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Challenges in Understanding the Redox Reaction Concept among Level 200 Students in Science Colleges of Education in Ghana

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Abstract

This study examines the common challenges and misconceptions pre-service teachers face in understanding redox reactions within electrochemistry. It also explores the effects of different instructional methods, comparing traditional lecture-based approaches with innovative strategies like problem-based learning. The study utilized a mixed methods approach, incorporating both qualitative and quantitative data. This methodology is effective in improving inferences and minimizing bias associated with single-method studies. The study aimed to address pre-service teachers' challenges in redox reactions by using a mixed method sequential explanatory design. This design involved first collecting and analyzing quantitative data, followed by qualitative data collection and analysis. The purpose of this design was to use qualitative findings to clarify and interpret quantitative results. In the quantitative phase, a diagnostic test for reduction-oxidation reactions (RORDT) was administered to identify and categorize challenges, followed by a questionnaire. The qualitative phase involved one-on-one interviews to explore the reasons behind these challenges. This approach was specifically tailored to study and find solutions for common redox reaction challenges among pre-service teachers in Ghana's Colleges of Education. After the quantitative analysis, students with various performance levels were interviewed to gain deeper insights into their reasoning. This study identifies the common difficulties in writing chemical equations, comprehending half-reactions, and the functions of salt bridges. Contributing factors to these misconceptions include language barriers, rote learning, and inadequate foundational knowledge coupled with ineffective teaching strategies. The findings underscore the importance of constructivist theories in addressing these educational challenges, emphasizing active learning, collaboration, and reflective thinking to enhance comprehension. This study contributes to the development of pedagogical content knowledge among chemistry educators, aiming to improve teaching practices and student outcomes in electrochemistry.

Keywords

Electrochemistry, Instructional Methods, Problem-Based Learning, Pedagogical Content Knowledge

1. Introduction

Reports indicate consistent underperformance in redox reactions among students. Pre-service teachers also show significant misunderstandings, impacting their teaching effectiveness and, consequently, their students' understanding.

The purpose of this study is to investigate the common challenges and misconceptions encountered by pre-service science teachers in learning redox reactions within the broader context of electrochemistry. Additionally, the study aims to evaluate the effectiveness of innovative instructional strategies, such as problem-based learning, in addressing these challenges and improving overall comprehension and performance.

The study was guided by the following objectives.

Identify and classify common challenges in learning redox reactions and evaluate their impact on both teaching practices and students' understanding of the concept as well as determining strategies to address and mitigate the effects of these challenges in teaching and learning redox reactions.

The significance of this study lies in its potential to enhance the quality of chemistry education by identifying and addressing the prevalent challenges and misconceptions in redox reactions among pre-service science teachers. By exploring effective instructional strategies, such as problem-based learning, the study aims to improve teaching methods, foster deeper understanding, and ultimately elevate student performance in electrochemistry. This study could contribute to the development of more effective pedagogical approaches, thereby strengthening the overall educational framework in chemistry and preparing future teachers to deliver higher-quality instruction.

Understanding electrochemistry, especially redox reactions, is challenging for pre-service science teachers. Traditional teaching methods often fail to address common challenges and misconceptions. This study explores these mistakes and examines the effectiveness of innovative strategies, such as problem-based learning, to improve comprehension and performance in electrochemistry through the following questions:

What are the most prevalent challenges and misconceptions among pre-service science teachers in understanding and balancing redox reactions in electrochemistry?

Which innovative teaching strategies, such as problem-based learning, are most effective in addressing and mitigating these challenges and misconceptions in the learning of electrochemistry?

1.1. Common Challenges and Misconceptions

Research has identified several areas of difficulty for students learning redox reactions. These include writing chemical equations, understanding oxidation and reduction half-reactions, the role of salt bridges, and balancing redox processes involving H_2O, H^+, and OH^- ions.

Factors Contributing to Misconceptions

Misconceptions in electrochemistry can stem from language barriers, rote learning approaches, a lack of foundational knowledge, and ineffective instructional strategies.

1.1.1. Teaching Methods and Their Impact

Traditional lecture-based methods have predominantly been used but have proven insufficient. Innovative instructional approaches such as problem-based learning (PBL), which emphasize critical thinking and problem-solving, show promise for enhancing comprehension.

2. Constructivism Theory

Constructivism, despite its varied interpretations, serves as the core learning theory for this study. It emerged as a response to the limitations of the stage model of cognitive development, stressing the importance of enabling students to construct and comprehend concepts rather than simply receiving transmitted information (Allen et al., 2002; Osborne, 1996). According to Hein (1991), individuals actively generate knowledge, perceiving learning as a student-centered process where learners make sense of concepts through engagement and experience (Tetzlaff, 2009). This perspective encourages learners to use their personal experiences and perspectives to interpret concepts, moving away from rote memorization and teacher-centered approaches (Tan, 2017).

Constructivism highlights the importance of active participation, constructive and complex learning processes, contextual understanding, collaborative learning environments, and reflective thinking (Tetzlaff, 2009). Knowledge is constructed through interactions with the environment and the meaningful processing of new information (Hein, 1991; Taber, 2011). Jones and Brader-Araje (2002) assert that constructivism fosters student ownership of learning, positioning teaching as a facilitative process that supports the construction and reconstruction of knowledge. This approach emphasizes the significance of learners' cognitive structures and their active role in making sense of new experiences (Taber, 2011).

In summary, constructivist learning theories are valued for their focus on students' active roles in constructing meaning, the importance of meaningful learning experiences, and active learner engagement (Jones & Brader-Araje, 2002). Luong & Kim (2022) characterize constructivism by key elements such as active meaning-making through interaction, cognitive engagement through challenges, collaboration to construct meaning, and reflection to refine understanding in authentic contexts as shown in **Figure 1**.

Figure 1. Students Active roles in constructing meaning (Luong & Kim, 2022).

2.1. The Concept of Reduction-Oxidation Reactions

Redox reactions have been historically explained through four models: the oxygen model, the hydrogen model, the electron model, and the oxidation number model, which are essential for contemporary chemistry education (Adu-Gyamfi et al., 2019).

1) Oxygen Model: Initially proposed by Stahl's phlogiston theory and later refined by Lavoisier, this model describes oxidation as the combination of oxygen with other elements.

2) Hydrogen Model: Defined by Liebig, this model describes oxidation as the loss of hydrogen atoms.

3) Electron Model: Based on Faraday's ion theory, this model explains oxidation as the loss of electrons and reduction as the gain of electrons.

4) Oxidation Number Model: Introduced by Lewis, this model uses shared electron pairs in covalent bonds to determine oxidation states, with oxidation involving an increase in oxidation number.

Balancing redox reactions can be achieved using the half-reaction method or the oxidation number method as illustrated in **Figure 2**. In acidic media, oxygen atoms are balanced with H_2O, and hydrogen atoms with H^+. In basic media, OH^- ions neutralize H^+ ions to form H_2O molecules (Qiang et al., 2003).

