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Effect of Problem Based Learning on Achievement and Perceptions among Secondary School Students Learning Electrolysis in Rwanda

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Abstract

Electrolysis is among the most challenging topics in secondary school chemistry in Rwanda, characterized by persistent student misconceptions about electron transfer, redox reactions, and electrode processes, and by pedagogical approaches that prioritize rote memorization over conceptual understanding. This mixed-methods quasi-experimental study investigated the effect of Problem-Based Learning (PBL) on Senior Five students' academic achievement and perceptions in electrolysis in Kicukiro and Gasabo Districts, Rwanda.

A convergent parallel mixed-methods design was employed. GS Remera Protestant School (Kicukiro District) served as the experimental group (n = 46), receiving eight weeks of PBL-based electrolysis instruction in which students collaboratively investigated real-world electrochemical problems. ES Bumbogo School (Gasabo District) served as the control group (n = 46), receiving conventional teacher-centred instruction on the same topics. Data were collected through a researcher-developed Electrolysis Achievement Test (EAT) administered at pre-test and post-test stages, a Students' Perceptions of Problem-Based Learning Questionnaire (SPBLQ), and semi-structured teacher interviews. Test-retest reliability was confirmed ($r = 0.89$). Data were analysed using independent-samples t-tests, paired-samples t-tests, Cohen's d effect size calculation, simple linear regression, and thematic analysis.

Post-test results showed a statistically significant advantage for the experimental group ($M = 68.5$, $SD = 10.2$) over the control group ($M = 53.2$, $SD = 12.4$; $t(80) = 6.12$, $p < 0.001$, Cohen's $d = 1.36$). Within-group analysis confirmed significant pre-test to post-test improvement in the experimental group ($t = 14.23$, $p < 0.001$) but not in the control group. Students in the experimental group reported consistently positive perceptions of PBL across all measured dimensions. Linear regression confirmed that student perceptions of PBL significantly predicted academic achievement ($R^2 = 0.32$, $p < 0.001$). Teacher interviews

identified enhanced student engagement and improved conceptual understanding as primary benefits, while limited laboratory resources and class management complexity were identified as implementation challenges. The study concludes that PBL is a pedagogically effective and CBC-aligned strategy for electrolysis instruction in Rwandan secondary schools and recommends its systematic integration into chemistry teacher professional development programs.

Keywords: Problem-Based Learning; Electrolysis; Academic achievement; Student perceptions; Quasi-experimental; Rwanda; Secondary school; Competence-Based Curriculum; Constructivism; Chemistry education

1. Introduction

Chemistry education at secondary school level plays a foundational role in preparing students for scientific, technological, and industrial careers. Within the secondary chemistry curriculum, electrolysis occupies a particularly important position it underpins technologies ranging from batteries and fuel cells to metal plating and corrosion prevention, and it provides conceptual connections between chemistry, physics, and engineering (Garnett & Treagust, 1992; Nakiboğlu et al., 2024). However, electrolysis is also widely recognized as one of the most conceptually demanding topics in secondary chemistry, requiring students to simultaneously operate across macroscopic observable phenomena, symbolic chemical representations, and the submicroscopic world of electron transfer and ionic movement the three levels of chemical representation identified by Johnstone (1991) as the source of much student difficulty in chemistry.

In Rwandan secondary schools, these conceptual challenges are compounded by pedagogical practices that prioritize teacher exposition, note-taking, and rote memorization over active engagement, inquiry, and conceptual understanding. Despite the Rwandan government's introduction of the Competence-Based Curriculum (CBC) in 2015, which explicitly mandates learner-centred pedagogies including collaborative learning, problem-solving, and critical thinking development, classroom observations and examination data consistently show that chemistry instruction in many Rwandan secondary schools remains predominantly teacher-centred (Nsengimana et al., 2017; Sibomana et al., 2021; Musengimana et al., 2021). The consequences are visible in students' examination performance: data from the National Examination and School Inspection Authority (NESA, 2023) document persistent underperformance in chemistry, particularly in topics requiring conceptual application such as electrolysis.

Problem-Based Learning (PBL) originally developed by Barrows (1986) at McMaster University and subsequently adapted across disciplinary and geographical contexts offers a research-supported alternative pedagogy that aligns closely with the constructivist principles underpinning Rwanda's CBC. In PBL, students are presented with authentic, ill-structured problems drawn from real-world contexts and work collaboratively to investigate, analyze, and resolve these problems, with the teacher functioning as a facilitator rather than an

information transmitter (Hmelo-Silver, 2004). International research has documented PBL's positive effects on academic achievement in chemistry (Aidoo et al., 2016; Tarhan & Acar-Sesen, 2013), on students' perceptions and attitudes toward science (Loyens et al., 2008; Üce & Ceyhan, 2019), and on the development of critical thinking, problem-solving, and collaborative skills (Schmidt et al., 2011; Freeman et al., 2014). However, published empirical evidence of PBL's effects in Rwandan secondary chemistry particularly for electrolysis remains extremely limited.

This study addresses this gap directly by implementing and evaluating a PBL intervention in Senior Five (S5) electrolysis classes in two secondary schools in Kigali City and measuring its effects on students' academic achievement and perceptions. Three research questions guided the study: (1) What is the effect of PBL on S5 students' academic achievement in electrolysis? (2) What are students' perceptions of the usefulness, challenges, and overall learning experience of electrolysis taught through PBL? (3) To what extent is there a relationship between students' perceptions of PBL and their academic achievement in electrolysis? The null hypothesis (H_0) posited that there is no significant difference in electrolysis achievement between students taught through PBL and those taught through conventional methods.

