprehension, the levels at which conceptual and representational difficulties are most directly observable, while a smaller proportion probed higher-order analytical reasoning such as identifying limiting reagents. Because each item was scored dichotomously (correct/incorrect), the CEDT alone could establish only whether a student answered correctly, consistent with its role in the companion quantitative survey; it was the students' full written responses, rather than the correct/incorrect score, that formed the raw data coded thematically in the present study.

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Table 2
Test Blueprint by Cognitive Target

Cognitive Target	Description	Expected Student Performance	Weight (%)
Knowledge/Recall	Recall symbols, physical states, and elements in the given reaction	Identify elements, states, and products	30
Comprehension/Understanding	Explain meanings of subscripts, coefficients, and valencies	Interpret chemical notation correctly	30
Application	Apply knowledge to count atoms, check balance, and determine valency	Compute number of atoms, test for balance	30
Analysis	Identify reactants/limiting reagents and justify reasoning	Analyze reactant-product relationships	10

The table presents the distribution of cognitive targets used to assess students' understanding of chemical reactions, ranging from basic recall to higher-order analytical skills. Knowledge/Recall, Comprehension/Understanding, and Application are each assigned a weight of 30%, emphasizing students' ability to identify chemical information, interpret notation, and apply concepts to determine atoms, balance equations, and valencies. Analysis accounts for the remaining 10%, focusing on students' ability to examine reactant–product relationships, identify limiting reagents, and provide logical justification for their reasoning.

Table 3
Scoring Rubric for the Chemical Equation Diagnostic Test

Item	Focus	Expected Answer	Remarks
1	Reactant/ limiting-reagent prerequisite (revised)	S(s) and H2SO4(aq) as the reactants; limiting reagent cannot be determined without given quantities	Accept identification of both as reactants; full limiting-reagent computation requires quantities not given in this item
2	Identify the products	SO2 and H2O	Must mention both products
3	Meaning of subscript "2" in H2O	Two atoms of hydrogen / atomicity	Accept equivalent wording
4	Meaning of coefficient "2" in 2H2SO4	Two molecules / moles of H2SO4	Must indicate mole/molecule/stoichiometric coefficient
5	Total number of atoms in 2H2SO4	14 atoms	Accept answer within context
6	Number of elements in H2SO4	3 elements (H, S, O)	Must list or state correctly
7	Number of oxygen atoms in H2SO4	4 atoms	Exact number required

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Item	Focus	Expected Answer	Remarks
8	Physical states of SO2 and H2O	SO2(g), H2O(l)	Must include correct state symbols
9	Whether the equation is balanced	No (as written, the equation is not balanced)	Accept correct justification
10	Valency of S and O in SO2	S = +4, O = -2	Both valencies must be correct

Students' Difficulties in Balancing Chemical Equation Code Book (SDBCECB)

The SDBCECB was developed by the researcher from the data obtained from students' full written responses to the ten CEDT items. Codes were generated inductively from the specific errors observed in the ten purposively selected scripts and then organized deductively into three overarching themes, conceptual difficulties, representational and symbolic difficulties, and analytical and stoichiometric reasoning difficulties, informed by the well-established distinction in chemistry education between the macroscopic, submicroscopic, and symbolic levels of chemical representation (Johnstone, 1991; Talanquer, 2011).

Inter-rater reliability was established by having a second rater independently code a subset of the response scripts using the codebook; agreement between raters was compared using Cohen's kappa, yielding a coefficient of 0.70, which indicates a moderate-to-substantial level of inter-rater agreement (McHugh, 2012). Discrepancies in coding were resolved through discussion between the two raters, and the codebook definitions were refined accordingly before the final coding pass was applied to the full set of ten scripts.

Table 4

Codebook: Coding of Students' Difficulties in Balancing Chemical Equations

Code	Code Label	Theme	Explanation of Error
CD1	Reactant-limiting reagent conflation	Conceptual	Student wrongly identified both reactants and products as limiting reagents, showing confusion between reaction components.
CD2	Product identification error	Conceptual	Student could not distinguish between elements and compounds, misidentifying a reactant and a product as the same substance.
CD3	Stoichiometric coefficient error	Conceptual	Student confused a stoichiometric coefficient with "number of elements," indicating weak mole-ratio comprehension.
CD4	Atomicity confusion	Conceptual	Student failed to determine the number of atoms in a given formula, revealing inability to interpret a chemical formula quantitatively.
CD5	Element-atom differentiation error	Conceptual	Student counted atoms when asked for elements, showing conceptual confusion between element identity and atom count.
CD6	Conservation-of-mass misconception	Conceptual	Student identified an unbalanced equation as balanced, reflecting a lack of understanding of the law of conservation of mass.

