

Teachers' Teaching Strategies, Opportunities, and Challenges When Developing Conceptual Understanding of Redox Reactions

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ABSTRACT

Teaching redox reactions requires careful investigation as learners often display a range of misconceptions, particularly in connecting the chemistry levels of representation: macroscopic, sub-microscopic, and symbolic. This study explores teachers' teaching strategies, opportunities, and challenges when developing conceptual understanding of redox reactions. The study is guided by the pedagogical link-making framework while supported by the expanding triangle chemistry-learning framework. An interpretive approach was followed using an interview protocol and observation criteria document to collect qualitative data. A purposely sampled group of ten chemistry teachers teaching in public schools in rural settings were interviewed, and three had lessons video/audio recorded and transcribed verbatim and analyzed using ATLAS-ti. The study results displayed as networks, Sankey frequency diagrams and text show that teachers used various strategies from passive to active strategies. Teachers adopted passive and active teaching strategies to enhance learners' learning progression of concepts. Teaching opportunities are presented as the positive applications of dimensions for conceptual understanding, contextualized analogical models and the provision of relevance of redox reactions. The teachers' active teaching strategies enhanced the relevance of the concepts by connecting them to learners' lives. Teaching challenges were limited content knowledge leading to challenges in shifting across levels of representation, particularly from the sub-microscopic level. Teachers demonstrated inadequate pedagogical skills that enhance conceptual understanding. Recommendations include developing focused professional development in pedagogical content knowledge of the particulate nature of matter, particularly the sub-microscopic level of representation of difficult topics and switching across different levels of representation.

KEY WORDS: Conceptual understanding; expanding triangle chemistry-learning framework; levels of chemistry representation, misconceptions; pedagogical link-making framework; redox reactions; teaching strategies

BACKGROUND

Bodner (2015) hypothesized that “*we can teach and teach well, without having the students learn*” (p. 181). The hypothesis suggests that not all learners interact with subject content, which results in learning. At the same time, Konicek-Moron and Keeley (2015) agreed and added that not all teaching results in understanding. Bodner (2015) and Konicek-Moron and Keeley (2015) suggested that more can be done to assist students in learning, particularly using learner-centered approaches and relevance through everyday life examples. However, despite extensive research on learner-centered approaches to teaching, learner problems with redox reactions are still reported in recent studies (Amponsah, 2020).

Redox reactions are challenging to understand due to the nature of the subject, Chemistry. These problems range from abstraction, philosophy of redox reactions, supervenience, reductionism, and emergence, competing models, approximates, and imprecise redox reactions laws, and redox reactions (chemistry) as a language. Contributory to the problematic

nature of the subject is the existence of redox reaction concepts in any of the three levels of representation (macroscopic, sub-microscopic, and symbolic) (Johnstone, 2010; Taber, 2013). By definition, the macroscopic representation includes all observed through the human senses; the sub-microscopic comprises atoms, molecules, ions, radicals, and sub-particles, while the symbolic representation involves symbols, chemical equations, language, mathematics, and mathematical modeling. Furthermore, chemists and chemistry education practitioners must navigate these problems as they switch across levels of representation and ensure learners acquire the relevant knowledge and skills of the subject through the teaching for conceptual understanding.

Previous studies (Adu-Gyamfi et al., 2015; Taber, 2019; Tsaparlis, 2019; Cole et al., 2021; Hadinugrahaningsih et al., 2022) reported learners' common incorrect or partially incorrect responses on questions involving redox reactions, with some responses not demonstrating any scientific knowledge or understanding. For example, in the grade 12 National School Certificate examination in South Africa, instead of learners

stating that MnO_4^- is a stronger oxidizing agent than Zn^{2+} , candidates used statements such as MnO_4^- is lower than/bigger than Zn^{2+} (Department of Basic Education (DBE), 2022, p. 246). These learner responses highlight the need to investigate how redox reactions are being taught and what can be done to develop conceptual understanding.

Rationale for the Study

Learners go through a prescribed curriculum where the learning progression is experienced across grades and topics (Jin et al., 2019). However, a prevalence of answers that lack scientific meaning, along with many scientific disconnections in national examinations, requires investigations to ascertain the causes and mitigatory responses. The study is positioned within the teaching of Redox reactions for conceptual understanding. Problems of teaching redox reactions have been extensively researched (Adu-Gyamfi et al., 2018; Goes et al., 2020a). However, most of these studies focused on learner experiences that culminated in different learner conceptions or levels of achievement without looking at the teachers' teaching strategies. The teachers' teaching strategies refer to all activities conducted by the teacher and their responsiveness in addressing learner challenges that retard or hinder learning. Despite contextualized studies on strategies to improve conceptual understanding (Goes et al., 2020; Guerra-Ramos, 2011), gaps still exist that require further studies using different approaches. This study explores teachers' teaching strategies, challenges, and opportunities when developing conceptual understanding of redox reactions. The aim of the study is addressed through the following research questions:

Research Questions

What are teachers' teaching strategies, challenges, and opportunities in promoting conceptual understanding of redox reactions? The main research question is addressed through the following research sub-questions.