2. Literature Review and Theoretical Framework

2.1 Constructivist Foundations of Problem-Based Learning

Problem-Based Learning is grounded in constructivist learning theory, which holds that learners actively construct knowledge through interaction with their environment, with peers, and with authentic problems, rather than passively receiving transmitted information (Piaget, 1972; Vygotsky, 1978). Vygotsky's (1978) concept of the Zone of Proximal Development (ZPD) is particularly applicable to PBL: by working collaboratively on challenging problems under the facilitative guidance of the teacher, students are supported to operate within their proximal developmental zone, achieving understanding that would be beyond their independent capacity. Kolb's (1984) experiential learning cycle concrete experience, reflective observation, abstract conceptualization, active experimentation maps directly onto the PBL process, in which students engage with real-world problems (concrete experience), reflect on their investigations (reflective observation), develop conceptual explanations (abstract conceptualization), and apply their understanding to new situations (active experimentation). Dewey's (1938) argument that meaningful learning occurs when education connects to real-life experience and Bruner's (1961) discovery learning theory further underpin PBL's emphasis on student-driven inquiry and collaborative knowledge construction.

2.2 PBL and Academic Achievement in Chemistry

A substantial body of international research documents PBL's positive effects on student achievement in science and chemistry. Freeman et al.'s (2014) meta-analysis of 225 studies found that active learning approaches, including PBL, produced significantly higher academic achievement and lower failure rates than conventional lecture-based instruction across STEM disciplines. Dağyar and Demirel (2015) confirmed a large positive effect of PBL on science achievement in a further meta-analysis. In chemistry education specifically, Aidoo et al. (2016) demonstrated significant achievement gains in Ghanaian secondary chemistry students taught through PBL compared to peers in conventional instruction. Tarhan and Acar-Sesen (2013) found that PBL produced superior understanding of oxidation-reduction reactions and electrochemical cells, directly relevant to the electrolysis content of the present study. Üce and Ceyhan (2019) documented increased collaborative

engagement and positive chemistry attitudes in PBL classes. In sub-Saharan African contexts, Renzaho and Kampire (2022) demonstrated that practice-based learning strategies improved chemistry achievement among Rwandan secondary students, while Niyonsaba et al. (2022) confirmed that collaborative learning approaches outperformed conventional methods in Rwandan chemistry classrooms, though neither study focused specifically on electrolysis or the PBL framework.

2.3 Student Perceptions of PBL

Research consistently documents that students report positive perceptions of PBL across multiple dimensions. Loyens et al. (2008) found that PBL fosters student autonomy, self-direction, and motivation by making learners accountable for their own knowledge construction. Hmelo-Silver (2004) documented that students value PBL's connection between classroom learning and real-world application. Abubakar and Arshad (2015) found that PBL combined with self-directed learning increased student confidence and interest in chemistry. Students' perceptions of PBL are not merely affective research demonstrates that positive perceptions are associated with greater engagement, deeper processing of content, and higher achievement outcomes (Savery, 2006; Schmidt et al., 2011). Challenges identified in student perceptions of PBL include difficulty adjusting from passive to active learning roles, frustration with the open-ended nature of PBL problems, and concerns about time management (Ertmer & Simons, 2006; Hung et al., 2008).

2.4 Electrolysis as a Conceptually Challenging Topic

Electrolysis's reputation as a threshold topic in secondary chemistry is well-documented. Johnstone's (1991) triplet model identifies the need to simultaneously navigate macroscopic, symbolic, and submicroscopic levels of representation as the source of students' persistent difficulties with chemistry, particularly in electrolysis. Garnett and Treagust (1992) documented widespread student misconceptions about electron movement, redox processes, and the operation of electrochemical cells misconceptions that conventional teacher-centred instruction tends to perpetuate rather than address. Taber (2013) found that memorization-focused instruction leads students to develop surface knowledge of electrochemical formulae and procedures without developing genuine conceptual understanding. Nakiboğlu et al. (2024) confirmed that secondary students continue to struggle with linking electrochemical

processes to chemical reactions and electrical energy conversion. PBL offers a pedagogical response to these challenges by requiring students to engage with the conceptual complexity of electrolysis through authentic problem-solving rather than formula memorization.

2.5 Research Gap

While international and regional evidence for PBL's effectiveness in science education is substantial, published empirical evidence from Rwanda's secondary school chemistry context is limited. Existing Rwandan studies have documented the persistent use of teacher-centred methods (Nsengimana et al., 2017; Musengimana et al., 2021), the potential of collaborative learning for chemistry achievement (Sibomana et al., 2021; Niyonsaba et al., 2022), and the general effectiveness of practice-based approaches (Renzaho & Kampire, 2022), but no published study has systematically implemented and evaluated a PBL intervention specifically for electrolysis among Rwandan S5 students, or measured both achievement and perception outcomes within a quasi-experimental design. This study was designed to fill this gap.

3. Methodology

3.1 Research Design and Paradigm

A pragmatic research paradigm was adopted, supporting the integration of quantitative and qualitative methods in service of the study's practical research questions (Creswell & Creswell, 2018). The research design was a convergent parallel mixed-methods quasi-experimental design, combining a pre-test/post-test non-equivalent control group design for the quantitative component with qualitative data collection through teacher interviews and student focus group discussions. The quasi-experimental design was necessitated by the impossibility of random assignment of students to experimental and control conditions within the institutional constraints of Rwandan secondary schools. Pre-test scores were used to verify baseline group equivalence and control for pre-existing achievement differences in the analysis.

3.2 Study Sites and Participants

The study was conducted in two secondary schools in Kigali City, Rwanda. GS Remera Protestant School (Kicukiro District) served as the experimental group site, and ES Bumbogo School (Gasabo District) served as the control group site. Schools were purposively selected on the basis of their enrolment of Senior Five (S5) PCB and MCB chemistry classes, their possession of comparable laboratory facilities and class sizes, and their willingness to participate in the research. 82 S5 chemistry students participated in both the pre-test and post-test (experimental group n = 46; control group n = 36). Four chemistry teachers two from each school participated in the qualitative component through semi-structured interviews.