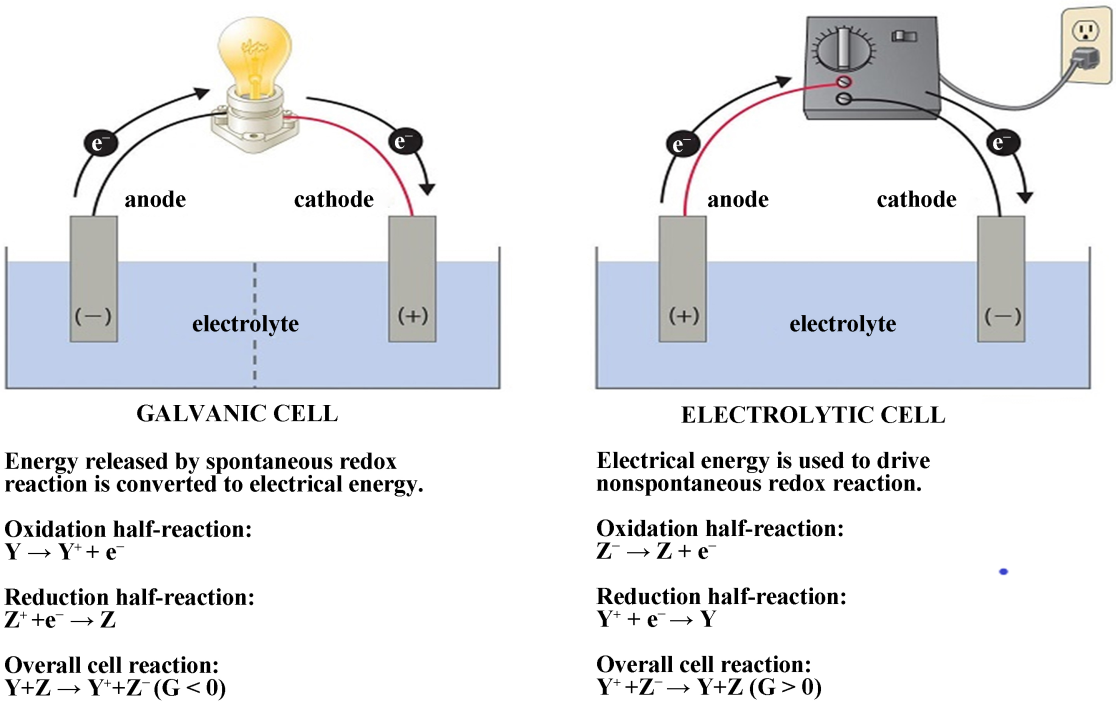

Figure 2. Oxidation-reduction cell. (Qiang et al., 2003).

2.1.1. Pedagogical Content Knowledge (PCK) in Chemistry

Shulman (1986) introduced the concept of Pedagogical Content Knowledge (PCK), which integrates subject matter expertise and teaching skills, enabling teachers to effectively convey content to students. PCK involves understanding the best ways to present content, catering to diverse student needs and abilities (Padilla & Van Driel, 2011).

Components of PCK

- Pedagogical Knowledge: This involves teaching processes and practices, such as classroom management, lesson planning, and student evaluation (Mishra & Koehler, 2006).
- Content Knowledge: This encompasses the subject matter to be taught.

Wongsopawiro et al. (2017). PCK evolves from teaching experience, knowledge of specific issues, and familiarity with curriculum materials (Padilla & Van Driel, 2011).

Effective Teaching with PCK

PCK helps teachers adapt content for diverse students, aiding meaningful knowledge construction (Mishra & Koehler, 2006). Effective teachers possess strong PCK, enabling them to analyze students' understanding, create exploratory activities, and facilitate discussions (Adu-Gyamfi et al., 2018).

2.2. Challenges in Teaching and Learning Redox Reactions

Numerous studies have highlighted the conceptual challenges students face in learning redox reactions (Adu-Gyamfi et al., 2018, 2019). Sensory learners particularly struggle with theoretical and equation-based explanations in chemistry (Felder, 1993). Students often find it difficult to transition between macroscopic and microscopic understandings of chemical concepts and to grasp that oxidation and reduction reactions occur simultaneously (Österlund & Ekborg, 2009).

The sequence in which topics are presented in textbooks can also contribute to these difficulties, as some concepts do not build sufficiently on each other (Ali, 2012). Additionally, while students can identify reducing agents easily, they often struggle to recognize oxidizing agents, sometimes incorrectly identifying compounds like water as the oxidizing agent (Österlund & Ekborg, 2009).

2.2.1. Teaching and Learning Strategies

Learning involves cognitive, physical, and affective processes, with depth referring to understanding, manipulating, applying, and communicating knowledge (Matorevhu, 2022). Constructivist theories emphasize active student involvement in building meaning through interaction with texts, the environment, and social contexts (Wilson & Peterson, 2006).

Constructivist instructional strategies that emphasize interactivity and engagement are most effective for facilitating behavior change (Allen et al., 2002). Teaching strategies should be diverse, including guided conversation, group work, and problem-based learning, to support effective learning. Adapting teaching tactics to fit students' learning strategies can reduce difficulties and improve understanding (Adu-Gyamfi, 2016).

2.2.2. Participatory Learning

The participatory approach involves participants in planning, executing, reflecting on activities, and evaluating outcomes, fostering local content inclusion in lessons (Greenwood, Whyte, & Harkavy, 1993). Participatory learning emphasizes teamwork and group involvement, enhancing pedagogical knowledge and assessment expertise (Adu-Gyamfi et al., 2019).

Participatory learning bridges theory and practice through practicality, collaboration, reflection, and intentionality (Trauth-Nare & Buck, 2011). It values all opinions, promotes collaboration, and prevents instructional planning from being solely developer-driven (Johnson, 2013). This method fosters peer learning, enhances understanding, and generates new ideas for lesson plans, leading to higher satisfaction and effective concept learning (Ainscow, 2005; Chan, 2010)

2.3. Recent Newman's Data

Since the early 1980s, the Newman approach to challenge analysis has gained popularity. This method involves interviewing individual students and categorizing their challenges based on the Newman hierarchy. In Malaysia, the Newman method found that over 90% of challenges by Grade 7 students were related to understanding or transformation (Faulkner & Kent, 2001).

Participatory learning, emphasizing the selection of strategies and reflection for effective instruction, aligns with constructivist learning theory, which posits that knowledge is constructed through interaction with concepts, reflection, and the environment (Pain et al., 2011; Hein, 1991; Lowenthal & Muth, 2008). Effective instruction combines student-centered and teacher-directed approaches, with social interactions playing a crucial role in enhancing learning (Taber, 2011; Tetzlaff, 2009). Understanding and preventing challenges is vital, with Newman identifying five types: reading, comprehension, transformation, process skills, and encoding challenges (White, 2010). The Newman procedure aids teachers in identifying and correcting these challenges (Sumule et al., 2018). Electrochemistry, a critical topic in high school chemistry, includes oxidation-reduction processes, redox titrations, electrochemical cells, and corrosion, posing significant challenges for pre-service science teachers. Common challenges and misconceptions include difficulties in writing chemical equations, understanding oxidation and reduction half-reactions, and balancing redox reactions involving H_2O, H^+, and OH^-, often due to language barriers, rote learning, and ineffective instructional strategies. While traditional lecture-based methods predominate, innovative approaches like problem-based learning (PBL) show promise for enhancing comprehension and retention of electrochemical concepts.

2.3.1. Population

The study focused on six Colleges of Education in Ghana, categorized into five zones: AshBa, CentWest, EaGa, Volta Region, and Northern Region. These colleges, designated as science colleges, include General Chemistry in their curriculum, which covers topics such as redox reactions. The participants of the study were Level 200 students, as redox reactions are taught during the second semester of their second year.