- What strategies do teachers use when teaching redox reactions for conceptual understanding?
- What are teachers' opportunities when teaching redox reactions for conceptual understanding?
- What are teachers' challenges when teaching redox reactions for conceptual understanding?

LITERATURE REVIEW

Conceptual understanding is the internalization of interlinked concepts within the mental structure of the learner and, in this study, is demonstrated through the pedagogical link-making framework (Konicek-Moron and Keeley, 2015; Scott et al., 2011). Conceptual understanding is when "the learner grasps the meaning of information by interpreting and translating what has been learned" (DBE, 2011, p. 153). Understanding forms part of cognitive knowledge taxonomy, which is assessed through skills of interpreting, exemplifying, comparing, explaining, inferring, and classifying (DBE, 2011; Krathwohl, 2002).

Redox reactions are cited among the most problematic chemistry topics for high school learners (Woldeamanuel

et al., 2014; DBE, 2021; Rahayu et al., 2022). The teaching of redox reactions presents many challenges due to the nature of Chemistry that is pertinent to its philosophy (Holme et al., 2015; Mahaffy, 2015; Haghghat, 2020; Erduran and Kaya, 2019), reductionism and emergence (Orgil et al., 2019) electron transfer at the epicenter of redox reactions, as explained by Marcus's theory on electron transfer (Scherer and Fischer, 2017). Marcus's theory is too advanced for learners in high school to understand. Therefore, the concept is simplified to the cognitive level of high school learners. There can be over-simplification or under-simplification of the concept to the extent of losing its scientific meaning (Silverstein, 2011). More ways losing scientific meaning are supervenience (Kidanamariam et al 2013; Newman, 2013; Woldeamanuel et al., 2014), approximate and imprecise chemistry laws (Zanello et al., 2019), competing models with redox reactions depicted around four different models (oxygen, hydrogen, oxidation numbers, and electron transfer) (Karen, 2015; Goes et al., 2020; Lipscher, 2023) that conflict in some circumstances, and chemistry as a language (Erduran and Mugaloglu, 2014; Tümay, 2016; Lipscher, 2023). The language of redox reactions is dominated by the terms oxidation numbers, oxidation, reduction, oxidized substance, reduced substance, oxidizing agent, reducing agent, oxidant, reductant, reductive, and electrode potential, and these are introduced almost at the same time as they complement each other. Lipscher (2023) reiterated that introducing such terms to novice learners creates a certain level of abstraction that requires addressing. Considering these challenges, teachers should navigate and ensure that learners overcome the challenges and achieve conceptual understanding.

The dimension statements for conceptual understanding were developed through professional consensus and have gained recognition in chemistry education (Cooper and Stowe, 2018). Examples of these dimensions include depth of reasoning (Strzalecki, 2014), transfer of knowledge (Chi and VanLehn, 2012; Jaber and BouJaoude, 2012; Talanquer, 2018), prediction and expansion of ideas, which is less common in chemistry due to supervenience (Erduran and Mugaloglu, 2014; Lipscher, 2023). Other recognized dimensions include problem-solving and critical thinking (Bodner, 2015; Robertson, 2017) and the ability to translate concepts across chemistry levels and representations (Ormrod, 2016; Talanquer, 2018).

To facilitate conceptual understanding, active teaching strategies are recommended (McConnell et al., 2017). Active teaching strategies include, for example, prediction-observation and explanation (POE) in practical demonstrations, concept mapping, scientific argumentation, and the use of models and modeling. In implementing active teaching strategies, teacher questioning techniques remain central to achieving the intended goals (Zwiers and Crawford, 2011). Timeously applying the "how" and "why" questions provide learners with an in-depth engagement in learning (Affalo, 2021).