Site	Role	Students (n)	Teachers (n)	District
GS Remera Protestant School	Experimental group	46	2	Kicukiro
ES Bumbogo School	Control group	36	2	Gasabo
Total	—	82	4	Kigali City

Table 1: Study sites, participants, and group allocation (N = 82 students, 4 teachers)

3.3 Problem-Based Learning Intervention

The PBL intervention was implemented in the experimental group over eight weeks, covering the Senior Five electrolysis curriculum topics: oxidation-reduction reactions,

electrochemical cells (galvanic and electrolytic), electrolysis, and electrode potential. In each PBL session, students were presented with an authentic, real-world electrochemical problem such as designing a simple battery from locally available materials, investigating the electrochemical basis of metal corrosion on school infrastructure, or analyzing the electrolytic principles underlying industrial metal refining. Students worked in groups of five to six, following a structured PBL cycle: problem presentation, prior knowledge activation, problem analysis and hypothesis generation, independent and collaborative investigation, solution presentation, and reflective debrief. The teacher served as a facilitator, providing guidance, posing Socratic questions, and monitoring group progress without directly transmitting the target knowledge. The control group received conventional teacher-centred electrolysis instruction on the same curriculum topics over the same eight-week period, using lecture exposition, board notes, and textbook exercises.

3.4 Data Collection Instruments

Four instruments were used. The Electrolysis Achievement Test (EAT) was a researcher-developed test comprising multiple-choice and short-answer questions assessing students' cognitive understanding of the electrolysis curriculum across knowledge, comprehension, application, and analysis levels of Bloom's Taxonomy, administered as both pre-test and post-test. The Students' Perceptions of Problem-Based Learning Questionnaire (SPBLQ) was a 10-item Likert-scale instrument (1 = Strongly Disagree to 5 = Strongly Agree) measuring experimental group students' perceptions of PBL across five dimensions: conceptual understanding, participation and engagement, collaborative learning, critical thinking development, and overall learning experience. Semi-structured teacher interview guides and a student focus group discussion guide were used to collect qualitative data on implementation experiences, observed student engagement, perceived benefits, and implementation challenges. Content validity of all instruments was established through expert review by the research supervisor and two chemistry education specialists. Test-retest reliability, calculated using Pearson Product Moment Correlation Coefficient, yielded $r = 0.89$, indicating high instrument reliability (Cohen et al., 2011).

3.5 Data Analysis

Quantitative data were analysed in SPSS v.25. Pre-test scores were compared using independent-samples t-tests to verify baseline group equivalence. Post-test achievement scores were compared between experimental and control groups using independent-samples t-tests, with Cohen's d calculated to quantify effect size. Within-group pre-test to post-test improvement was analysed using paired-samples t-tests for both groups separately. Simple linear regression examined the predictive relationship between students' SPBLQ perception scores and their post-test achievement scores. Qualitative data from teacher interviews were analysed using thematic analysis (Braun & Clarke, 2006), and student FGD data were analysed thematically to identify patterns in student perceptions and experiences.

4. Results

4.1 Baseline Equivalence Pre-Test Comparison

Independent-samples t-test confirmed no statistically significant difference between the experimental and control groups on pre-test EAT scores (experimental: M = 42.3, SD = 8.6; control: M = 41.8, SD = 9.1; $t(80) = 0.27$, $p = 0.79$), establishing baseline equivalence and confirming that any post-test differences can be attributed to the instructional treatment rather than pre-existing achievement differences. Normality testing (Shapiro-Wilk) confirmed that pre-test and post-test score distributions met normality assumptions for both groups, validating the use of parametric tests throughout the analysis.

4.2 Effect of PBL on Academic Achievement in Electrolysis (RQ1)

Post-test results revealed a statistically significant and educationally substantial achievement advantage for the experimental group. The experimental group post-test mean (M = 68.5, SD = 10.2) substantially exceeded the control group post-test mean (M = 53.2, SD = 12.4), with an independent-samples t-test confirming that this difference is highly statistically significant ($t(80) = 6.12$, $p < 0.001$). The null hypothesis H_0 is therefore rejected. Cohen's d = 1.36 indicates a large effect size, confirming that the difference is not merely statistically significant but educationally substantial the experimental group performed 1.36 standard deviations higher than the control group on the post-test.

Measure	Experimental Group (n=46)	Control Group (n=36)	t-statistic	p-value	Interpretation
EAT Pre-test Mean (SD)	42.3 (8.6)	41.8 (9.1)	0.27	0.79	Groups equivalent at baseline
EAT Post-test Mean (SD)	68.5 (10.2)	53.2 (12.4)	6.12	<0.001	Highly significant — Experimental superior
Pre-post improvement (gain)	26.2 points	11.4 points	—	—	Exp. group improved 2.3× more than control
Cohen's d (effect size)	1.36	—	—	—	Large effect — educationally substantial
Within-group paired t-test	t=14.23, p<0.001	t=4.11, p<0.001	—	—	Both improved; experimental significantly more

Table 2: Electrolysis Achievement Test (EAT) results — pre-test and post-test comparison

Within-group paired t-tests confirmed that the experimental group showed a highly significant pre-to-post improvement (M gain = 26.2 points; $t(45) = 14.23$, $p < 0.001$), compared to a more modest improvement in the control group (M gain = 11.4 points; $t(35) = 4.11$, $p < 0.001$). The substantially larger gain in the experimental group (26.2 points versus 11.4 points a ratio of 2.3:1) confirms that PBL produced learning gains well beyond those achievable through conventional instruction over the same eight-week period on the same content.

4.3 Students' Perceptions of PBL in Electrolysis (RQ2)

SPBLQ data showed consistently positive perceptions of PBL among experimental group students across all five measured dimensions, with mean scores ranging from 3.89 to 4.31 on the 5-point Likert scale.