The accessible population consisted of 1211 pre-service teachers who were studying Chemistry as an elective. These students were also majoring in various subjects, including Primary Education, JHS Education, Early Grade Education, and Home Economics Education. Enrolment figures were obtained from the Academic Affairs offices of the selected colleges and confirmed by chemistry tutors.

2.3.2. Sample and Sampling Techniques

The entire accessible group of 1211 pre-service teachers were selected as the sample through the stages below:

Stage One: Purposive sampling selected six colleges from the 46 Colleges of Education in Ghana, affiliated with the University A and offering chemistry as an elective.

Stage Two: Purposive sampling selected specific levels from the chosen colleges, focusing on those studying the mole concept and redox reactions.

Stage Three: Purposive sampling selected two respondents from each college, for interviews based on test results, choosing those who scored extremely high or low marks (Garbo et al., 2023).

The results are shown in **Table 1** below:

Table 1. The number of science colleges that were selected and the number of students sampled.

ZONE	NAME OF SELECTED COLLEGEOF EDUCATION	NUMBER OF STUDENTS OFFERING GENERAL CHEMISTRY
ASHBA	A	288
	B	123
CENT WEST	C	269
	D	302
EGA	E	217
VOLTA	F	12
Total		1211

Source: Colleges' Academic Affairs Offices (2023).

2.4. Instrumentation Overview

Primary research instruments: tests, questionnaires, and interviews.

Reduction-Oxidation Reaction Diagnostic Test (RORDT)

The Reduction-Oxidation Reaction Diagnostic Test (RORDT) is a standardized assessment designed to identify and address difficulties in understanding redox reactions. This test evaluates participants' struggles with the concept and suggests potential remedies. The scoring of the RORDT is consistent with the method used for end-of-semester exams at the Institute of Education, University A.

The development of the RORDT involved a thorough process, including planning, preparation, review, revision, and validation to ensure alignment with the chemistry curriculum at the Colleges of Education (Kubiszyn & Borich, 2024). To guarantee its consistency and effectiveness in measuring the intended constructs, the test was piloted with a sample of pre-service teachers.

2.4.1. Questionnaire (Adapted Newman Hierarchical Challenge Model)

The questionnaire, adapted from the Newman Hierarchical Challenge Model, was designed for data collection during the quantitative phase of the study. It included both open-ended and closed-ended questions to measure specific variables, as outlined by Baburajan et al. (2020). The model was tailored to fit the context of Ghanaian Colleges of Education.

The questionnaire was divided into three sections: the first gathered demographic information, the second focused on items related to redox reactions, and the third sought pre-service teachers' suggestions on effective teaching methods as shown in **Table 2**. A 5-point Likert scale was utilized for its proven reliability and validity in analysis, as supported by de Rezende and de Medeiros (2022) and Sullivan & Artino (2013). The increased number of points on the scale enhances its reliability and validity.

Organization of the Research Instrument

Table 2. Research questionnaire.

SECTION	CONTENT	NUMBER OF ITEMS
A	Demographic data of respondents	4
B	Questions on redox reactions	14
C	Suggestions from pre-service teachers on how tutors should teach the concepts of mole and redox reaction	2

2.4.2. Interview Protocols

Semi-structured interviews were conducted to gather detailed and in-depth responses from pre-service teachers. These interviews, lasting between 15 and 20 minutes, focused on predetermined questions aligned with the study's research questions (Lapan et al., 2011). The sessions were designed to be flexible and interactive, allowing for the capture of rich, contextually relevant data (Adams, 2015). The data collected were manually transcribed and subsequently verified with the respondents to ensure accuracy.

2.5. Validity and Reliability

Test Validity and Reliability: The KR-20 coefficient was used to assess reliability, with a value of 0.70 indicating strong internal consistency (Pallant, 2020). Tests were reviewed by experts and piloted to ensure validity.

Questionnaire Reliability: Cronbach's alpha coefficient for the questionnaire was 0.808, indicating good reliability (Jayaraman & Ghazali, 2023; Merriam & Tisdell, 2009).

2.5.1. Pre-Testing of Questionnaire and Test

Administered to a sample of 30 pre-service teachers to identify and assess challenges, with reliability checked using Cronbach's alpha coefficients of 0.808 and 0.871 for the questionnaire and test, respectively.

2.5.2. Data Collection Procedures

Data were collected from 1200 pre-service teachers at six colleges. Procedures included obtaining consent, briefing participants, and ensuring accurate data collection through tests, questionnaires, and interviews.

2.6. Qualitative Data Transcription

Data from interviews were transcribed and coded for accuracy. Respondent validation ensured data authenticity (Creswell & Miller, 2000).

Quantitative Data Collection and Analysis

Quantitative data were gathered and analyzed using SPSS. Various statistical techniques (mean, standard deviation, factor analysis, regression) addressed research questions and tested hypotheses regarding challenges in learning redox reactions.

2.7. Ethical Considerations

Ethical integrity was maintained by obtaining permissions, ensuring voluntary participation, and safeguarding anonymity and confidentiality (Sharma et al., 2022).

3. Results and Discussion

The study focused on understanding and improving pre-service teachers' grasp of redox reactions. It aimed to identify common challenges, categorize these challenges, assess their impact on learning, and suggest remedies.

Presentation of Results and Interpretation

Research Question One: Prevalent Challenges and Misconceptions Among Pre-service Science Teachers in Understanding and Balancing Redox Reactions

Objective 1:

- The study identified challenges through responses to items designed based on existing literature on redox reaction challenges.
- Responses were analyzed using mean and standard deviation on a five-point Likert scale (1 = strongly disagree to 5 = strongly agree).
- A mean score above 3.0 indicated agreement with the statements regarding challenges, while below 3.0 indicated disagreement or neutrality.

The results, summarized in **Table 3**, provided insights into common student challenges in learning redox reactions based on the collected data.

Table 3. Students' challenges in learning redox reactions.

Challenges	Mean	Std. Deviation
Difficulties in solving problems without the use of formulae	3.17	1.412
Difficulty reading problems involving oxygen, hydrogen, electron, and oxidation number models	3.33	1.324
Don't know that reduction and oxidation reactions happen concurrently, I thought they are mutually exclusive	3.27	1.241
Difficulty in understanding what the question is asking for, whether loss or gain of hydrogen, loss or gains of oxygen, loss or gain of electron and decrease or increase of oxidation number	3.20	1.288
I have the notion that oxygen always plays a role in reduction-oxidation reaction	3.31	1.363
I have no problem recognizing reducing agents but struggle to recognize oxidation agents	2.92	1.303
I have no problem recognizing oxidation agents but struggle to recognize reducing agents	2.97	1.293
I believe that an oxygen atom in a molecule or a complex like water causes oxidation, hence, I refer to the molecule as the oxidizing agent	3.21	1.318
Difficulty in identifying what to be used in solving the question involving the four oxidation-reduction models	3.76	1.193
Difficulty in showing working steps in writing half-reaction for the equations	3.52	1.320
Difficulty in writing the overall balanced equations	2.89	1.547

Field survey, Michael Owusu (2023).

Summary of Findings from Table 3.