Concerns were raised about the use of active teaching strategies, as they were perceived to potentially hinder teaching for conceptual understanding, for instance, in models and modeling, a mishmash of analogies used by teachers results in not achieving intended objectives (Guerra-Ramos, 2011), teachers' actions and processes hinge on the teachers' subject content knowledge and pedagogical skills and that could be poor (Goes et al., 2020). The effective implementation of POE can be limited due to large classes and low levels of learner prior knowledge (Tsaparlis, 2019; Woldeamanuel et al., 2014). Developing problem-solving skills is a critical component of many high school curricula; unfortunately, it has remained problematic due to differences in definition and understanding of the concept (Adu-Gyamfi et al., 2018). For instance, learners are given numerous problems to improve their problem-solving skills (Cole, 2015) without addressing the underlying strategies, cognitive processes, and critical thinking skills needed to effectively address complex problems independently. Scientific argumentation offers an opportunity to integrate the chemistry language that has been neglected for too long due to the challenges and complexity of teaching it (Lipscher, 2023; Mani, 2016; Markic and Childs, 2016). Teachers need to develop skills to create scenarios that enable learners to articulate scientific arguments and counterarguments effectively (Cole, 2015; Talanquer, 2018). Concept mapping allows teachers to demonstrate the ability to connect concepts and teach them as a unit but can be problematic in practice (Konicek-Moron and Keeley, 2015; Wong et al., 2024). To achieve conceptual understanding, these highlighted challenges need to be addressed.

Theoretical Framework

The pedagogical link-making framework postulated by Scott et al., (2011), supported by the expanding triangle chemistry-learning framework (Chittleborough, 2014) underpin this study. The Pedagogical link-making framework provides a guide in teaching for conceptual understanding while embedded in the constructivist active teaching strategies (Mudadigwa and Msimanga, 2019). The expanding triangle chemistry learning framework encompasses the triple nature of chemical concepts, namely macroscopic, symbolic, and sub-microscopic, highlighting the interconnectedness and the importance of connecting the three levels of representations to develop abstract representations. The levels of representations ideally expand equally in all three directions (Taber, 2013; Treagust et al., 2003).

The pedagogical link-making framework consists of three primary forms: support knowledge building, promote continuity, and encourage emotional engagement (Scott et al., 2011). According to these authors, pedagogical approaches support primary forms in drawing links.

The support knowledge-building form is anchored around six pedagogical approaches where links are drawn between every day and scientific ways of explaining (Mahaffy, 2015; Stuckey et al., 2013); scientific concepts, as depicted by Novak,

(2010) and Tseng, (2020) when making concept maps showing the interconnection of concepts, scientific explanations, and real-world phenomena (Mahaffy et al., 2018; Talanquer, 2018); modes of representation such as chemical equations, half equations, ionic symbols, electrode potential table and values, and oxidation numbers, and the macroscopic, sub-microscopic, and symbolic levels of chemistry representation (Koopman, 2017; Mudadigwa and Msimanga, 2019); moving between different levels and scales of explanation.

In Chemistry, the emphasis is on explaining concepts across the different levels of representation - macroscopic, sub-microscopic, and symbolic (Jaber and BouJaoude, 2012; Johnstone, 2010; Koopman, 2017) and fostering analogical link-making (Talanquer, 2018). Unfortunately, the link-making framework does not emphasize the development of levels of representation at the same rate in knowledge building. Subsequently, the pedagogical link-making framework is complimented by the expanding triangle learning framework that emphasizes the connecting of levels of representations equally in all directions (Taber, 2013; Treagust et al., 2003).

The second form of the pedagogical link-making framework, promoting continuity, is supported by two approaches illustrating the time-dependent nature of teaching and learning. The progression of scientific concepts is based on content coherence and sequencing ideas in chemistry (Jin et al., 2019; Lehesvuori and Ametller, 2021). The two continuity approaches include developing a scientific story and managing/organizing the teaching process, however, teachers restructure the content sequence in their own way (Sibanda and Hobden, 2016).

Finally, the third form encourages emotional engagement and highlights the teacher-learner or learner-learner interaction during different teaching and learning activities (Sinatra et al., 2015). The two approaches involved are when addressing substantive content, for instance, in practical experiments (Lewthwaite, 2014; White and Gunstone, 1992; White and Gunstone, 2010; Rollnick, 2021; Schmidt, 2021) and using generic approaches (Scott et al., 2011).

METHODOLOGY

The study adopted an exploratory qualitative case study design. Within a case study design, an interpretative approach was followed (Creswell, 2013; Stake, 2010; Yin, 2018). The case is limited to Physical Sciences (Chemistry) teachers teaching redox reactions to senior high school learners in a rural area of South Africa. Only rural schools were considered because they share similar characteristics of limited resources, unlike most urban schools in the district.

