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Evaluation of an innovative pedagogical approach combining flipped classroom and mutual learning in electrochemistry: Analysis of performance and satisfaction of secondary school students in Fez-Meknes

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ABSTRACT

Innovative pedagogical strategies are critical to enhance STEM education quality in resource-constrained educational environments. This quasi-experimental study (2021-2023) evaluates a frugal approach combining flipped classroom and mutual learning within Morocco's GENIE program in Fez-Meknes guided by the ICAP cognitive engagement framework and frugal innovation principles. Over two academic years, 160 secondary students (94 in 2021-2022 and 66 in 2022-2023) were divided into experimental and control groups. The 12-hour intervention structured into electrochemistry modules utilized locally adapted materials and peer interactions to optimize resources. Data from a validated SEEQ questionnaire ($\alpha > 0.83$) revealed significant academic improvements in experimental groups versus controls: +2.30/+3.22 points (2021-2022 and $p < 0.01$) and +2.54 points (2022-2023 and $p < 0.01$), contrasting with control declines. Satisfaction metrics progressed across multiple dimensions, learning scores arise from 3.10 to 4.43, enthusiasm increased from 3.62 to 4.75, and group interaction advanced from 3.13 to 4.75. Qualitative feedback highlighted students' progression through engagement levels, transitioning from rote memorization to collaborative conceptual understanding with wall charts achieving 97% approval. This study demonstrates how frugal innovation approaches aligned with sustainable development goal 4 on quality education can transform science education in resource-limited contexts through strategic adaptation of evidence-based pedagogies within local educational frameworks.

Contribution/Originality: This study addresses a critical gap in science education research by quantifying how frugal pedagogical innovations can overcome electrochemistry teaching challenges in resource-constrained environments. It uniquely demonstrates that strategically combining flipped classrooms with mutual learning significantly improves academic outcomes without requiring expensive infrastructure, offering an evidence-based, sustainable model for developing contexts.

1. INTRODUCTION

Education innovation in resource-constrained environments represents a critical frontier in development studies, especially in STEM (science, technology, engineering, and mathematics) teaching where complex subjects like electrochemistry represent significant educational challenges. In such contexts, frugal innovation defined as the ability to "do more with less" (Radjou & Prabhu, 2015) becomes mandatory to develop effective educational solutions, especially in southern countries where education's quality and social justice are intrinsically linked (Tikly & Barrett, 2013).

In teaching electrochemistry at the high school level, these issues take on particular importance within the broader context of educational development. The topic requires understanding multiple levels of representation macroscopic, sub microscopic, and symbolic (Johnstone, 1991; Talanquer, 2011) making it particularly difficult in resource-limited contexts. This situation (UNESCO, 2021) is identified as a critical challenge in STEM education in developing countries, where innovative pedagogical approaches must bridge resource gaps while maintaining educational quality.

Research by Aparicio, Bacao, and Oliveira (2017) and Alsabawy, Cater-Steel, and Soar (2016) demonstrates that such innovation's effectiveness depends not on expensive infrastructures but rather on the quality of pedagogical integration. The World Bank (Hawkins, Trucano, Cobo, Twinomugisha, and Ciarrusta (2020)) has specifically highlighted how sustainable innovation in developing contexts emerges through strategic resource optimization and local capacity building, especially when educational institutions focus on maximizing existing resources rather than waiting for major infrastructure investments.

This sustainable innovation approach is particularly relevant in the Moroccan context where educational institutions must balance quality improvement with resource constraints.

The combination of flipped classroom methodology with mutual learning represents a promising approach to frugal innovation in education, particularly in resource-constrained environments (Radjou & Prabhu, 2015; Tikly, 2019). Recent meta-analyses show that this combined approach can significantly improve learning outcomes in science education (Al-Zahrani, 2015; Hawkins et al., 2020; Sakti, Jalinus, & Wulansari, 2023). Studies, such as Alsalhi, Eltahir, and Al-Qatawneh (2019) have demonstrated tangible improvements in both academic performances and student engagement in sciences education within resource-constrained environments, highlighting the potential of such approaches in developing contexts.

This approach aligns with emerging theories of innovation in developing countries as articulated by Foster and Heeks (2013) who created a comprehensive framework for understanding how successful innovation implementation highly depends on adapting solutions to local contexts, especially through what they call "inclusive innovation" approaches that maximize existing resources while strengthening local capacities. This approach to sustainable innovation is particularly relevant in the Moroccan context where educational institutions must balance quality improvement with resource constraints.

The effectiveness of this pedagogical approach highly relies on its ability to promote deep cognitive engagement among learners. As defined in the ICAP theory, Chi (2009) and Chi and Wylie (2014) argue that this engagement can be observed and categorized into four distinct levels: interactive, constructive, active, and passive. In the context of teaching electrochemistry, interaction engagement manifests when students actively collaborate to build their understanding, while constructive engagement occurs when they generate explanations that go beyond the given information. Active engagement involves content manipulation without generating new knowledge, and passive engagement corresponds to the simple reception of information.

Understanding these different levels of engagement is particularly relevant in the context of developing countries, where optimizing educational resources requires special attention to the quality of students' engagement. Recent research by Menekse, Stump, Krause, and Chi (2013) has shown that activities that promote interactive and constructive engagement lead to significantly better learning outcomes than those limited to active or passive engagement.