Students' Agreement on Challenges:

Students reported difficulties with several aspects of redox reactions:

- Difficulty in reading problems involving oxygen, hydrogen, electrons, and oxidation number models (M = 3.33, SD = 1.324).
- Misunderstanding that reduction and oxidation reactions occur simultaneously, not mutually exclusively (M = 3.27, SD = 1.241).
- Difficulty in interpreting questions about the loss or gain of hydrogen, oxygen, electrons, and changes in oxidation numbers (M = 3.20, SD = 1.288).
- Belief that oxygen always plays a role in redox reactions (M = 3.31, SD = 1.363).
- Misconception that oxygen causes oxidation and refers to the molecule as the oxidizing agent (M = 3.21, SD = 1.318).
- Challenges in identifying the appropriate model for solving redox questions (M = 3.76, SD = 1.193).
- Difficulty in showing working steps for writing half-reactions (M = 3.52, SD = 1.320).

Students' Disagreement on Challenges:

Students disagreed with statements about:

- Problems recognizing reducing agents but not oxidation agents (M = 2.92, SD = 1.303).
- Problems recognizing oxidation agents but not reducing agents (M = 2.97, SD = 1.293).
- Difficulty in writing overall balanced equations (M = 2.89, SD = 1.547).

Common challenges included challenges with reading and interpreting redox reactions, misconceptions about the role of oxygen, and difficulty in identifying the correct models and showing working steps.

Interviews further elaborated on these challenges.

S1 In redox reactions, I struggle to understand what the question is asking, particularly whether it's about the loss or gain of hydrogen, oxygen, electrons, or the increase or decrease in oxidation number. Aside from that, I think I'm okay.

S2 I know the four models of redox, but I have difficulty identifying which to use when solving questions involving these models, which I think is my biggest problem with redox.

S3 When a question asks for a half-reaction equation in redox, I always have difficulty showing the working steps for writing the half-reaction. Sometimes I guess correctly, but I can't explain how I arrived at it.

S4 Regarding redox reactions, I don't remember what the teachers taught us in high school or what the topic entails, especially about oxidizing and reducing agents.

S5 I have difficulty figuring out what to use when solving questions involving the four oxidation-reduction models. It's not my fault; we didn't have a chemistry teacher in high school until a National Service Person taught us in our final year, but not in detail.

S6 I wasn't taught redox reactions in high school, so I relied on my own *readings. I first heard about the four redox models here in college. Therefore, I struggle with identifying which model to use for solving questions.*

S7 I believe oxygen is always present in redox reactions. Whenever I read a question and don't see oxygen, I don't recognize it as a redox reaction question.

S8 Some challenges I make in redox reactions include difficulty showing the working steps for writing half-reactions and trouble reading the problem to understand what the question demands.

S9 My only challenge in redox is showing the step-by-step process for writing half-reactions.

S10 The challenges I make in redox reactions stem from difficulties reading the problem and understanding what the question demands. I don't really grasp the meaning when I read the question.

S11 For me, redox is a very complicated topic in chemistry because I didn't know that reduction and oxidation reactions happen simultaneously; I thought they occurred at different times.

S12 Reading the redox question for understanding isn't a problem for me. The issue is identifying what's needed to solve the problem, which is my biggest challenge.

Summary of Interview Responses and Categorizations

Interview Responses:

Pre-service teachers reported:

- Struggles in systematically writing redox half-equations and overall equations.
- Difficulty understanding whether questions involve the loss or gain of oxygen, hydrogen, or electrons.
- Challenges in identifying the appropriate oxidation-reduction model to use for solving questions.

These findings are consistent with the quantitative data results.

Categorizations of Challenges

Objective 2: Identify possible categorizations of challenge in learning redox reactions.

Method: Responses were analyzed using exploratory factor analysis (EFA), suitable for identifying structural patterns in challenge categorizations.

Approach: Principal axis factor analysis with Oblimin (oblique rotation) was used for examining the component correlation matrix.

Data Analysis: EFA was conducted on 14 items assessing challenge made by students in understanding redox reactions.

Table 4. KMO and Bartlett's Test for possible categorizations of challenge of students in learning redox reactions.

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.715
Bartlett's Test of Sphericity	Approx. Chi-Square	3078.566
	Df	45
	Sig.	0.000

Table 5. Total Variance Explained for possible categorizations of challenge of students in learning redox reactions.

Total Variance Explained									
Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.334	33.342	58.342	3.334	33.342	58.342	2.274	22.739	22.739
2	1.447	14.467	72.808	1.447	14.467	72.808	1.956	19.563	42.302
3	1.163	11.628	84.436	1.163	11.628	84.436	1.713	17.134	59.436
4	1.001	10.013	93.448	1.001	10.013	93.448	1.114	11.645	93.448
5	0.781	7.806	96.254						
6	0.682	6.824	98.078						
7	0.312	3.122	100.000						

Extraction Method: Principal Component Analysis.

Summary of Exploratory Factor Analysis and Challenge Impact Analysis

Exploratory Factor Analysis (EFA):

- Kaiser-Meyer-Olkin Measure: KMO = 0.715, indicating adequate sampling for factor analysis (Beavers et al., 2019).
- Bartlett's Test: Significant (0.000), confirming that the assumption of sphericity was met. Eigenvalues: Four challenge categorizations had eigenvalues above 1, explaining 93.448% of the variance.
- Variance Explained: First categorization = 33.342%, Second = 14.467%, Third = 11.628%, Fourth = 10.013%.
- Monte Carlo PCA for Parallel Analysis: Confirmed the four-challenge categorization solution with the same accumulated variance, validating the structure.

Challenge Impact Analysis

Objective 3:

Objective: Identify which challenges significantly contribute to difficulties in learning redox reactions.

Method: Responses on challenge impact were analyzed using multiple regression, which assessed the influence of various predictor challenges (comprehension, transformation, process skills, encoding) on the criterion variable (redox reactions).

Assumptions Checked: Normality and linearity assumptions were verified prior to regression analysis (see **Figure 3**).

Summary of Regression Analysis Preparation

- Linearity and Normality: A straight normal probability plot, as described by Pallant (2020), indicates that the data meet the assumptions of linearity and normality.
- Regression Analysis: Since the assumptions were satisfied, performing a multiple regression test was appropriate.

- Results: Tables 4-9 present the results identifying the challenges that most significantly contribute to students' difficulties in learning redox reactions.

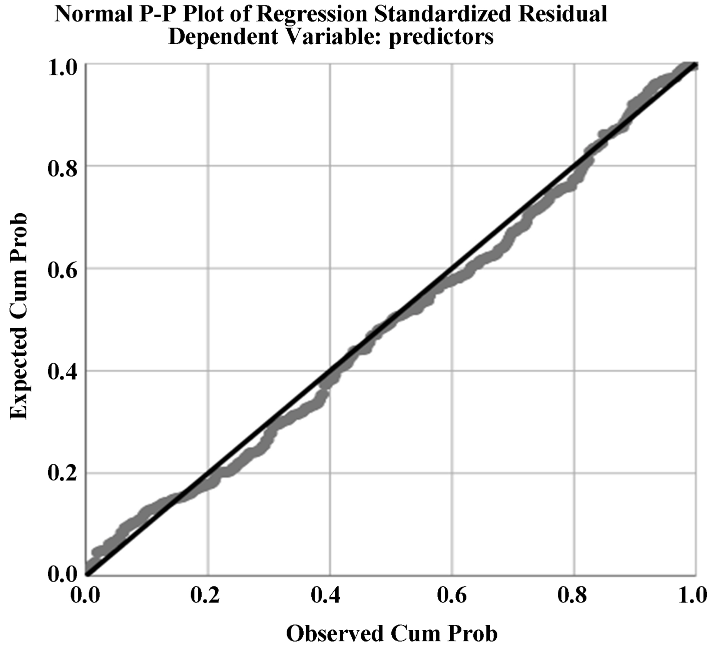

Figure 3. Diagnostic Test of Normality and Linearity.