The study used an interview protocol and observation criteria document for data collection. A purposive sampling procedure was used to select participants ($n = 13$). The sample comprised 10 males and 3 females, and had teaching experience spanning from 5 to 26 years. The set criteria for participating in the study

were Chemistry or Physical Sciences teaching qualification and teaching Chemistry in a public school. Ten interviews were conducted, lasting between 25 and 30 min while audio recorded, and three 30–35 min lesson video/audio recordings were captured while teaching redox reactions.

Results Presentation and Analysis

ATLAS-ti computer software aided the coding and categorizing of observation criteria and interview data. In the data, links were drawn to the connections between concepts or prior knowledge and new concepts, and segments were highlighted and assigned codes. The coding and re-coding of data had a gestation period of over a calendar month. Similar codes were merged to reduce redundancy. All related codes were grouped into categories. The related group codes generated themes that address-specific research questions. The code generation and theme interpretation were guided by the pedagogical link-making framework and the expanding triangle chemistry-learning framework.

What Strategies Do Teachers Use When Teaching Redox Reactions for Conceptual Understanding?

The research question is addressed through three themes: a learner-centered approach to teaching for conceptual understanding, enhancing learning progression through building blocks of concepts, and switching across levels of representation.

A learner-centered approach to teaching for conceptual understanding

Various learner-centered approaches were employed to ensure active learner participation; for instance, during a practical experiment/demonstration, learners responded to related questions before, during, and after the activity. In the process, questioning techniques involving guiding and follow-up questions requesting learner reflection on responses, and these responses allowed more connecting of concepts, for instance, "... where will the electrons be coming from?" (Participant ED2V). The teacher's wait time ranged from two to nine seconds, averaging four seconds before following up on a question or commenting on a learner's response. Intentionally or unintentionally, teachers facilitated formal and informal discussions on activities; for instance, learners discussed among themselves after being asked about the color of observed iron filings (Participant ED1V). Teacher modeling featured prominently in facilitating the visualization of concepts. Eight of the teachers allowed learners to review models of oxidation-reduction among the other activities. Only three teachers did the fostering of scientific argumentation.

Enhancing learning progression through building blocks of concepts

Knowledge building is progressive as concepts get interconnected. Gap filling played a significant role in linking concepts; for instance, "we had to go back and look at the atomic structure and identify together the location of electrons and what happens when we say an atom loses

electrons and when it gains electrons" (Participant ED1R). There was progressive connecting of concepts when teaching new concepts, "...after making learners know how atoms gain and lose electrons, I introduced the half-reactions showing learners the gaining and loss of electrons" (Participant ED7R).

Switching across levels of chemistry representation

Teachers switched across levels of chemistry levels of representations, the macroscopic, the sub-microscopic, and the symbolic. Interviews and observation criteria data in Figure 1 show the connections across levels of representations, including direction of connection.

The results in Figure 1 show disproportionate levels of connections of representations, with some being more prominent than others, for instance, symbolic to the sub-microscopic (very high) compared to symbolic to the macroscopic (very low) representation. Specific links were profound in one direction and weaker in the opposite direction, for instance, more frequent connections from the symbolic to the sub-microscopic representations compared to sub-microscopic to the symbolic representations. Connecting the sub-microscopic to the other levels of chemistry representation is very low, and to the level of zero connection with the macroscopic. However, there are improved connection frequencies from the symbolic to the sub-microscopic and even from the macroscopic to the sub-microscopic representation. Connecting to the symbolic, either from or to, is prevalent for the teachers. The connecting of concepts within the same level of representation is average, neither high nor low (Figure 1).

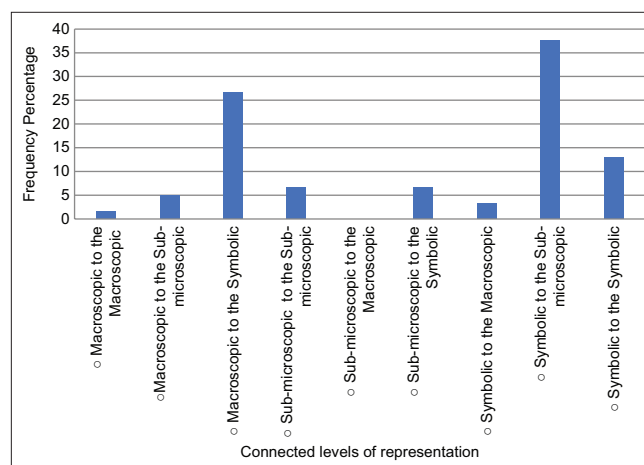


Figure 1: Switching across levels of representation

What are Teachers' Opportunities When Teaching Redox Reactions for Conceptual Understanding?