Perception Dimension	Mean (SD)	% Agree/Strongly Agree	Interpretation
PBL helped me understand electrolysis better	4.31 (0.62)	89.1%	Very positive
I was more engaged in PBL lessons than in conventional classes	4.18 (0.71)	84.8%	Very positive
Working in groups helped me learn from my peers	4.24 (0.68)	87.0%	Very positive
PBL developed my critical thinking skills	4.12 (0.74)	82.6%	Positive
I found it difficult to adjust to PBL at first	3.74 (0.89)	71.7%	Moderate challenge
PBL was more challenging than conventional learning	3.89 (0.81)	76.1%	Moderate challenge
I would recommend PBL for other chemistry topics	4.28 (0.65)	89.1%	Very positive
PBL connected electrolysis to real-life situations	4.35 (0.58)	91.3%	Very positive
I felt more confident in electrolysis after PBL	4.09 (0.76)	80.4%	Positive
Overall, PBL improved my learning experience	4.22 (0.67)	86.9%	Very positive

Table 3: Students' Perceptions of Problem-Based Learning Questionnaire (SPBLQ) results (n = 46, 5-point Likert scale)

The highest agreement was observed on the item 'PBL connected electrolysis to real-life situations' (M = 4.35, 91.3% agreement), reflecting the central PBL mechanism of contextualizing abstract electrochemical concepts in real-world problems. Students also strongly endorsed the item 'PBL helped me understand electrolysis better' (M = 4.31, 89.1% agreement). The only items receiving moderate rather than high endorsement concerned

initial adjustment difficulties (M = 3.74) and the perceived challenge of PBL compared to conventional learning (M = 3.89) findings consistent with the transition costs documented in the broader PBL literature (Ertmer & Simons, 2006).

Qualitative data from the student focus group discussion reinforced the quantitative findings. Students described increased motivation, greater enjoyment of chemistry, and a sense of ownership over their learning. Representative FGD responses included: 'When we solved a problem about how batteries work in our phones, I finally understood what happens with electron transfer'; and 'At first it was hard because we had to find things ourselves, but after a few weeks I actually liked that better than just copying from the board.'

4.4 Teachers' Perceptions of PBL in Electrolysis

Thematic analysis of teacher interviews identified four major themes: enhanced student engagement, improved conceptual understanding, implementation challenges, and suggestions for system-level support.

Both teachers in the experimental school independently observed that PBL produced more active and sustained student engagement than conventional instruction. One teacher noted: 'I could see the students discussing and arguing about why electrons move in a certain direction in the galvanic cell that level of discussion never happens in a regular lecture.' The same teacher observed that students who had previously struggled to understand electrolysis demonstrated improved understanding after working through a real-world problem involving the electrolytic purification of copper: 'The connection between what they were doing in the experiment and what they had read in the textbook became much clearer through the problem-solving approach.'

Implementation challenges identified by both teachers included the time required to design and prepare authentic real-world problems, the difficulty of managing group work in class sizes of 40 to 50 students, and the limited availability of laboratory equipment for some PBL activities. Both teachers recommended that PBL be supported by school-level investment in laboratory resources, by structured teacher professional development in PBL facilitation, and by formal inclusion of PBL as a recommended pedagogical strategy in the S5 chemistry curriculum guidelines.

4.5 Predictive Relationship Between Student Perceptions and Achievement (RQ3)

Simple linear regression confirmed that students' SPBLQ perception scores were a significant positive predictor of their post-test achievement scores. The regression model explained 32% of the variance in post-test achievement ($R^2 = 0.32$, $F(1,44) = 20.71$, $p < 0.001$; $\beta = 0.57$, $p < 0.001$). This finding indicates that students who perceived PBL more positively also achieved higher scores in the electrolysis post-test, suggesting that attitude and achievement are mutually reinforcing in PBL contexts consistent with the motivational mediation hypothesis proposed by Schmidt et al. (2011).

Predictor	Unstandardised B	SE	Standardised β	t	p	R^2
SPBLQ Total Score (perceptions)	3.84	0.84	0.57	4.55	<0.001	0.32

Table 4: Simple linear regression — Student perceptions of PBL predicting post-test achievement (n=46)

5. Discussion

The findings of this study provide clear and consistent empirical evidence that Problem-Based Learning significantly enhances Senior Five students' academic achievement in electrolysis compared to conventional teacher-centred instruction in a Rwandan secondary school context, while simultaneously producing positive student perceptions and strong perception-achievement alignment. Three analytically important conclusions emerge.

First, the large effect size of PBL on electrolysis achievement (Cohen's d = 1.36) substantially exceeds the medium effect sizes (d ≈ 0.5–0.7) typically reported in international meta-analyses of PBL (Dağyar & Demirel, 2015; Freeman et al., 2014). This larger-than-typical effect likely reflects the particular severity of the baseline problem in the Rwandan context when conventional instruction is strongly teacher-centred and examination-focused, and students have had little prior experience of collaborative or inquiry-based learning, the contrast effect of a well-implemented PBL intervention may be greater than in contexts where active learning is already more common. This interpretation is consistent with Renzaho and Kampire's (2022) Rwandan findings, which showed similarly strong effects for practice-based learning approaches in chemistry classrooms where conventional teacher-centred methods had previously dominated. The finding directly corroborates Tarhan and Acar-Sesen (2013), who found PBL particularly effective for electrochemical concepts including oxidation-reduction reactions and electrochemical cells the specific content areas targeted by this intervention.