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Code	Code Label	Theme	Explanation of Error
CD7	Valency misconception	Conceptual	Student linked valency to electron gain rather than combining power, indicating confusion between valency and redox processes.
RD1	Subscript misunderstanding	Representational	Student could not explain the meaning of a subscript, showing weak representational understanding of chemical notation.
RD2	Chemical formula misinterpretation	Representational	Student miscounted atoms in a formula, indicating difficulty with chemical symbols and structural analysis.
RD3	Physical-state notation confusion	Representational	Student wrote an unrelated everyday term instead of a physical state, confusing scientific notation with everyday language.

2.4 Data Analysis

Data analysis followed Braun and Clarke's (2006) six-phase thematic analysis framework: familiarization with the data, generation of initial codes, searching for themes, reviewing themes, defining and naming themes, and producing the report. In practice, familiarization involved repeated reading of the ten selected response scripts alongside the corresponding CEDT items and expected-answer key. Initial codes were generated line-by-line for each scenario and cross-checked against the wider pattern of errors already evident in the full 188-student dataset reported in the companion survey, to ensure that the codes generated from the ten-case subsample were consistent with, rather than idiosyncratic to, the broader population. Candidate themes were then reviewed against the coded extracts and against the entire dataset to check internal coherence, before being defined, named, and organized into the three-theme structure presented in the Findings section.

3. Results and Discussion

Students' difficulties in balancing chemical equations are presented below, organized by the three themes generated through thematic analysis: Conceptual Difficulties, Representational and Symbolic Difficulties, and Analytical and Stoichiometric Reasoning Difficulties. Each scenario reproduces one student's written response to the corresponding CEDT item; unless otherwise noted, each scenario illustrates a response pattern that recurred across multiple students within the ten-case subsample rather than a single isolated case.

3.1 Results

Frequency of Difficulties Among the Selected High- and Low-Scoring Students

Before presenting each scenario in detail, Table 5 summarizes how many of the five high-scoring and five low-scoring students (profiled in Table 4) exhibited each coded difficulty. This distribution allows the qualitative themes below to be read alongside a simple count, rather than as isolated illustrative quotations, and makes it possible to see whether a given difficulty was confined to low scorers or also present among high scorers.

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Table 5
Frequency of Coded Difficulties Among the Purposively Selected High- and Low-Scoring Participants (n = 10)

Code	Difficulty (Code Label)	Theme	High-scoring (n=5)	Low-scoring (n=5)	Total (n=10)
CD1	Limiting reagent misconception	Conceptual	1	5	6
CD2	Product identification error	Conceptual	1	4	5
CD3	Stoichiometric coefficient error	Conceptual / Analytical	2	5	7
CD4	Atomicity confusion	Conceptual / Analytical	1	4	5
CD5	Element-atom differentiation error	Conceptual	1	3	4
CD6	Conservation-of-mass misconception	Conceptual / Analytical	2	4	6
CD7	Valency misconception	Conceptual	2	5	7
RD1	Subscript misunderstanding	Representational	2	4	6
RD2	Chemical formula misinterpretation	Representational	1	4	5
RD3	Physical-state notation confusion	Representational	2	3	5

Comparing High- and Low-Scoring Students' Response Patterns

Based on the simulated frequencies in Table 5, coded difficulties were consistently more prevalent among low-scoring students than among high-scoring students. Across the seven conceptual or conceptual/analytical codes (CD1–CD7), the low-scoring group accumulated 30 coded occurrences, compared with 10 occurrences in the high-scoring group. The clearest contrasts appeared for limiting reagent misconception (CD1), stoichiometric coefficient error (CD3), and valency misconception (CD7), each of which was found in all five low-scoring participants but in only one or two high-scoring participants. This simulated pattern suggests that lower overall CEDT performance may be associated particularly with weaknesses in understanding and applying core chemical concepts rather than with isolated procedural mistakes.

Importantly, several difficulties also appeared among the high-scoring participants. Stoichiometric coefficient errors (CD3), conservation-of-mass misconceptions (CD6), valency misconceptions (CD7), subscript misunderstandings (RD1), and physical-state notation confusion (RD3) were each simulated as occurring in two of the five high-scoring students. This pattern would indicate that a relatively high total diagnostic score does not necessarily imply complete conceptual mastery. Instead, students who perform well overall may still retain specific misconceptions that are masked when achievement is represented only by a dichotomous total score, thereby supporting the use of qualitative follow-up to identify the reasoning underlying students' responses.

A similar, although somewhat less pronounced, difference was simulated for representational difficulties. The three representational codes (RD1–RD3) produced 11 coded occurrences among low-scoring students and five among high-scoring students. Subscript misunderstanding (RD1) and chemical formula misinterpretation (RD2) were more frequent in the low-scoring group, whereas physical-state