Four themes were generated that addressed the research question. The themes accountable to the opportunities for teaching redox reactions for conceptual understanding include positive applications of dimensions for conceptual understanding, mechanisms of enhancing conceptual understanding, stimulating learner engagement, and ascertaining the relevance of redox reactions to learners.

Positive applications of dimensions for conceptual understanding

The Sankey frequency diagram of dimensions of conceptual understanding as applied by participants in two data collection processes is presented in Figure 2.

The diagram shows similarities and differences in the frequencies of application of dimensions for conceptual understanding orally and in practice. The frequencies are not high, considering the amount of data analyzed.

Figure 3 network shows samples of excerpts for the application of the dimensions of conceptual understanding. There are notable levels of contextualization of the dimension of conceptual understanding within the excerpts. The network shows dimensions overlapping in many instances, showing their connectedness.

Enhancing conceptual understanding through local analogical representations

The use of analogies in teaching chemistry concepts is profound, with redox reactions no exception. Various types of analogical modeling, such as practical experiments and demonstrations, were used to connect scientific concepts. For instance, the teacher used a pencil to show graphite in the

physical presentation of real objects in modeling. A different example is the pictorial analogical modeling, where the teacher explained the change in oxidation numbers while making learners visualize the oxidation and reduction process through the number line (Participant ED2V). Teachers accompanied analogical modeling with various types of questions that allowed learners to engage in the learning process. The process of analogical representations was accompanied by learners being asked questions before, during, and after the activity. Apart from analogical representations, modeling was used in the form of chemistry modes of representations and levels of chemistry representations.

Stimulating learner engagement ensured active learner participation

Participating teachers ensured learners remained engaged in the learning process and various activities, and managed the process. During practical experiments/demonstrations, teachers kept learners actively engaged by asking questions before, during, and after the activity. Learners actively followed guiding and follow-up questions, requested to reflect on responses, and initiated formal and informal discussions and brainstorming. Teachers frequently used an average four-second wait time for a response from learners and responded

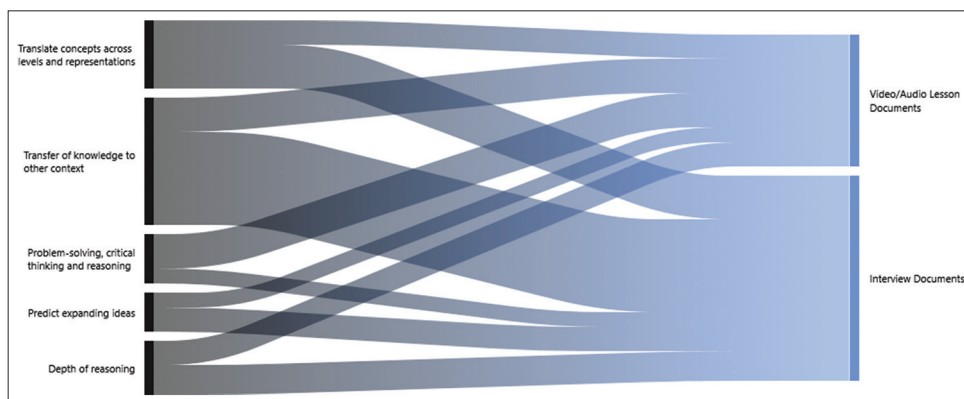


Figure 2: Sankey diagram of dimensions of conceptual understanding

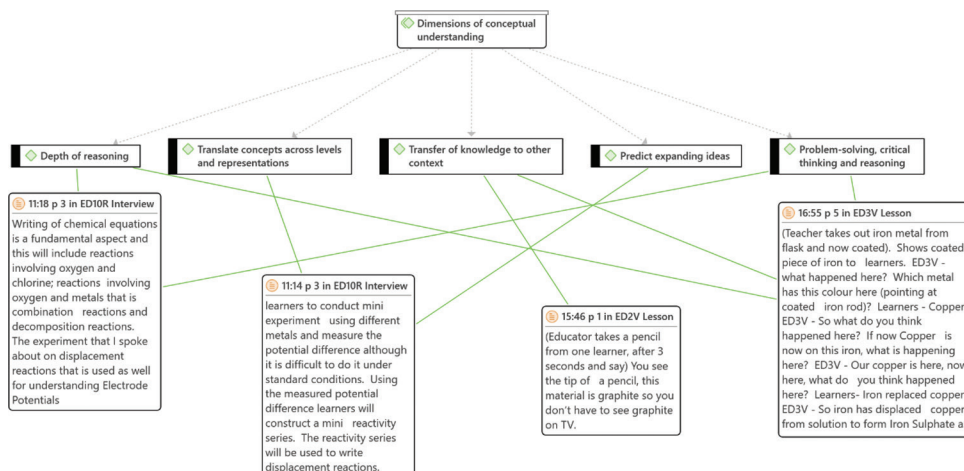


Figure 3: Applying dimensions of conceptual understanding

or comment on responses. However, there were deviations in wait-time depending on activity type and questioning. Problem-solving and scientific argumentation activities allowed learners to remain engaged and move across activities.