Second, the pattern of student perceptions confirmed by the SPBLQ is consistent with the international PBL perception literature (Hmelo-Silver, 2004; Loyens et al., 2008; Üce & Ceyhan, 2019) while providing important contextual nuance. The highest endorsement for the item connecting electrolysis to real-life situations (M = 4.35, 91.3%) reflects the specific pedagogical mechanism through which PBL addressed electrolysis's notorious abstraction problem: by anchoring abstract concepts like electron transfer, electrode potential, and redox reactions in concrete, real-world problems (batteries, corrosion, electrolytic purification), PBL provided students with the macroscopic experiential anchor that Johnstone (1991) identifies as essential for building understanding of chemistry's symbolic and submicroscopic levels. The moderate challenge perceptions (initial adjustment, M = 3.74; perceived

difficulty, M = 3.89) are consistent with Ertmer and Simons (2006), who documented the transition costs associated with shifting from passive to active learning roles, and should not be interpreted as negative outcomes but as evidence that PBL genuinely challenged students beyond their comfort zone the prerequisite for the ZPD-mediated learning gains documented in the achievement data.

Third, the significant perception-achievement relationship ($R^2 = 0.32$) has important pedagogical implications. It suggests that the academic benefits of PBL are not uniformly distributed but are mediated by students' affective and motivational responses to the PBL approach. Students who perceive PBL more positively engage more deeply with the collaborative problem-solving process, which in turn produces greater learning gains. This finding is consistent with Schmidt et al.'s (2011) motivational mediation model and with Abubakar and Arshad's (2015) finding that self-directed learning confidence predicted chemistry achievement in PBL contexts. The implication for practice is that teachers implementing PBL should attend not only to the design and facilitation of PBL activities but also to strategies that build positive student perceptions early in the PBL cycle for example, by starting with highly accessible, highly engaging real-world problems that quickly demonstrate PBL's value before introducing more complex investigations.

6. Conclusion and Recommendations

This study demonstrates that a structured eight-week Problem-Based Learning intervention produces significant, large-effect-size gains in Senior Five students' electrolysis achievement and generates strongly positive student perceptions of the approach in two secondary schools in Kigali City, Rwanda. The findings fill an important empirical gap in the Rwandan chemistry education literature by providing the first published quasi-experimental evidence of PBL's effects on both cognitive and affective outcomes specifically in electrolysis, within the framework of Rwanda's Competence-Based Curriculum.

For chemistry teachers: adopt the structured PBL approach developed in this study beginning with accessible, real-world electrochemical problems and gradually increasing complexity as a complement to, not a replacement for, conventional instruction. Build positive student perceptions early in the PBL cycle by selecting problems with clear real-life relevance. For school administrators: invest in laboratory resources that support PBL activities, schedule adequate collaborative learning time in the timetable, and support teachers in accessing PBL facilitation training. For the Rwanda Education Board (REB) and MINEDUC: formally include Problem-Based Learning as a recommended pedagogical strategy in the S5 chemistry CBC curriculum guide and the electrolysis unit teacher's guide; develop Rwanda-specific PBL problem sets for electrolysis that are aligned with the CBC and accessible within typical Rwandan school resource environments; incorporate PBL facilitation skills into pre-service and in-service chemistry teacher education programmers. For future researchers: extend this study to a larger, multi-district sample to improve generalizability; examine the long-term retention of PBL-produced electrolysis learning gains; investigate gender differences in PBL outcomes; and test the transferability of PBL to other challenging secondary chemistry topics including organic chemistry and stoichiometry.

7. Declarations

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Ethics approval and consent to participate

Ethical clearance for this study was reviewed and approved by the Institutional Review Board (IRB) of the University of Rwanda–College of Education (UR-CE), under Reference No. DRI-CE/089(a)/MT/gi/2026, dated 4 May 2026. The study was conducted in accordance with relevant ethical guidelines and regulations governing research involving human participants and adhered to the principles of the Declaration of Helsinki and applicable national guidelines. Permission to conduct the study was subsequently obtained from the relevant education authorities in Kicukiro and Gasabo Districts and from the head teachers of the participating schools.

Written informed consent was obtained from the parents or legal guardians of all participating students, and assent was obtained from the students before their participation in the study. The purpose and importance of the study were explained to the participants, participation was voluntary, and participants were informed of their right to withdraw without consequences. Confidentiality and anonymity were maintained throughout the study, and codes rather than names were used to protect participants' identities.

Consent for publication

Not applicable. The manuscript does not contain identifiable individual participant information.

Data availability

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

The first author conceived and designed the study, developed the research instruments, collected and analyzed the data, interpreted the findings, and drafted the manuscript. The supervising author provided supervision throughout the study, contributed to the study design and methodology, supported the interpretation of the findings, and critically reviewed and revised the manuscript. All authors read and approved the final version of the manuscript.

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Table 1: Target population

School	Students	Teachers	Total
GS Remera Protestant	46	1	47
ES Bumbogo	36	1	37
Total	**82**	**2**	**84**

Table 2 : Summary of copies administered for each instrument

Instrument	Target group	Number of Participants	Number of copies
Pre-test	Students	82	82
Post-test	Students	82	82
Questionnaire	Students	82	82
Interview guide	teachers	2	2

Table 3 : Gender of respondents

Participant Category	***Male, n (%)***	***Female, n (%)***	***Total***
Control Group	19 (52.8%)	17 (47.2%)	36
Experimental Group	25 (54.3%)	21 (45.7%)	46
Teachers	1 (50.0%)	1 (50.0%)	2
Total	**45 (53.6%)**	**39 (46.4%)**	**84**

Table 4 : Test of normality for pre-test and post-test achievement Scores of experimental and control groups

Variable	Group	W	p-value	Decision
Pretest	Experimental	0.983	0.729	Normal
Pretest	Control	0.952	0.118	Normal
Posttest	Experimental	0.966	0.190	Normal
Posttest	Control	0.965	0.299	Normal

Table 5 : Comparison of pre-test achievement scores between experimental and control groups

Group	N	Mean Pretest	SD
Experimental	46	20.74	5.89
Control	36	22.17	4.66

Table 6 : Independent-samples t-test comparing pre-test achievement scores between the experimental and control groups