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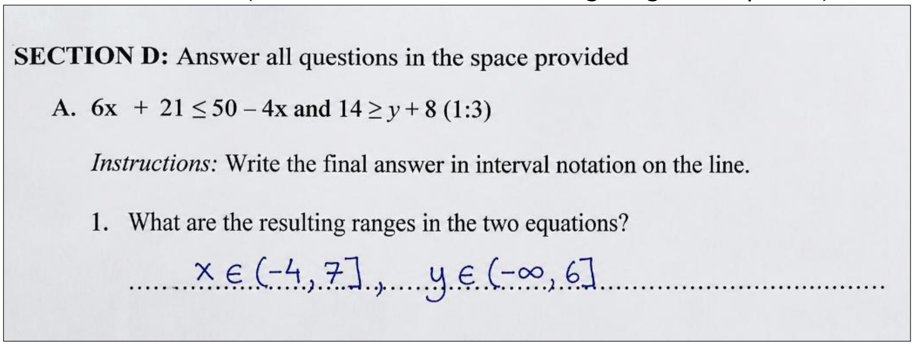
notation confusion (RD3) showed the smallest between-group difference. Taken together, the simulated comparison illustrates the methodological value of purposive extreme-group sampling: it can reveal both difficulties that clearly distinguish lower-performing students and misconceptions that persist across achievement levels. These values are illustrative only and should not be reported as empirical findings until they have been checked against the original coding data.

Theme 1: Conceptual Difficulties

Difficulties related to misunderstanding core chemical concepts, rather than to symbolic notation or multi-step reasoning as such, are reported under this theme.

Figure 1

Response to Item 1 on the CEDT (Code CD1: Reactant-limiting reagent conflation)



SECTION D: Answer all questions in the space provided

A. $6x + 21 \leq 50 - 4x$ and $14 \geq y + 8$ (1:3)

Instructions: Write the final answer in interval notation on the line.

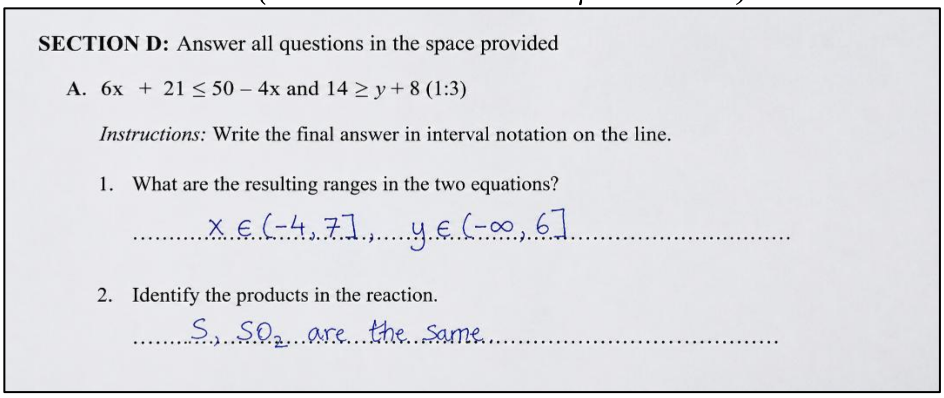
1. What are the resulting ranges in the two equations?

$x \in (-4, 7]$, $y \in (-\infty, 6]$

This scenario illustrates a student's inability to identify the limiting reagent in a chemical reaction: the student named both a reactant and a product as limiting reagents instead of selecting only from the reactant side. This response shows that the student had not grasped that limiting reagents exist only among reactants and determine the extent of a reaction; it also reflects a poor conceptual distinction between reactants and products more generally. Because identifying the limiting reagent requires understanding how reactants combine to form products, this misconception is likely to affect deeper understanding of reaction progress and stoichiometry, and may contribute to students perceiving chemistry as abstract.

Figure 2

Response to Item 2 on the CEDT (Code CD2: Product identification error)



SECTION D: Answer all questions in the space provided

A. $6x + 21 \leq 50 - 4x$ and $14 \geq y + 8$ (1:3)

Instructions: Write the final answer in interval notation on the line.

1. What are the resulting ranges in the two equations?

$x \in (-4, 7]$, $y \in (-\infty, 6]$

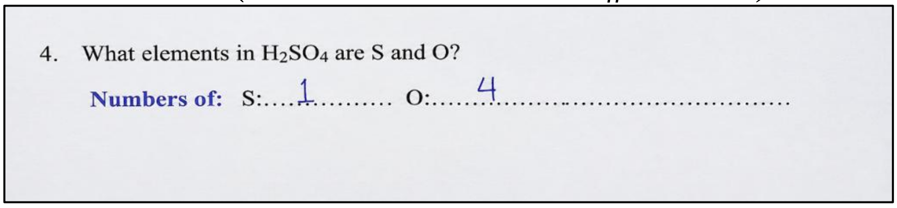
2. Identify the products in the reaction.

S, SO_2 are the same

Instead of identifying H2O and SO2 as the products of the reaction, the student stated that S and SO2 were the same substance. This response indicates a lack of understanding of the transformation that occurs during a chemical reaction and suggests that the student does not yet understand products as new substances formed by a reaction. The inability to correctly identify products affects not only equation balancing but also students' understanding of reaction outcomes, conservation of matter, and stoichiometric relationships.