Table 6. Correlations analysis of redox reaction challenges.

		REDOX	REDOXCOM	REDOXTRANS	REDOXE	REDOXP
Pearson Correlation	REDOX	1.000	0.604	0.429	0.550	0.720
	REDOXCOM	0.604	1.000	0.187	0.167	0.428
	REDOXTRANS	0.429	0.187	1.000	0.427	0.245
	REDOXE	0.550	0.167	0.427	1.000	0.744
	REDOXP	0.720	0.428	0.245	0.744	1.000
Sig. (1-tailed)	REDOX	.	0.000	0.001	0.000	0.000
	REDOXCOM	0.000	.	0.097	0.123	0.001
	REDOXTRANS	0.001	0.097	.	0.001	0.043
	REDOXE	0.000	0.123	0.001	.	0.000
	REDOXP	0.000	0.001	0.043	0.000	.

Table 7. Model summary of multiple regression analysis.

Model Summary[b]									
Model	R	R Square	Adjusted R Square	Std. Challenge of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	0.824[a]	0.679	0.650	4.68874	0.679	23.758	4	1195	0.000

a. Predictors: (Constant), REDOXP, REDOXTRANS, REDOXCOM, REDOXE; b. Dependent Variable: REDOX.

Table 8. ANOVA table for multiple regression analysis.

ANOVA[a]						
	Model	Sum of Squares	Df	Mean Square	F	Sig.
1	Regression	2089.207	4	522.302	23.758	0.000[b]
	Residual	989.293	1195	21.984		
	Total	3078.500	1199			

a. Dependent Variable: REDOX; b. Predictors: (Constant), REDOXP, REDOXTRANS, REDOXCOM, REDOXE.

Table 9. Coefficients table for multiple regression analysis.

Coefficients[a]										
Model		Unstandardized Coefficients		Standardized Coefficients	T	Sig.	Correlations		
		B	Std. Challenge	Beta			Zero-order	Partial	Part
1	(Constant)	19.489	2.755		7.073	0.000			
	REDOXCOM	1.232	0.355	0.343	3.470	0.001	0.604	0.459	0.293
	REDOXTRANS	1.179	0.487	0.233	2.423	0.019	0.429	0.340	0.205
	REDOXE	0.133	0.858	0.022	0.155	0.878	0.550	0.023	0.013
	REDOXP	1.404	0.410	0.499	3.424	0.001	0.720	0.455	0.289

a. Dependent Variable: REDOX. Redox = 19.489 + 0.343 (REDOXCOM) + 0.233 (REDOXTRANS) + 0.022 (REDOXE) + 0.499 (REDOXP)

Summary of Regression Analysis Results

- Overall Model Significance: The regression model is significant ($F = 23.758$, $p < 0.05$), showing that the independent variables (comprehension, transformation, process skills, and encoding) are influential in predicting challenge in redox reactions.
- Model Explanation: The model explains 67.9% of the variance in redox reactions ($R^2 = 0.679$), with a correlation of 0.824 between the challenges and redox reactions.
- Significant Predictors: Comprehension challenges ($p = 0.001$), transformation challenges ($p = 0.019$), and process skills challenges ($p = 0.001$) are statistically significant predictors. Process skills challenges have the highest impact ($\beta = 0.499$), followed by comprehension challenges ($\beta = 0.343$) and transformation challenges ($\beta = 0.233$).

Influence of Challenges: Process skills challenges are identified as the most significant predictor of difficulties in learning redox reactions.

According to Table 10, the challenges have a weak negative and statistically insignificant effect on learning redox reactions ($r = -0.026$, $p > 0.05$).

Responses from the oral interviews regarding the extent to which challenges affect pre-service teachers' learning of redox reactions were gathered through discussions with them. The summarised responses are as follows:

Table 10. Students' challenge influencing learning of redox reaction.

Correlations			
		TOTALSCORE	REDOX
Challenge	Pearson Correlation	1	−0.026
	Sig. (2-tailed)		0.360
	N	1200	1200
REDOX	Pearson Correlation	−0.026	1
	Sig. (2-tailed)	0.360	
	N	1200	1200

S1 I consistently make mistakes with my final calculations and the overall balanced equation because I struggle to understand what the question is asking, especially regarding the loss or gain of hydrogen, oxygen, electrons, and changes in oxidation numbers.

S2 Although I am familiar with the four redox models, I have difficulty identifying which one to use when solving problems involving these models.

S3 I frequently get the overall balanced equations incorrect. I also face challenges in demonstrating the working steps needed to write half-reactions for redox equations.

S4 I lack interest in redox reactions and don't recall anything about oxidizing and reducing agents.

S5 I rarely practice redox exercises independently because I have trouble determining which methods to use for solving questions related to the four redox models.

S6 I rely on my limited knowledge to solve redox questions, as I struggle to identify the correct approach for the four redox models.

S7 I don't believe challenges negatively impact my learning of redox reactions. Although I understand that oxygen is typically present in redox reactions, I disregard questions without oxygen as not being related to redox reactions.

S8 I often make challenges with the overall balanced equations due to difficulties in showing the working steps for writing half-reactions.

S9 My difficulty in demonstrating step-by-step working for half-reactions leads to incorrect overall balanced equations.

S10 My results are often incorrect because I have trouble understanding what the problem is asking.

S11 I struggle to identify both oxidation and reduction agents in a single reaction because I mistakenly thought reduction and oxidation occur at different times.

S12 Although my final equations might be correct, they are often unbalanced due to my general inability to balance chemical equations.

Summary of Interview Findings and Remedies

Interview Findings: Most pre-service teachers struggled with identifying appropriate methods for solving redox reaction questions and showing working steps for half-reactions. These challenges affected their ability to write final balanced equations. This contrasts with quantitative data, which did not show a significant impact of these challenges on learning.

Research Question Two: Innovative Teaching Strategies to Address and Mitigate Challenges and Misconceptions in Learning Electrochemistry.

Remedies:

Objective: To gather suggestions on how to improve the teaching of redox reactions.

Method: An open-ended and closed-ended questionnaire was distributed to 1200 students, with 1197 responding.

Analysis: Responses were categorized and analyzed for frequency and percentage to identify common suggestions for improving redox reaction teaching.

Findings: Detailed in Table 11.

Table 11. Redox reaction.

Opinions	Number of students	Percentage
Redox must be taught using real life explanations rather than book knowledge.	91	7.6
I think doing laboratory work will foster better understanding rather than just theory which always do not yield good results	301	25.1
Students should be made to do peer collaborative work when it comes to learning of redox reaction. This leads to sharing of ideas among students, and I think it will produce better understanding.	143	11.9
Students must be made aware of the usefulness of redox reaction. I think this will make us do our best to learn and never forget.	17	1.4
Tutors must help teach the Redox reaction in terms of oxygen model, hydrogen model, electron model, and oxidation number model. This is because, we students find it extremely difficult understanding Redox in terms of these four models.	91	7.6
Students must be motivated to learn the concept of redox.	17	1.4
Tutors should not assume that topics like 'balancing of chemical equation' is already taught in other areas in chemistry and that is enough for redox reaction. It must be taught as if we don't know anything about it at all.	104	8.7
Tutors must encourage small groups to corporately work together, this commands respect among friends and to enhance their understanding in the topic. We did that in SHS, and it really helped us.	141	11.8
Tutors must acquire pedagogical content knowledge to be able to teach the redox very well. From the way most of our SHS chemistry tutors teach the Redox, it looks like they do not have a good background of the pedagogical content knowledge. This is normally seen when students ask them questions during the teaching of Redox reaction. They will be seen diverting from the question and saying different things all together.	275	23.0

Continued

Most of the tutors think students do not know anything about Redox reaction, hence, they do not allow the students to participate in the teaching and learning of the topic. I suggest that students can also be made to also participate during the teaching and learning of redox reaction to enhance understanding.	17	1.4
Total	1197	100

Field survey, Michael Owusu (2023).