Providing relevance of Redox reaction to learners

Teachers viewed the relevance of redox reactions as fundamental to learning for conceptual understanding. Teachers minimized the abstractness of the Redox reactions concept by using local context as examples; for instance, "we have to relate to specific equations from those particular industries that apply redox reactions, for example, *extraction of iron, extraction of iron ore, learners will understand better*" (Participant ED8R). This example is given in the context of iron ore mining in the district. According to the extract, teachers connected redox reactions to learners' everyday lives and career opportunities, "*brainstorm with the learners on career opportunities that relate to redox reactions*" (Participant ED3R). Teachers suggested engaging in outside-classroom activities that promote interest in learners and connect redox reactions to societal issues.

What Are Teachers' Challenges When Teaching Redox Reactions for Conceptual Understanding?

The challenges are presented under four themes: teacher content knowledge from a high school perspective, teachers' alternative conceptions, teachers' challenges, negative teachers' pedagogical practices, and influential factors to pedagogical practices.

Teacher content knowledge from a high school perspective

In the process of assisting learners in understanding redox reactions, teachers presented the content at a high school cognitive level. The teachers' knowledge from a high school perspective included teachers' deliberately inaccurate conceptual knowledge; for instance, "*we spoke of ionic bonding saying there is a total transfer of electrons*" (Participant ED3R). The individual teachers invented or coined their terms, "*.... if you see electrons on the right, know that the process is oxidised*" (Participant ED4R), and empirical representation without scientific significance, in particular mnemonics, and fail to explain that the representation only facilitates in simplifying the concept for easier understanding. One example of many other cases is relating the charge of the element to oxidation number (Participant ED1V; ED2V; ED3V; ED2R).

Teachers' Challenges and Misconceptions Retarding Teaching for Conceptual Understanding

Teachers manifested false beliefs, for instance, "*elements can attain different charges depending on their ability to accept electrons or donate electrons culminating in the concept of electronegativity*" (Participant ED1R), flawed mental models, for instance, "*we spoke of ionic bonding saying there is total transfer of electrons*" (Participant ED3R). The cited example is of a flawed mental model presented in textbooks

and consequently, can be termed as deliberately inaccurate conceptual teacher knowledge.

The ontological miscategorization appeared several times, and one typical example is, "*....because what we have here is not pure oxygen, so I wanted to supply this one with more Activation Energy*" (Participant ED3V). Teachers' failure to distinguish everyday language from chemistry language resulted in misconceptions as per the example, "*.... but now we have a situation whereby oxygen is taken away for example, when fire is dwindling but not burning it means you are removing oxygen and the aspect of removing the oxygen is what is referred to as reduction*," (Participant ED2R). In such cases, teachers fail to distinguish when to use everyday language and chemistry language. Furthermore, teachers use empirical explanations with no scientific meanings, although analogies are prevalent in redox reactions.

Pedagogical practices contrary to teaching for conceptual understanding

Some teacher pedagogical practices are viewed as contrary to active teaching strategies that promote conceptual understanding. These include teachers' belief in developing understanding, for instance, repeating an explanation of a concept, using the exact words that learners claim not to understand, without providing an alternative explanation that closes the knowledge gap (Participant ED1V). The casual use of chemistry language, for instance, "*I will ask them a few questions after having taught them that the concept redox reactions means oxidation and reduction*" (Participant ED2R), demonstrates consideration of the definition of Redox reaction. Using empirical explanations of concepts without attaching scientific meaning does not promote conceptual understanding. The chemistry language versus everyday language was profound in eight teachers, as the scientific meaning was sometimes lost; for instance, "*the process where oxygen is added to a metal is what we refer to as oxidation*" (Participant ED2R). Additional examples of poor pedagogical practices include teachers narrating conceptual definitions to learners, verbal exposition of concepts without active learner involvement, and learners reproducing definitions.