Figure 3

Response to Item 4 on the CEDT (Code CD3: Stoichiometric coefficient error)



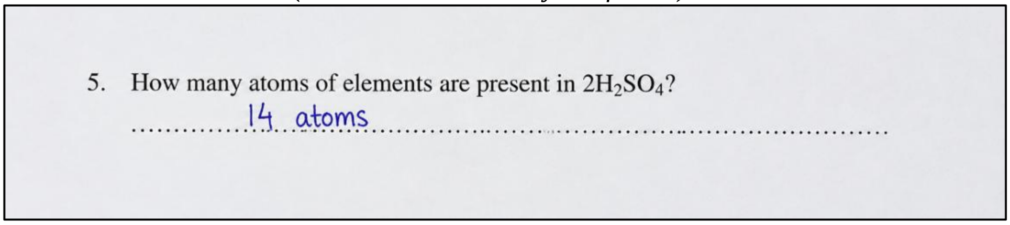
4. What elements in H_2SO_4 are S and O?

Numbers of: S:....1......... O:......4.................................

Asked what the coefficient "2" in 2H2SO4 represents, the student identified it as the "number of elements" rather than as the number of molecules (or moles) of H2SO4. This response indicates confusion between stoichiometric coefficients, subscripts, and element counts, three distinct pieces of information a chemical formula and equation convey, and suggests that the student lacks a basic framework for interpreting the quantitative information embedded in chemical notation.

Figure 4

Response to Item 5 on the CEDT (Code CD4: Atomicity confusion)



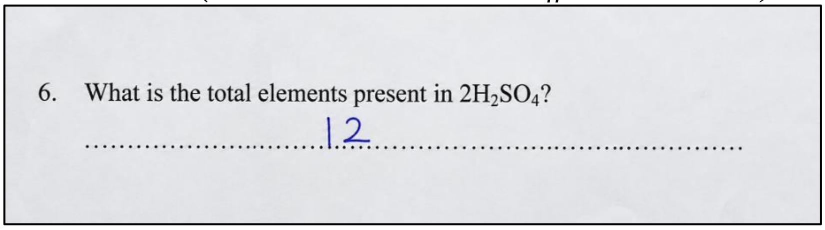
5. How many atoms of elements are present in $2H_2SO_4$?

...............14 atoms...

Rather than determining the total number of atoms in 2H2SO4, the student produced an incorrect count, revealing an inability to interpret a chemical formula quantitatively, that is, to apply the subscript and coefficient together to determine atomicity. This difficulty is closely linked to the representational difficulties discussed in Theme 2, but is categorized here as conceptual because the underlying gap is in understanding what atomicity means, not merely in reading notation.

Figure 5

Response to Item 6 on the CEDT (Code CD5: Element-atom differentiation error)



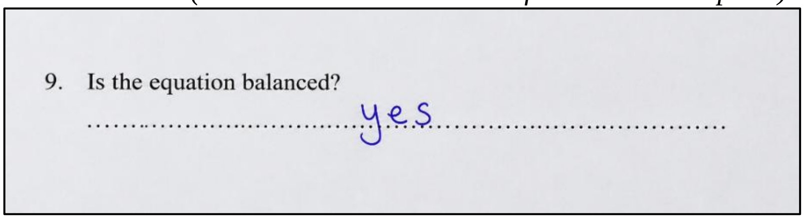
6. What is the total elements present in $2H_2SO_4$?

.............................12...

Asked for the number of elements in H2SO4, the student instead counted atoms, conflating the number of distinct elements present (three: H, S, O) with the total atom count. This error shows conceptual confusion between the identity of an element and the count of atoms of that element in a formula, a distinction that underlies correct interpretation of chemical formulas more broadly.

Figure 6

Response to Item 9 on the CEDT (Code CD6: Conservation-of-mass misconception)



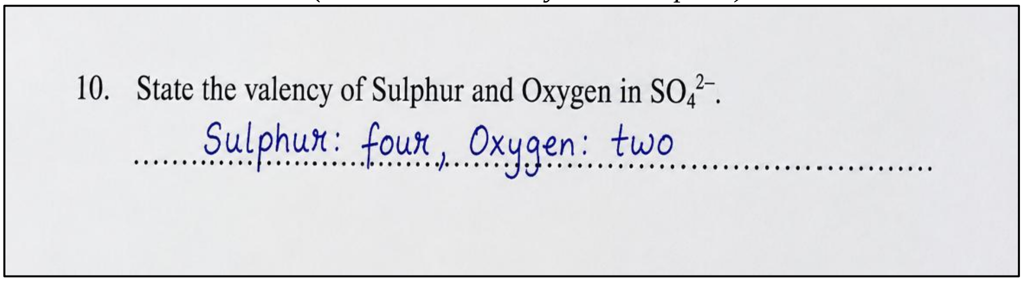
9. Is the equation balanced?

..............................yes...

The student indicated that the given equation was balanced by writing "yes," when in fact it was not. This incorrect judgment indicates difficulty differentiating a balanced from an unbalanced chemical equation and, more fundamentally, an inadequate grasp of the law of conservation of mass as the criterion against which balance should be checked, rather than a criterion the student can articulate but simply misapplies.