Summary of Remedies

Remedies for Challenge in Learning Redox Reactions (**Table 11**).

Laboratory Work: Recommended by 301 respondents (25%) as it enhances understanding more effectively than theoretical instruction alone.

Pedagogical Content Knowledge: Suggested by 275 students (23%) to ensure tutors have a strong grasp of teaching methods, addressing the observed lack of expertise among SHS chemistry teachers.

Peer Collaborative Work: Recommended by 143 students (11.9%) to facilitate learning through idea sharing and better comprehension.

Small Group Work: Suggested by 141 students (11.8%) to foster respect and improve understanding based on positive experiences.

Comprehensive Teaching: Advised by 104 students (8.4%) to ensure that topics like 'balancing chemical equations' are thoroughly taught, rather than assuming prior coverage.

4. Discussion

The results are systematically discussed according to the sequence of the research questions, as outlined in the following subheadings.

Research Question One: Prevalent Challenges and Misconceptions Among Pre-service Science Teachers in Understanding and Balancing Redox Reactions

The study identified several prevalent challenges and misconceptions among pre-service science teachers regarding redox reactions. One significant issue is their difficulty in translating word problems into chemical equations, which hinders their ability to effectively solve these problems. Many students struggle with this conversion process, resulting in a disconnect between the descriptive elements of a problem and the corresponding chemical representation. Additionally, there is a common misunderstanding regarding the simultaneity of reduction and oxidation; students often fail to grasp that these processes occur simultaneously in redox reactions. This lack of understanding contributes to confusion about the nature of redox processes, particularly regarding whether a problem involves the loss or gain of hydrogen, oxygen, or electrons. Furthermore, misconceptions about the role of oxygen are prevalent, as students mistakenly believe that oxygen is always involved in redox reactions and that oxygen-containing molecules are invariably oxidizing agents. Lastly, many pre-service teachers encounter difficulties with problem-solving approaches, particularly in identifying the appropriate methods for solving redox questions and writing half-reaction equations. These challenges highlight the need for targeted instructional strategies to enhance students' comprehension and application of redox concepts.

Pre-service teachers often experience difficulties when it comes to identifying appropriate methods for solving redox reaction questions and presenting the working steps for half-reactions. These challenges, which are closely related to their conceptual understanding, impact their ability to write final balanced equations accurately. According to studies using observational methods, these struggles are frequently observed in practical classroom settings, where many pre-service teachers fail to demonstrate a systematic approach to problem-solving in redox chemistry (Gonçalves Costa et al., 2024). Third-party assessments further support this finding, as independent evaluators have noted consistent issues with the teachers' ability to connect theoretical knowledge with practical application (Baier et al., 2021).

Interestingly, despite these observed difficulties, quantitative data from standardized tests and other formal assessments often show no significant impact on overall learning outcomes (McConlogue, 2020). This discrepancy suggests that while conceptual struggles exist, they may not always translate into lower test scores, possibly due to the compensatory strategies students employ during assessments or the nature of test design that emphasizes memorization over deep understanding. Therefore, while the observational methods highlight clear learning challenges in redox chemistry, these issues may not be as readily apparent through traditional quantitative measures.

Research Question Two: Innovative Teaching Strategies to Address and Mitigate Challenges and Misconceptions in Learning Electrochemistry

To address and mitigate the identified challenges and misconceptions, several innovative teaching strategies have been explored. Problem-based learning (PBL) emerges as one of the most effective approaches. Key strategies include:

Remedies for addressing the challenges in learning redox reactions can be understood through both observational methods and third-party assessments. Laboratory work was identified by 301 respondents (25%) as a key method for enhancing understanding, as it provides hands-on experience that complements theoretical instruction (Agustian et al., 2022). Observations in classroom settings further highlight that students who engage in lab-based learning demonstrate a deeper comprehension of redox processes compared to those solely receiving theoretical instruction. Additionally, 275 students (23%) suggested the need for stronger pedagogical content knowledge among teachers, emphasizing the importance of tutors having both subject expertise and effective teaching strategies (Cotronei-Baird et al., 2023).

Peer collaborative work and small group learning were also recommended by students—143 (11.9%) and 141 (11.8%) respectively—as valuable approaches to learning redox reactions. Observational studies show that these methods promote active learning through idea sharing and foster better comprehension (Adu-Gyamfi et al., 2019). Finally, 104 students (8.4%) advocated comprehensive teaching, particularly for foundational topics like balancing chemical equations, which are often assumed to have been previously covered but remain challenging for many students. Third-party assessments also support these remedies, highlighting the effectiveness of collaborative and experiential learning in addressing gaps in students' understanding of redox reactions (Saraf et al., 2023).

Categorization and Impact of Challenges

The challenges students face in learning redox reactions can be categorized into four main types, each with significant implications for their learning outcomes. First, comprehension challenges arise from misunderstandings of the questions, often because educators fail to emphasize the simplification of complex concepts during instruction. This lack of clarity in foundational understanding makes it difficult for students to grasp the essential principles needed for problem-solving (Aaltola, 2022). Second, transformation challenges occur when students struggle to determine the correct approach to solve a problem, often linked to computational difficulties and the inability to translate theoretical knowledge into practical steps (St-Onge Carle, 2022). Third, process skills challenges involve difficulties in systematically applying formulae and methods, usually due to insufficient understanding or practice with problem-solving techniques. Without adequate opportunities to develop these skills, students find it hard to execute the correct procedures (Fazio et al., 2023). Lastly, encoding challenges happen when students fail to present their solutions properly, even though they may have solved the problem correctly. This suggests a gap in their ability to communicate their thought process or accurately format their answers (Wilson, 2011). Addressing these categories of challenges is essential to improving students' overall comprehension and performance in redox reactions.

Recommendations for Teaching Redox Reactions

To effectively address the challenges and misconceptions students face in learning redox reactions, several strategies are recommended. First, teachers should balance the instruction of quantitative concepts with practical skills, allowing students to apply theoretical knowledge in real-world scenarios, which is critical for deep learning (Fazio et al., 2023). Improved instructional strategies, such as problem-based learning and constructivist approaches, should emphasize comprehension and process skills over rote memorization, promoting a more thorough understanding of the subject (Baier et al., 2021). Providing historical and evolutionary contexts where appropriate can also enhance engagement and improve conceptual clarity by helping students connect the abstract principles of redox chemistry with their development and applications over time (Cole, 2020).