Influential factors to pedagogical practices

Teaching in practice is influenced by other factors that are not teacher-dependent; however, the teacher manipulates the factors to manage teaching for conceptual understanding. Teachers cited factors influencing their teaching as they focused on ensuring learners pass their end-of-year examinations; for instance, "*we focus on changes in oxidation numbers than loss of hydrogen or addition of oxygen because this is what is asked examinations*" (Participant ED1R). Teaching focused on examination requirements, conducting experiments, and demonstrations. The class size influenced activities organized by teachers, with five teachers citing conducting practical demonstrations to accommodate large class sizes and limited time for practical experiments. Seven teachers cited the need for more time to teach the abstract concept of redox reactions

and the extensive syllabus content that needed coverage. Consequently, lecture-based teaching methods were used.

DISCUSSIONS

Teaching for conceptual understanding requires a systematic approach to teaching concepts that integrates new knowledge into the learners' knowledge framework. Teachers were found teaching concepts as isolated units, instead of showing connections and relationships between different conceptions, as in concept mapping. This finding was contrary to the pedagogical link-making approach in knowledge building, which supports connecting concepts across different levels.

Cited dimensions for conceptual understanding results in Figure 2 show teachers applied the dimensions at the macroscopic level of representation compared to the symbolic level. The teachers rarely (14%) applied the sub-microscopic level of representation. In cases where learners were required to apply the sub-microscopic levels, they either used the macroscopic explanation instead of the sub-microscopic representation or wrongly used the sub-microscopic representation. Woldeamanuel et al. (2014) found that macroscopic representations were used to explain other macroscopic representations instead of the sub-microscopic representation. Furthermore, Haigh et al. (2012) found similar results where the use of a sub-microscopic level of representation was almost non-existent. Their study found that learners' conceptual difficulties at the sub-microscopic level of representation were profound and created many other problems for learners achieving conceptual understanding. Disproportionate use of levels of representation created inconsistent use of the levels as they were not applied at the appropriate levels according to the expanding triangle chemistry-learning framework.

The expanding triangle chemistry-learning framework emphasizes the chemistry levels of representation developing equally in three directions (Taber, 2013; Treagust et al., 2003). Unfortunately, the disparities in representational proportions show different results. The results affirm the suggestion made in previous studies that teachers struggle to switch across levels of representation (Talanquer, 2018; Chittleborough, 2014)). Teachers demonstrated a lack of awareness of classifying the levels of chemistry representation as macroscopic, sub-microscopic, and symbolic, despite applying them. The lack of awareness impacts the switching across the levels. Teachers are expected to move across from where they are going, where (with reference to levels of representation)? The question is only answered when teachers become aware of the concept of the levels of chemistry representation and the expected expansion of the different levels of representation. Studies on visual representations of the chemistry levels of representation in high school textbooks in Brazil (Goes et al., 2020) and Chinese communities (Mainland China, Hong Kong, Taiwan, and Malaysia) (Chen et al., 2019) showed similar results of disproportionate frequency of connections between the levels.

Results from these two studies similarly highlight the problem as lying with teachers and curriculum materials.

A lack of physical properties characteristic of redox reactions, like other reactions, such as acids and bases, contributes to the disproportionate connection frequencies. The redox reactions are characterized by electron transfer, which is part of the sub-microscopic representation. The electron transfer is further presented at the symbolic level of chemistry representation. Subsequently, the expected results should show more connections from the sub-microscopic representation. The results point in the opposite. The results differ because most teachers' challenges and misconceptions appeared at the sub-microscopic level. Teachers' poor topic content knowledge at the sub-microscopic chemistry level of representation has implications for explaining or justifying the macroscopic levels of representation. Similarly, Woldeamanuel et al. (2014) found that teachers used other macroscopic representations to explain a different macroscopic instead of the sub-microscopic representation.

The suggestion by Johnstone (2010) to teach from the macroscopic level before the other representations is irreconcilable with the low proportion of the macroscopic representation connections to other representations. Wood (2013) further established improved conceptual understanding when macroscopic observations are made while deploying sub-microscopic models. Brandriet (2014) got similar results where macroscopic-symbolic had more traction than the rest of the connections, and went further in establishing that learners understood better at that level.

Teachers dispelled the notion of chemistry having no significance and meaning in learners' lives by connecting redox reactions to real-life examples through reviewing associated career opportunities and solving societal challenges. Szozda et al. (2022) reiterated the inclusion of the human factor into Chemistry to enhance relevance, which is essential for conceptual understanding. As in Tsakeni (2018), teachers made an effort in making chemistry relevant as guided by the curriculum, and transferred concepts to other contexts. Connecting redox reactions concepts to learners' lives motivates and promotes learner engagement in the teaching and learning process.