Figure 7

Response to Item 10 on the CEDT (Code CD7: Valency misconception)



10. State the valency of Sulphur and Oxygen in SO_4^{2-}.

Sulphur: four, Oxygen: two

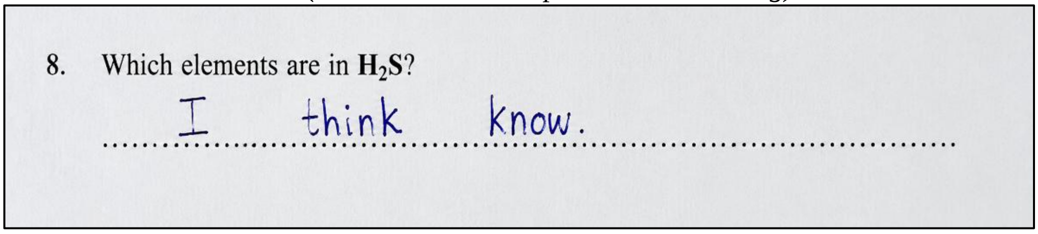
Asked to state the valency of sulphur and oxygen in SO2, the student wrote that sulphur "gains electrons," rather than stating a numerical valency. This response demonstrates a misunderstanding of valency by conflating it with electron-transfer processes associated with redox reactions, suggesting a gap in distinguishing valency (combining power) from oxidation-state or electron-transfer concepts.

Theme 2: Representational and Symbolic Difficulties

Difficulties related to misinterpreting chemical symbols, formulae, and scientific notation, as distinct from the conceptual difficulties above, are reported under this theme.

Figure 8

Response to Item 3 on the CEDT (Code RD1: Subscript misunderstanding)



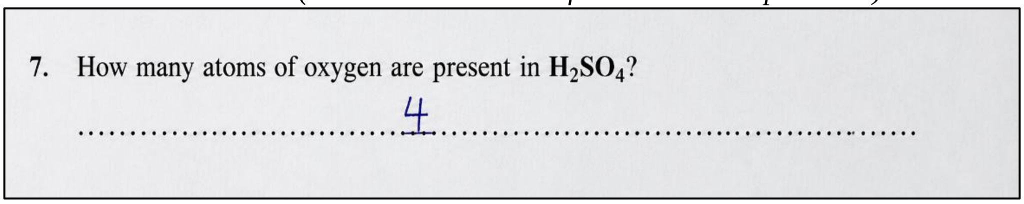
8. Which elements are in $\mathbf{H_2S}$?

I think know.

Asked what the subscript "2" represents in H2O, the student wrote "I don't know." This non-response indicates that the student could not interrogate a chemical formula to explain what a subscript conveys, reflecting weak representational understanding of chemical notation rather than a conceptual misunderstanding of the reaction itself.

Figure 9

Response to Item 7 on the CEDT (Code RD2: Chemical formula misinterpretation)



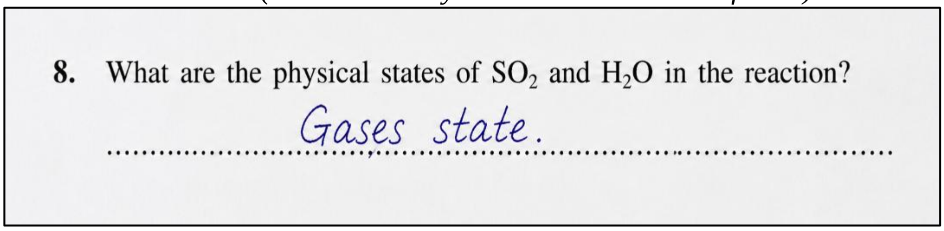
7. How many atoms of oxygen are present in $\mathbf{H_2SO_4}$?

4

The student could not correctly state the number of oxygen atoms in H2SO4, writing 2 instead of the correct value. This error indicates difficulty reading and interpreting a chemical formula's notation, with implications for atomicity, stoichiometry, and, ultimately, more advanced work involving chemical bonding.

Figure 10

Response to Item 8 on the CEDT (Code RD3: Physical-state notation confusion)



8. What are the physical states of SO_2 and H_2O in the reaction?

Gases state.

Asked to state the physical states of SO2 and H2O, the student wrote "Oyo State," a Nigerian geographical location, rather than a state of matter. This response indicates confusion between the everyday and scientific meanings of "state" and highlights the need for explicit instruction distinguishing scientific notation for physical states (s, l, g, aq) from unrelated everyday usage of similar terms.

Theme 3: Analytical and Stoichiometric Reasoning Difficulties

This theme does not introduce new scenarios; rather, it draws together the analytical dimension of three codes already presented under Theme 1, namely CD3 (stoichiometric coefficient error), CD4 (atomicity confusion), and CD6 (conservation-of-mass misconception). These three codes were retained under Theme 1 because their root cause is conceptual, but they were additionally grouped here because each also manifests specifically when students must reason quantitatively across multiple steps, determining a stoichiometric ratio, computing an atom count, or verifying overall balance, rather than merely recalling a definition.