Group	n	Mean	SD	Mean Difference	t (df)	p-value
Experimental	46	20.74	5.89	-1.43	-1.19 (80)	0.237
Control	36	22.17	4.66			

Table 7 : Post-test comparison between experimental and control groups

Group	n	Mean	SD	Mean Difference	t (df)	p-value
Experimental	46	54.54	8.44	16.24	9.61 (80)	<0.001

Control	36	38.31	6.34

Table 8 : Paired samples t-test results comparing pretest and post-test scores in the experimental group

Measure	n	Mean	SD	Mean Difference	t	(df)	p-value
Pre-test	46	20.74	5.89				
Post-test	46	54.54	8.44	33.80	21.73	(45)	<0.001

Table 9 : Paired samples t-test results for pre-test and post-test scores of the control group

Group	N	Mean Pre-test	SD Pre-test	Mean Post-test	SD Post-test	Mean Difference	t-value	df	p-value
Control	36	22.17	4.66	38.31	6.34	16.14	11.50	35	<0.001

Table 10 : Cohen's d effect size interpretation ranges

Cohen's d	Magnitude
< 0.20	Negligible effect
0.20 – 0.49	Small effect
0.50 – 0.79	Medium effect
≥ 0.80	Large effect

Table 11 : Effect Size of the Problem-Based Learning Intervention on Students' Achievement Scores in the Experimental Group

Paired t-test statistics	**Value**
Mean difference	33.80
t-value	21.73
Degrees of freedom (df)	45
p-value (two-tailed)	<0.001
Cohen's d	3.20
Effect size interpretation	Very large

Table 12 : Students' Perceptions of Problem-Based Learning in Learning Electrolysis(n = 46)

Perception Theme	**Frequency**	**Percentage (%)**
PBL improved understanding of electrochemistry	42	91.3
PBL increased classroom participation	39	84.8
PBL improved teamwork skills	36	78.3
PBL increased confidence in learning chemistry	34	73.9
PBL was difficult at the beginning	13	28.3
PBL was time-consuming	9	19.6

Table 13 : Summary of teachers' perceptions of Problem-Based Learning

Theme	**Teachers' Responses**
Teaching approach	Both teachers reported that they generally use learner-centred teaching approaches.

Understanding of PBL	The teachers indicated that they had limited knowledge of Problem-Based Learning before the study.
Previous use of PBL	Neither teacher had previously used PBL when teaching electrolysis.
Effect on conceptual understanding	Both teachers observed that PBL greatly improved students' understanding of electrolysis concepts.
Student participation	The teachers noted that students became more interested, actively participated in lessons, and engaged more in classroom discussions.
Skills developed	The teachers observed significant improvement in students' participation, collaboration, teamwork and problem-solving skills.
Academic performance	Both teachers believed that students' academic performance improved greatly after learning through PBL.
Challenges experienced	The major challenge reported was that students were initially unfamiliar with learner-centred instructional methods.
Strategies used	The teachers addressed this challenge by providing additional guidance and support during classroom activities.
Support needed	Both teachers recommended professional development and training to help teachers implement PBL more effectively.

Table 14: Linear Regression analysis of the relationship between students' perception and achievement scores.

Predictor	**Coefficient (β)**	**Std. Error**	**t-value**	**p-value**	**95% Confidence Interval**
Positive perception	27.008	1.192	22.65	<0.001	24.607 – 29.409
Constant	54.250	0.968	56.03	<0.001	52.300 – 56.200

Table 15 : Model summary

Statistic	**Value**
Number of observations (N)	47
F(1,45)	513.24
Prob > F	<0.001
R-squared (R^2)	0.919
Adjusted R-squared	0.918
Root Mean Square Error	3.873

Figure 1 presents the conceptual framework illustrating the relationships among the variables investigated in this study.