Additionally, the creation of active learning environments—student-centered, knowledge-centered, assessment-centered, and community-centered—fosters greater participation and deeper understanding (Aaltola, 2022). Tailoring teaching methods to align with students' preferred learning styles can significantly enhance comprehension and retention, as it personalizes the learning experience (Wilson, 2011). Despite resource limitations, educators should strive to utilize available teaching aids and resources to help students better visualize and conceptualize complex chemistry concepts (St-Onge Carle, 2022). Finally, teachers must build on students' prior knowledge and experiences, using these as a foundation to facilitate better learning outcomes and to bridge gaps in understanding (Burner & Svendsen, 2020). By adopting these strategies, educators can significantly improve students' grasp of redox reactions, reducing challenges and misconceptions while fostering a more engaging and effective learning environment.

5. Conclusions and Suggestions for Further Studies

The study revealed that students faced significant challenges in understanding questions and demonstrating systematic problem-solving steps. This struggle was closely linked to a lack of conceptual understanding, particularly when using formulae without comprehending the underlying principles. Furthermore, tutors frequently lacked adequate pedagogical content knowledge and often assumed that students had a prior understanding of key concepts, which contributed to the learning gaps. To address these issues, it is recommended that small group learning and cooperative approaches be encouraged to foster deeper understanding and collaborative. Future research could explore redox reactions and other chemistry concepts in different institutions and settings to address gaps identified in this study.

6. Recommendations

To enhance students' grasp of redox concepts, it is important to design assessments that specifically evaluate their conceptual understanding and their ability to comprehend the language used in redox reactions. Instruction should emphasize the principles behind redox processes, moving away from rote memorization and fostering a deeper understanding. Clear and thorough explanations of models involving oxygen, hydrogen, electrons, and oxidation numbers are essential. Additionally, teaching the concurrent nature of oxidation and reduction reactions will help students grasp the interdependent aspects of these processes. Misconceptions, especially those regarding oxygen's role in redox reactions, should be addressed by ensuring students fully understand what is being asked in questions. Finally, a focus on improving students' skills in writing and interpreting half-reactions will solidify their understanding of redox reactions.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Aaltola, K. (2022). Modern Learning Environments in the Acquisition of Skills. *JYU Dissertations, 108,* 1017-1054.

Adams, W. C. (2015). Conducting Semi-Structured Interviews. In J. S. Wholey, H. P. Hatry, & K. E. Newcomer (Eds.), *Handbook of Practical Program Evaluation* (pp. 492-505). Jossey-Bass.

Adu-Gyamfi, K. (2016). *Improving Chemistry Students' Conception of Redox Reactions Using the Participatory Teaching and Learning Approach.* Doctoral dissertation, University of Cape Coast.

Adu-Gyamfi, K., Ampiah, J. G., & Agyei, D. D. (2018). Teachers' Problems of Teaching of Oxidation-Reduction Reactions in High Schools. *European Journal of Education Studies, 5,* 53-71. https://doi.org/10.5281/zenodo.1471731

Adu-Gyamfi, K., Ghartey Ampiah, J., & Darko Agyei, D. (2019). Participatory Teaching and Learning Approach: A Framework for Teaching Redox Reactions at High School Level. *International Journal of Education and Practice, 8,* 106-120. https://doi.org/10.18488/journal.61.2020.81.106.120

Agustian, H. Y., Finne, L. T., Jørgensen, J. T., Pedersen, M. I., Christiansen, F. V., Gammelgaard, B. et al. (2022). Learning Outcomes of University Chemistry Teaching in Laboratories: A Systematic Review of Empirical Literature. *Review of Education, 10,* e3360. https://doi.org/10.1002/rev3.3360

Ainscow, M. (2005). Developing Inclusive Education Systems: What Are the Levers for Change? *Journal of Educational Change, 6,* 109-124. https://doi.org/10.1007/s10833-005-1298-4

Ali, T. (2012). A Case Study of the Common Difficulties Experienced by High School Students in Chemistry Classroom in Gilgit-Baltistan (Pakistan). *Sage Open, 2.* https://doi.org/10.1177/2158244012447299

Allen, W., Kilvington, M., & Horn, C. (2002). *Using Participatory and Learning-Based Approaches for Environmental Management to Help Achieve Constructive Behaviour Change.* SPREP.

Baburajan, V., e Silva, J. D. A., & Pereira, F. C. (2020). Open-ended versus Closed-Ended Responses: A Comparison Study Using Topic Modeling and Factor Analysis. *IEEE Transactions on Intelligent Transportation Systems, 22,* 2123-2132. https://doi.org/10.1109/tits.2020.3040904

Baier, F., Maurer, C., Dignath, C., & Kunter, M. (2021). Fostering Pre-Service Teachers' Theoretical Knowledge Application: Studying with and without Text-Based Cases. *Instructional Science, 49,* 855-876. https://doi.org/10.1007/s11251-021-09560-7

Beavers, A. S., Lounsbury, J. W., Richards, J. K., Huck, S. W., Skolits, G. J., & Esquivel, S. L. (2019). Practical Considerations for Using Exploratory Factor Analysis in Educational Research. *Practical Assessment, Research, and Evaluation, 18,* Article 6.

Burner, T., & Svendsen, B. (2020). A Vygotskian Perspective on Teacher Professional Development. *Education, 141,* 11-20.

Chan, H. O. K. (2010). *How do Teachers' Beliefs Affect the Implementation of Inquiry-Based Learning in the PGS Curriculum? A Case Study of Two Primary Schools in Hong Kong.* Master's Thesis, Durham University.

Cole, M. H. (2020). *The Effect of Adding Relevant and Irrelevant Visual Images to an Animation of an Oxidation-Reduction Reaction on Students' Conceptual Understanding.* Master's Thesis, Middle Tennessee State University.

Cotronei-Baird, V. S., Chia, A., Paladino, A., & Johnston, A. (2023). Examining the Influence of Professional Development on Tutors' Teaching Philosophies. *Higher Education Research & Development, 42,* 1338-1361. https://doi.org/10.1080/07294360.2022.2146060

Creswell, J. W., & Miller, D. L. (2000). Determining Validity in Qualitative Inquiry. *Theory Into Practice, 39,* 124-130. https://doi.org/10.1207/s15430421tip3903_2

de Rezende, N. A., & de Medeiros, D. D. (2022). How Rating Scales Influence Responses' Reliability, Extreme Points, Middle Point and Respondent's Preferences. *Journal of Business Research, 138,* 266-274. https://doi.org/10.1016/j.jbusres.2021.09.031

Faulkner, A., & Kent, J. (2001). Innovation and Regulation in Human Implant Technologies: Developing Comparative Approaches. *Social Science & Medicine, 53,* 895-913. https://doi.org/10.1016/s0277-9536(00)00389-0

Fazio, C., Gallitto, A. A., Galiano, C. G., Giarratano, G., Grazia, I., Termini, G., & Battaglia, O. R. (2023). An Approach to Research-Based Design of Teaching-Learning Sequences in the Context of Physics Education: Theoretical Frameworks, Pedagogical Methods, and Examples of Data Analysis. *Il Nuovo Cimento, 46,* 199-227.

Felder, R. (1993). Reaching the Second Tier: Learning and Teaching Styles in College Science Education. *Journal of College Science Teaching, 23,* 286-290.