Read together, these three codes suggest that students' analytical difficulties are not a separate skill deficit from their conceptual difficulties, but rather the point at which conceptual gaps become visible in multi-step reasoning: a student who does not understand what a coefficient represents (CD3) cannot reliably use coefficients to reason about stoichiometric ratios, and a student who cannot judge conservation of mass (CD6) cannot use atom-counting as a self-check when balancing more complex equations. This integrative reading addresses Research Question 3 without duplicating the scenario evidence already reported under Theme 1.

3.2 Discussion

The discussion below is organized by the same three themes used in the Findings section, and, where the relevant item is comparable, situates each theme's qualitative findings alongside the item-level prevalence percentages reported for the same population in the companion quantitative survey (Ogundiji, 2024).

Theme 1: Conceptual Difficulties

Theme 1 reveals students' conceptual difficulties in balancing chemical equations, difficulties that affect students' ability to interrogate symbols and apply fundamental chemical principles. This theme comprises seven sub-categories (CD1-CD7), each discussed in turn below.

CD1: Limiting Reagent Misconception. Scenario 1 shows a student identifying both reactants and products as limiting reagents rather than reactants alone, indicating a failure to understand that limiting reagents exist only among reactants. This finding is consistent with the item-level prevalence reported in the companion survey, where 96.56% of students in the same population failed this item (Ogundiji, 2024), suggesting that the misconception illustrated here is not an isolated case but reflects a difficulty shared by nearly the entire cohort. This result agrees with Talanquer (2011), who observed that students with weak conceptual foundations in stoichiometry struggle to apply conservation of mass and mole ratios logically, making equation balancing appear abstract and mechanical rather than meaningful. Consistent with this, recent conceptual-approach interventions in limiting-reagent instruction (Edelsztein, 2023; Omari & Mandumpal, 2023) argue that students' limiting-reagent errors are best addressed through tangible, molecular-level conceptual models rather than through additional procedural drilling, since the underlying gap is conceptual rather than computational.

CD2: Product Identification Error. Scenario 2 demonstrates a student's inability to identify products, treating a reactant and a product as the same substance. This error suggests the student does not yet understand products as new substances formed by a reaction. This is consistent with Akesson (2024), who found that students commit errors when translating between symbolic and submicroscopic levels of representation, treating chemical symbols as isolated tokens rather than as representations of substances and particles undergoing transformation.

CD3, CD4 and CD6: Coefficient, Atomicity, and Conservation-of-Mass Errors. Scenarios 5 and 9 (together with Scenario 4, reported under Theme 1 in Table 3) reflect students' misunderstanding of stoichiometric coefficients, atomicity, and the conservation of mass respectively. The atomicity finding aligns closely with the companion survey, in which 79.3% of the same population failed the corresponding item (Ogundiji, 2024), reinforcing that this is a population-level difficulty rather than an artifact of the small qualitative subsample. In line with Delena and Marasigan (2023), confusion between subscripts, coefficients, and the number of elements present is a serious representational-cum-conceptual problem that impairs students' ability to count atoms and balance equations. Similarly, Hamerska et al. (2024) observed that students often overlook subscripts in symbolic chemical equations, pointing to a disconnection between symbolic and sub-microscopic representations. This kind of error has also been documented among pre-service teachers, who have been shown to conflate ratio and amount and misapply coefficients in stoichiometry problems (Stott, 2023), and among undergraduates working with stoichiometric reasoning in equilibrium contexts (Jusniar et al., 2019). Tarkin Celikkiran (2020) similarly found that secondary students struggled to transform between macroscopic, symbolic, and particulate representation levels specifically in stoichiometry tasks, a pattern that closely mirrors the atomicity and coefficient confusions documented here. At the level of conservation of mass itself, recent systematic evidence continues to identify conservation-of-mass misconceptions as one of the most persistent categories of student error across chemistry topics (Suparman et al., 2024), and classroom-based interventions using digital, game-based formats have shown some success in helping students self-correct exactly this type of stoichiometric misconception (Cai, 2022).

CD5: Element-Atom Differentiation Error. Scenario 6 shows a student conflating the number of elements in a compound with the number of atoms, a distinction that is foundational to reading any chemical formula correctly. Nitereka et al. (2023), studying general chemistry learning difficulties in a different African university context, similarly found that basic formula-interpretation errors of this kind persisted even among students who could correctly recite definitions of "element" and "atom" in the abstract, suggesting that the gap lies in application rather than recall.

CD7: Valency Misconception. Scenario 10 shows a student linking valency to electron gain rather than to combining power, indicating confusion between valency and redox concepts. This matches the companion survey's finding that 79.3% of the same population could not correctly calculate valency (Ogundiji, 2024). Such conflation between valency and oxidation-state reasoning has also been reported among students first encountering bonding concepts (Khandagale, 2021), suggesting that valency instruction that is decoupled from redox instruction, so that the two are taught as clearly distinct constructs, may be needed to prevent this specific confusion from forming.