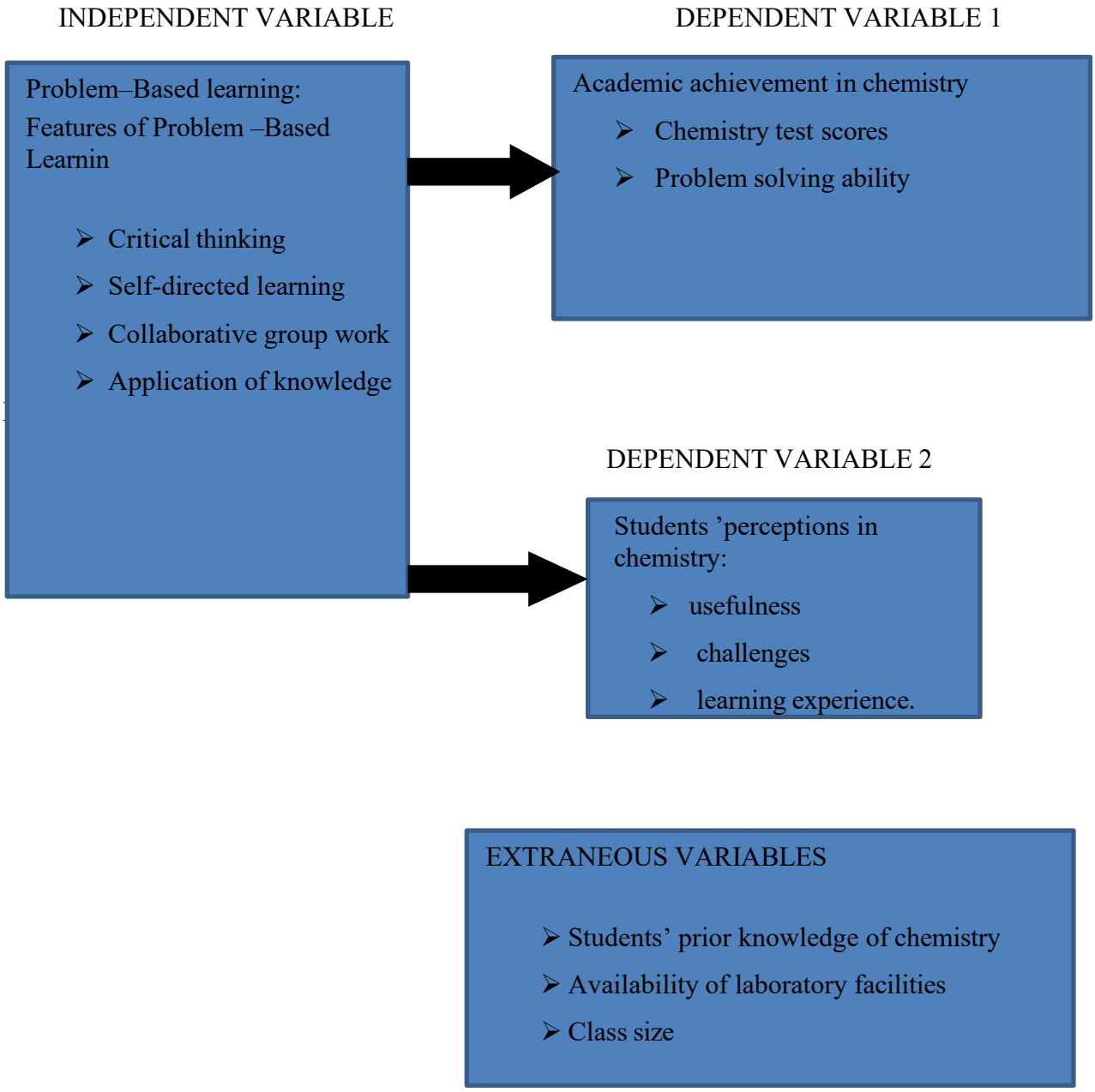


Figure 1 : Variables in conceptual framework

Figure 2 presents the distribution of post-test scores for students in the experimental group. The scores range from approximately 35 to 68, with most students obtaining scores between 50 and 65. The distribution shows that the highest proportion of students scored around 50–56, suggesting that many students achieved relatively high post-test scores after the intervention. Overall, the graph indicates a generally positive distribution of students' post-test academic achievement in the experimental group.

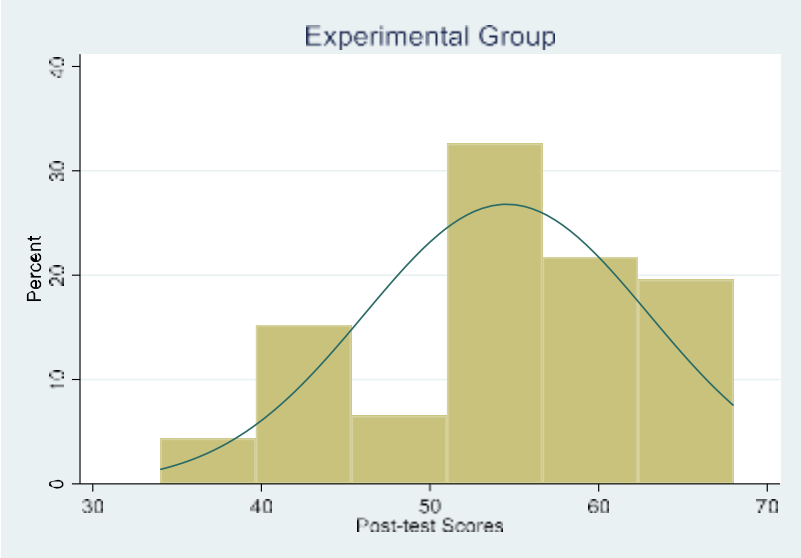


Figure 2 : Histogram of post-test achievement scores for the experimental group

Figure 3 presents the distribution of post-test achievement scores for students in the control group. The histogram shows that most students scored between approximately 35 and 45, with the highest concentration around 38–42. Overall, the scores appear to follow an approximately normal distribution, as indicated by the fitted curve.