Garbo, J. M., Lopres, J. R., Novenario, M. P., Esternon, C. E. G., Pilapil, G. M. P., Gomez, B. L. et al. (2023). Distance Learning Barriers and Bottlenecks: A Phenomenological Inquiry on the Conduct of English Language Arts (ELA) Standard Assessments. *International Journal of Learning, Teaching and Educational Research, 22,* 39-65. https://doi.org/10.26803/ijlter.22.8.3

Gonçalves Costa, G., J. D. Nascimento Júnior, W., Mombelli, M. N., & Girotto Júnior, G. (2024). Revisiting a Teaching Sequence on the Topic of Electrolysis: A Comparative Study with the Use of Artificial Intelligence. *Journal of Chemical Education, 101,* 3255-3263. https://doi.org/10.1021/acs.jchemed.4c00247

Greenwood, D. J., Whyte, W. F., & Harkavy, I. (1993). Participatory Action Research as a Process and as a Goal. *Human Relations, 46,* 175-192. https://doi.org/10.1177/001872679304600203

Hein, G. E. (1991). *Constructivist Learning Theory.* Institute for Inquiry. http://www.Exploratorium.edu/ifi/resources/constructivistlearning.html

Jayaraman, T. K. T., & Md Ghazali, N. H. B. C. (2023). The Validity, Reliability and EFA of an Instrument to Evaluate Professional Learning Community (PLC) Implementation. *International Journal of Academic Research in Progressive Education and Development, 12,* 2132-2147. https://doi.org/10.6007/ijarped/v12-i2/17229

Johnson, M. (2013). *How Social Media Changes User-Centred Design-Cumulative and Strategic User Involvement with Respect to Developer-User Social Distance.*

Jones, M. G., & Brader-Araje, L. (2002). The Impact of Constructivism on Education: Language, Discourse, and Meaning. *American Communication Journal, 5,* 1-10.

Kubiszyn, T., & Borich, G. D. (2024). *Educational Testing and Measurement.* John Wiley & Sons.

Lapan, S. D., Quartaroli, M. T., & Riemer, F. J. (2011). *Qualitative Research: An Introduction to Methods and Designs.* John Wiley & Sons.

Lowenthal, P., & Muth, R. (2008). Constructivism. *Encyclopaedia of the Social and Cultural Foundations of Education, 46,* 177-179.

Luong, T., & Kim, E. (2022). A Constructivism-Based Training Course for Hospitality and Tourism Instructors in Vietnam to Improve Their Self-Confidence in Synchronous Online Teaching. *Interactive Technology and Smart Education, 19,* 360-389. https://doi.org/10.1108/itse-04-2021-0070

Matorevhu, A. (2022). Teacher Educators' Nature of Understanding of Adult Learning Theories Application in Pre-Service Teachers' Classes. *Electronic Journal of Education,* *Social Economics and Technology, 3,* 15-23. https://doi.org/10.33122/ejeset.v3i1.50

McConlogue, T. (2020). *Assessment and Feedback in Higher Education: A Guide for Teachers.* UCL Press. https://doi.org/10.2307/j.ctv13xprqb

Merriam, S. B., & Tisdell, E. J. (2009). *Dealing with Validity, Reliability, and Ethics.* Qualitative Mishra & Koehler。

Mishra, P., & Koehler, M. J. (2006). Technological Pedagogical Content Knowledge: A Framework for Teacher Knowledge. *Teachers College Record, 108,* 1017-1054.

Osborne, J. F. (1996). Beyond Constructivism. *Science Education, 80,* 53-82. https://doi.org/10.1002/(sici)1098-237x(199601)80:1<53::aid-sce4>3.0.co;2-1

Österlund, L., & Ekborg, M. (2009). Students' Understanding of Redox Reactions in Three Situations. *Nordic Studies in Science Education, 5,* 115-127. https://doi.org/10.5617/nordina.345

Padilla, K., & Van Driel, J. (2011). The Relationships between PCK Components: The Case of Quantum Chemistry Professors. *Chemistry Education Research and Practice, 12,* 367-378. https://doi.org/10.1039/c1rp90043a

Pain, R., Kesby, M., & Askins, K. (2011). Geographies of Impact: Power, Participation and Potential. *Area, 43,* 183-188. https://doi.org/10.1111/j.1475-4762.2010.00978.x

Pallant, J. (2020). *SPSS Survival Manual: A Step-by-Step Guide to Data Analysis Using IBM SPSS.* Open University Press.

Qiang, Z., Chang, J., & Huang, C. (2003). Electrochemical Regeneration of Fe2+ in Fenton Oxidation Processes. *Water Research, 37,* 1308-1319. https://doi.org/10.1016/s0043-1354(02)00461-x

Saraf, M., Roy, M. A., Yarur Villanueva, F., Kundu, A., Tran, H., Ghosh, M. et al. (2023). Perspectives from the 2022 Cohort of the American Chemical Society Summer School on Green Chemistry & Sustainable Energy. *ACS Sustainable Chemistry & Engineering, 11,* 13822-13835. https://doi.org/10.1021/acssuschemeng.3c02935

Sharma, G., Shah, M., Ahluwalia, P., Dasgupta, P., Challacombe, B. J., Bhandari, M. et al. (2022). Development and Validation of a Nomogram Predicting Intraoperative Adverse Events during Robot-Assisted Partial Nephrectomy. *European Urology Focus, 9,* 345-351. https://doi.org/10.1016/j.euf.2022.09.004

Shulman, L. S. (1986). Those Who Understand: Knowledge Growth in Teaching. *Educational Researcher, 15,* 4-14. https://doi.org/10.3102/0013189x015002004

St-Onge Carle, M. (2022). *Investigating the Effects of Teaching and Learning Tools in Chemistry Education.* Master's Thesis, Université d'Ottawa/University of Ottawa.

Sullivan, G. M., & Artino, A. R. (2013). Analyzing and Interpreting Data from Likert-Type Scales. *Journal of Graduate Medical Education, 5,* 541-542. https://doi.org/10.4300/jgme-5-4-18

Sumule, U., Amin, S. M., & Fuad, Y. (2018). Error Analysis of Indonesian Junior High School Student in Solving Space and Shape Content PISA Problem Using Newman Procedure. *Journal of Physics: Conference Series, 947,* Article ID: 012053. https://doi.org/10.1088/1742-6596/947/1/012053

Taber, K. S. (2011). An Essay Review. *Understanding the Nature and Processes of Conceptual Change, 14,* 1-17.

Tan, C. (2017). Constructivism and Pedagogical Reform in China: Issues and Challenges. *Globalisation, Societies and Education, 15,* 238-247. https://doi.org/10.1080/14767724.2015.1105737

Tetzlaff, T. N. (2009). *Constructivist Learning Verses Explicit Teaching: A Personal Discovery of Balance.* Master's Thesis, University of Massachusetts Boston.

Trauth-Nare, A., & Buck, G. (2011). Using Reflective Practice to Incorporate Formative Assessment in a Middle School Science Classroom: A Participatory Action Research Study. *Educational Action Research, 19,* 379-398. https://doi.org/10.1080/09650792.2011.600639

White, A. L. (2010). Numeracy, Literacy and Newman's Challenge Analysis. *Journal of Science and Mathematics Education in Southeast Asia, 33,* 129-148.

Wilson, M. L. (2011). *Students' Learning Style Preferences and Teachers' Instructional Strategies: Correlations between Matched Styles and Academic Achievement.* Master's Thesis, Liberty University.

Wilson, S. M., & Peterson, P. L. (2006). *Theories of Learning and Teaching: What Do They Mean for Educators?* National Education Association.

Wongsopawiro, D. S., Zwart, R. C., & van Driel, J. H. (2017). Identifying Pathways of Teachers' PCK Development. *Teachers and Teaching, 23,* 191-210. https://doi.org/10.1080/13540602.2016.1204286