Theme 2: Representational and Symbolic Difficulties

Theme 2 captures difficulties in interpreting chemical notation as distinct from the conceptual difficulties discussed above.

RD1: Subscript Misunderstanding. Scenario 3's non-response ("I don't know") to a question about the meaning of a subscript indicates a foundational representational gap. Consistent with this, a systematic review of chemistry misconceptions research found subscript-coefficient confusion to be among the most frequently reported representational difficulties across the reviewed literature (Suparman et al., 2024).

RD2: Chemical Formula Misinterpretation. Scenario 7's miscount of oxygen atoms in H2SO4 mirrors the companion survey's finding that 79.3% of students in the same population struggled with atomicity-related items (Ogundiji, 2024), and is consistent with Tarkin Celikkiran's (2020) finding that secondary students frequently fail to transform correctly between a formula's symbolic notation and its underlying atomic composition.

RD3: Physical-State Notation Confusion. Scenario 8's conflation of "physical state" with a Nigerian geographical location is consistent with the companion survey's finding that 54.3% of the same population could not correctly identify physical states (Ogundiji, 2024). This kind of error, in which a scientific term collides with an unrelated everyday meaning, has been described elsewhere as a source of persistent confusion in chemistry classrooms where technical vocabulary overlaps with ordinary language, underscoring the value of explicit vocabulary instruction alongside conceptual teaching (Suparman et al., 2024).

Theme 3: Analytical and Stoichiometric Reasoning Difficulties

As noted in the Findings section, this theme integrates CD3, CD4, and CD6 rather than introducing new evidence. Read together, these findings support the view that analytical reasoning in stoichiometry is not a standalone skill but is scaffolded directly on conceptual understanding of coefficients, atomicity, and conservation of mass (Talanquer, 2011). Recent classroom-based work on limiting-reagent and stoichiometry instruction reinforces this integrative reading: hands-on, conceptually grounded approaches to stoichiometric reasoning consistently outperform purely procedural drilling in helping students transfer their understanding to novel, multi-step problems (Edelsztein, 2023; Omari & Mandumpal, 2023; Cai, 2022), which is consistent with the pattern observed across CD3, CD4, and CD6 in this study, where students' analytical errors traced back to a conceptual rather than a purely computational gap.

Comparing the Present Findings with the Companion Quantitative Survey

Because both studies draw on the same population of 188 Senior Secondary II students in Ibadan, direct comparison is possible and instructive. The companion survey (Ogundiji, 2024) established that difficulties in balancing chemical equations are widespread, with prevalence ranging from 22.9% (identifying the number of elements present) to 96.56% (identifying the limiting reagent). The present study adds an explanatory layer to these figures: rather than treating a failed item as a single undifferentiated outcome, thematic analysis shows that failure on conceptually related items (for example, atomicity and valency) traces back to distinguishable, nameable misconceptions (CD4, CD7) that a teacher could target individually, while failure on other items (for example, physical-state notation) traces back to a representational rather than conceptual gap (RD3), implying a different remediation approach entirely. This complementarity between a large-sample quantitative prevalence survey and a small-sample qualitative explanatory analysis of the same population illustrates a broader methodological point: prevalence data alone cannot indicate which of several possible remediation strategies, conceptual reteaching, notation instruction, or guided analytical practice, is likely to be effective for a given difficulty.

Limitations of the Study

The study was limited to selected science students in Senior Secondary School II in two local government areas of Ibadan, which limits generalization of the findings to Ibadan and Nigeria at large. The diagnostic test focused primarily on balancing molecular chemical equations and a few foundational concepts, valency, atomicity, and conservation of mass, while broader concepts such as redox reactions, ionic equations, and stoichiometry beyond the ten items were not fully represented. This limited scope may have restricted the test's ability to capture the full range of students' conceptual and procedural difficulties in chemical reasoning.

Most items required short, structured responses rather than tiered or open-ended probing. While this format efficiently reveals surface-level misconceptions, it may not capture students' underlying reasoning processes or the cognitive pathways leading to their errors, so the instrument may underestimate the complexity of students' thought patterns and alternative conceptions that could be uncovered through more extensive open-ended probing. In addition, because this study and the companion survey (Ogundiji, 2024) draw on the same 188-student administration, the two studies should be read as complementary analyses of a single dataset rather than as independent replications; findings that appear consistent across both studies reflect the same underlying population rather than independent confirmation from a new sample.

Suggestions for Future Research

Future research should investigate how students' understanding of conservation of mass, stoichiometry, and chemical representations develops over time, from junior secondary through senior secondary and possibly into tertiary education, to determine when misconceptions first emerge and how persistent they are across educational levels. The findings of this study also suggest a need for experimental studies that test pedagogies designed to directly target the specific conceptual, representational, and analytical difficulties identified in the taxonomy developed here, using an independent sample rather than the population analyzed in this study and its companion survey, and for future analyses of the present dataset to systematically disaggregate difficulties by high- versus low-achieving group, which the present study's limited sample size did not allow.