Simplifying chemistry concepts has been problematic due to reductionism and emergence as explained by Orgil et al., (2019). Simplification of concepts to learners' cognitive knowledge level by removing or leaving elements of the scientific definition results in a high school knowledge perspective. Over-simplification or under-simplification of concepts results in the remaining definition conflicting with the actual scientific definition or no longer applicable in all relevant scenarios. The high school knowledge perspective is presented in textbooks as correct scientific knowledge. Consequently, this presents problems when applying the concept to other scenarios. The problem is further exacerbated when textbooks are considered unequivocal and undisputable (Bergqvist and

Rundgren, 2017). The high school knowledge perspective leave learners confused as teachers use their prerogative for instance on the four redox reaction models (Ali et al., 2022). Learners struggle to identify what constitutes a redox reaction as the four models conflict with each other. The expectation is for teachers to cite the limitations of the concept to allow learners to expand their knowledge base and subsequently view the knowledge as non-contradictory.

Teachers manifested various types of conceptual challenges and misconceptions similar to those reported in previous studies (Adu-Gyamfi et al., 2018; Hadinugrahaningsih, Rahmawati, and Suryani, 2022; Tümay, 2016). At the heart of conceptual challenges and misconceptions is the sub-microscopic level of chemistry representation, which is part of the particulate nature of matter. Literature elaborated on teachers' struggle with the particulate nature of matter (Brandriet and Bretz, 2013). The teacher challenges were found to significantly retard teaching for conceptual understanding, as previous studies found that teachers inadequately teach or do not teach certain concepts due to poor topic content knowledge, for example, the Hydrogen Electrode Potential Table (DBE, 2021; Tsaparlis, 2019) is well cited.

Chemistry language versus everyday language came to the fore as reported by many other studies (Quílez, 2019). Teachers viewed chemical entities as physical matter that can be removed or added manually, for example, adding oxygen or hydrogen. The sub-microscopic particle movement is described at the macroscopic level, where the substance can be added or removed. Unfortunately, this is the removal/addition of atoms or molecules. Furthermore, from a chemical equation, teachers refer to the removal/addition of oxygen or hydrogen without referring to the process at the sub-microscopic level. The chemistry language versus everyday language problem emanates from failure to think in levels of chemistry representation, but think in everyday or undefined language. When applying the knowledge to the levels of representation, there is bound to be an interchange of levels, resulting in misconceptions.

Teachers' perception of chemistry as a practical subject saw the conducting of experiments/demonstrations as a modus operandi in various instances. In such circumstances, practical experiments/demonstrations were not aligned with the concept to be learned, or the parameters of observations were not clear. The practicals focused on science process skills, and the "what" questions were asked that only required surface knowledge. Surface knowledge contributes minimally to conceptual understanding. This is typical of studies reported by Rollnick (2021) in a book review of studies across 12 African countries. In promoting conceptual understanding, the "how" and "why" probing questions need prominence as they assist learners in interconnecting concepts (Aflalo, 2021).

CONCLUSIONS AND RECOMMENDATIONS

Teachers in this study have shown much promise in improving the teaching of redox reactions as they applied

dimensions for conceptual understanding through active teaching strategies and enhanced the relevance of the concepts by connecting them to learners' lives. The use of contextualized analogical models enhanced learner participation and engagement in the learning of concepts. Despite teachers striving to build blocks of chemistry concepts through active teaching strategies, the teaching process was unsystematic and inconsistent with several concepts taught as isolated and disconnected units. Teachers presented content knowledge from a high school perspective amid failing to identify limitations of the concepts and generate alternative conceptions. Several reported learners' conceptual challenges and misconceptions in many studies are school-generated as teachers are found to be part of their source. Achieving conceptual understanding requires pedagogical practices that enhance the process; unfortunately, several teachers' practices were contrary to the principles as they allowed external factors to influence their practice.

Teachers are unaware of the levels of chemistry representation despite unintentionally using them. Teachers struggle to switch across levels of representation, particularly from the sub-microscopic level of chemistry representation. This could be due to poor content knowledge on the particulate nature of matter. The failure to synchronize the teaching of the concepts at the same depth as the levels of representation renders the effort worthless, as misalignment of the levels of representation results in a generation of misconceptions. Since the sub-microscopic level of chemistry representation is deeply rooted in the particulate nature of matter, systematic professional development on the pedagogical content knowledge is required. Targeted workshop training for teachers on the sub-microscopic level of representation of difficult topics and switching across different levels of representation is recommended. Current trends and practices in Chemistry education should be emphasized during professional development.

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