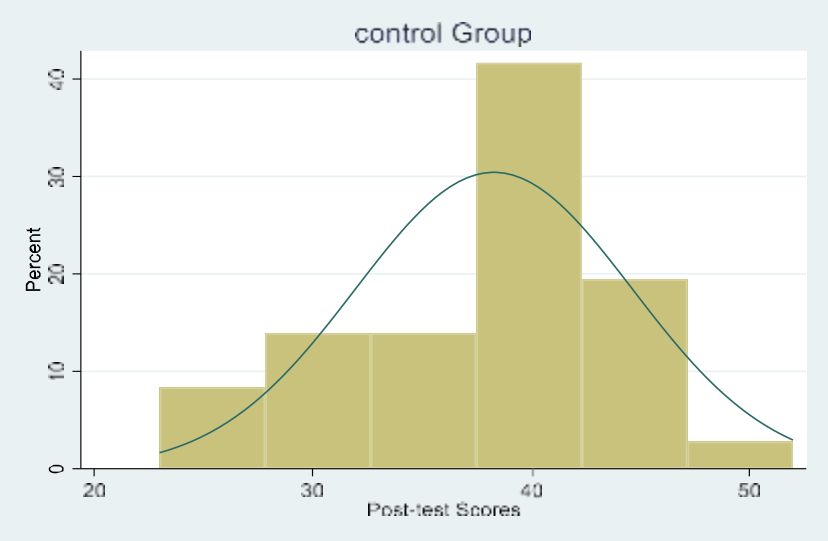


Figure 3 : Histogram of post-test achievement scores for the control group

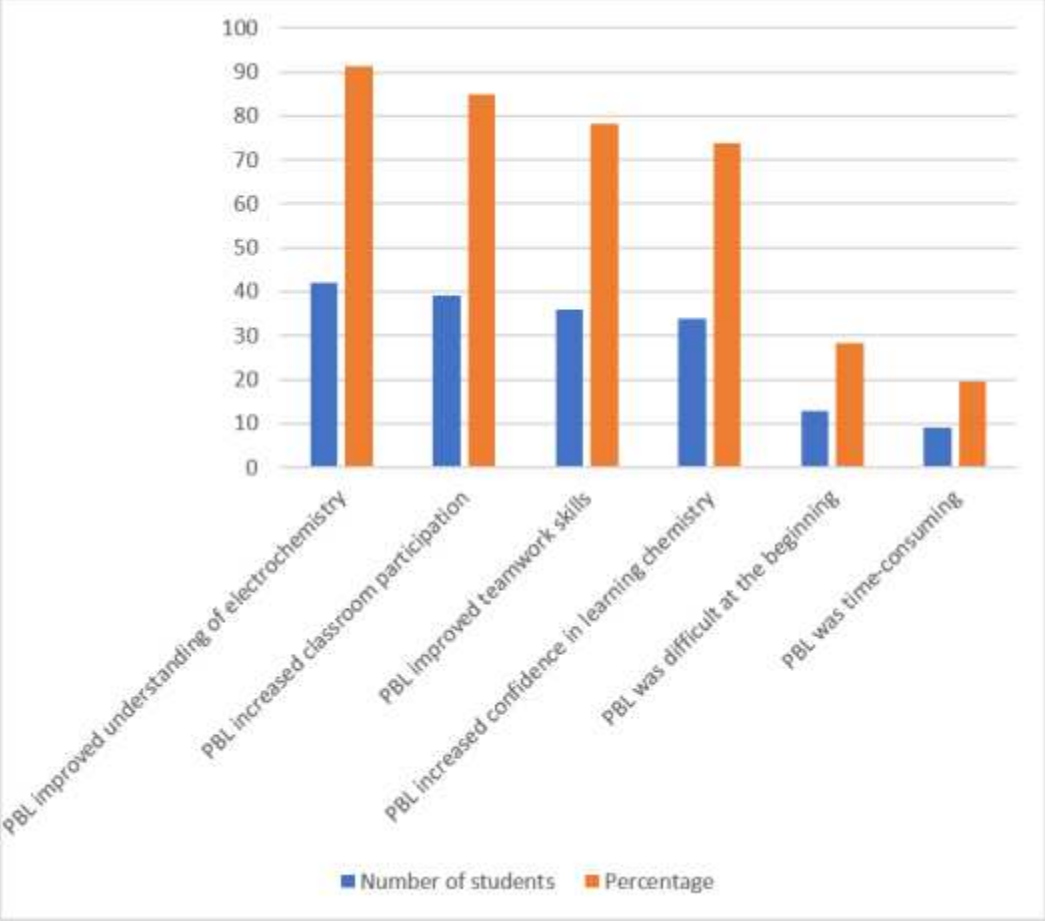


Figure 4 : Students' perceptions of problem-based learning in electrochemistry

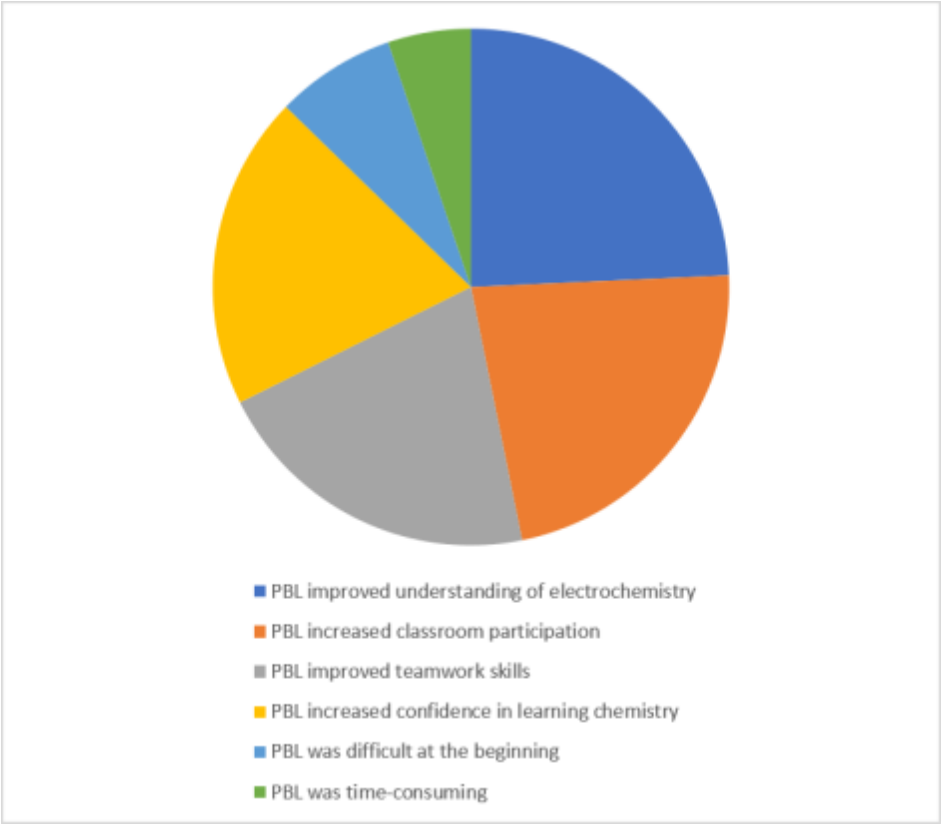


Figure 5 : Percentage distribution of students' perceptions of of Problem-Based Learning



Figure 6: Variation in achievement scores among students with positive and negative perceptions

Supplementary Files

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