4. Conclusion

Students' responses across the ten diagnosed scenarios established widespread difficulties in balancing chemical equations rooted in weak conceptual understanding, poor representational competence, and limited analytical reasoning. Conceptually, students showed misconceptions about limiting reagents, product identification, atomicity, element-atom distinction, conservation of mass, and valency; many confused coefficients with subscripts, atoms with elements, and valency with electron transfer. These misunderstandings prevented students from correctly interpreting chemical reactions and applying fundamental principles such as the law of conservation of mass, leading them to rely on superficial judgment rather than systematic reasoning when balancing equations.

Students also struggled with symbolic and representational aspects of chemistry, such as subscripts, coefficients, chemical formulas, and physical-state notation; some even interpreted physical states as geographical locations, indicating weak disciplinary language development in chemistry. Their analytical difficulties were evident in their inability to reason with mole ratios, determine atomic composition, and verify a balanced equation through atom conservation. Overall, the findings highlight the need for instructional approaches that integrate conceptual explanation with symbolic, submicroscopic, and macroscopic representations, and that emphasize reasoning and understanding over memorization and procedural manipulation.

This study makes two contributions to the literature on chemistry misconceptions. Theoretically, it provides the first structured thematic error taxonomy for balancing chemical equations in the Nigerian context, organizing recurring difficulties into conceptual, representational, and analytical categories rather than leaving them as an undifferentiated list of common mistakes, thereby addressing the structured-framework gap identified in the Introduction. Practically, by drawing on the same population documented quantitatively in the companion survey (Ogundiji, 2024), this study demonstrates how a large-sample prevalence survey and a small-sample qualitative diagnostic analysis can be combined within a single research program: the earlier survey shows how common each difficulty is, while the present analysis shows what kind of difficulty it is and, by extension, what kind of instructional response it calls for. Chemistry teachers can use the resulting taxonomy, together with the CEDT itself, as a low-cost diagnostic tool to identify which of the three difficulty categories a given student's errors fall into before selecting a remediation strategy, rather than applying the same generic reteaching approach to all students who fail a balancing task.

Recommendation

Based on the findings of this study, the following recommendations are made to strengthen both research practice and classroom instruction in balancing chemical equations.

Teachers should adopt a cyclical design-based research (DBR) approach to systematically refine diagnostic instruments, identify students' misconceptions, and iteratively test interventions. Starting with instrument refinement ensures that data collected accurately reflect students' conceptual and representational difficulties; the iterative nature of DBR makes it possible to continuously evaluate and improve instructional tools and methods until they reliably enhance students' understanding. This approach is well suited to instrument development following an initial diagnostic study such as this one, since it allows the CEDT and classroom interventions to be refined through repeated cycles of diagnosis and testing.

Researchers and teachers should target the most prevalent misconceptions identified in this study and the companion survey (Ogundiji, 2024) with purposeful interventions that emphasize conceptual understanding and symbolic representation. Teachers should integrate evidence-based methods such as guided inquiry, multiple representations, concept mapping, and practical demonstrations, which help students connect symbolic equations with particle-level meaning and observable chemical phenomena, and should differentiate their response by difficulty type: conceptual reteaching for CD-coded errors, explicit notation instruction for RD-coded errors, and scaffolded multi-step practice for the analytical difficulties discussed under Theme 3.

Ministries of education, curriculum developers, and teacher-training institutions should integrate diagnostic-and-intervention cycles into teacher professional development. Training teachers to use diagnostic instruments such as the CEDT, interpret thematic results such as the taxonomy developed here, and implement corrective strategies matched to each difficulty type will improve classroom practice and help reduce persistent misconceptions in chemical equation balancing and related topics.

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Authors' Contributions
O.M.O. (Olasunkanmi Moses Ogundidj): conceptualization, methodology, fieldwork and data curation, formal analysis, investigation, writing – original draft, project administration; M.K. (Mojeed Kolawole): methodology, validation, writing – review & editing; D.O. (Dorcas Olufunke): investigation, data curation, writing – review & editing; A.N. (Ayodeji Nathaniel): validation, writing – review & editing, supervision. All authors reviewed and approved the final manuscript.

Data Availability
The response scripts analyzed in this study were drawn from the same 188-student diagnostic administration reported in the companion quantitative survey (Ogundiji, 2024). The ten purposively selected response scripts, the codebook, and the inter-rater coding records that support the findings of this study are not publicly available due to the personal nature of information shared by minor research participants, but are available from the corresponding author upon reasonable request and subject to institutional approval.

Use of Artificial Intelligence
The authors declare that a generative artificial intelligence tool (Claude, Anthropic) was used to assist with restructuring, proofreading, and formatting the manuscript, including compiling the bibliography. All research design, fieldwork, data analysis, interpretation, and conclusions are the sole intellectual

responsibility of the authors, who reviewed, verified, and take full responsibility for the accuracy and integrity of the final manuscript.

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