Our implementation in the Moroccan educational context, particularly through the GENIE program (Generalization of Information and Communication Technologies in Education) was conducted over two academic years (2021-2023) in the Fez-Meknes region. This study demonstrates how systemic innovation in education can emerge from local contexts (Lundvall, Joseph, Chaminade, & Vang, 2009) maximizing learning outcomes even in schools with limited resources. The GENIE program launched in 2005 as a national initiative to enhance teaching and learning quality through technology integration (Ismaili, 2022) provides the institutional framework for our intervention. GENIE aimed to align Moroccan education with global pedagogical shifts rooted in equipping schools with Information and Communication Technology (ICT) infrastructure and promoting digital literacy among teachers. However, challenges, such as insufficient technical support and uneven teacher training persist, limiting its full potential (Ismaili, 2022). Our methodology focuses on optimizing existing resources and human capital, exemplifying what the World Bank describes as sustainable innovation in education through strategic integration of available resources (Hawkins et al., 2020).

For example, wall charts created from locally available materials replace costly digital displays while structured peer-to-peer interactions compensate for the limited equipment of the laboratory through the collaborative conceptual exploration.

This work is particularly timely given the growing recognition of frugal innovation's role in achieving the Sustainable Development Goals, especially the SDG 4 on quality education. Our study contributes to understanding how developing countries can improve science teaching while working within resource constraints, addressing what the OECD (2022) identifies as a critical challenge in educational development through systematic assessment of student outcomes in electrochemistry. This approach aligns with recent theoretical frameworks on innovation systems in developing countries (Kraemer-Mbula, Tijssen, Wallace, & McLean, 2020) and it addresses what the OECD (2022) identifies as critical educational challenges in resource-constrained environments, particularly regarding the implementation of innovative teaching practices through locally adapted solutions.

Our study addresses three key research questions:

1. How does this frugal innovation approach, combining flipped classroom and mutual learning contribute to improving learning outcomes in electrochemistry within educational contexts with limited resources?
2. To what extent does this resource-efficient teaching methodology influence the satisfaction and engagement of the students with electrochemistry concepts in the context of a developing country?
3. What factors influence the successful implementation of this frugal educational approach in teaching electrochemistry in the Moroccan education system in high schools?

Through systematic evaluation of student satisfaction and academic performance, we assess whether this resource-efficient educational innovation can effectively improve the understanding of complex electrochemical concepts while working within existing constraints, contributing to broader discussion on innovation capabilities in the contexts of developing countries (Bell & Figueiredo, 2012).

2. MATERIALS AND METHODS

2.1. Research Design

We employed a quasi-experimental design suited to evaluating educational innovations in authentic school settings (Cook & Campbell, 1979). This approach allowed us to assess the effectiveness of our pedagogical intervention while working within the existing structures of the Moroccan educational system. The study was conducted over two consecutive academic years (2021-2023) in the Fez-Meknes region, enabling both immediate evaluation and assessment of progress over time.

2.2. Research Hypotheses

Based on our research objectives, we formulated three main hypotheses:

H_1: The combined pedagogical intervention significantly improves learning, enthusiasm, organization and group interaction among students.

H_{01}: The pedagogical intervention has no significant effect on these aspects.

H_2: The effectiveness of the pedagogical intervention improves with time and experience (between 2021/2022 and 2022/2023).

H_{02}: There is no significant difference in the effectiveness of the intervention between the two academic years.

H_3: Students in the experimental group achieve significantly higher academic performance in electrochemistry compared to students in the control group.

H_{03}: There is no significant difference in academic performance between the experimental and control groups.

2.3. Participants and Groups

This study involved 160 second-year baccalaureate students in physical sciences over two consecutive academic years (2021-2023) at 11 Janvier Qualifying Secondary School in Ain Taoujdate. This establishment was selected as representative of the typical resource constraints faced in Morocco's semi-urban education settings, serving approximately 1300 students from socio-economic backgrounds characterized by reliance on agriculture and artisan activities, with limited access to educational resources and relatively high unemployment rates.

In 2021/2022, 94 students participated (control group: n=32 and experimental group: Exp1 n=29 and Exp2 n=30) with 34 experimental students completing the satisfaction questionnaire. In 2022/2023, 66 students participated (control: n=34 and experimental: n=32), with 23 experimental students completing the questionnaire.

2.4. Course Content and Implementation Strategy

Our teaching intervention was structured around two main units of electrochemistry using a systematic four-step teaching process designed to optimize resource utilization in a constrained environment.

2.4.1. Teaching Structure

Each session followed a consistent four-step process.

Table 1 illustrates the structure of the basic teaching process implemented in this study. It organizes the pedagogical intervention into four sequential phases which are as follows: in- depth discussion, practical demonstration, collaborative work, and synthesis- detailing the duration, purpose, and implementation strategy for each component.

Table 1. Structure of the basic teaching process

Phase	Duration	Purpose	Implementation
In-depth discussion	25 min	Concept verification and clarification	Interactive exchange
Practical demonstration	25 min	Visual and experimental learning	Hands-on experience
Collaborative work	60 min	Active learning and peer teaching	Group activities
Synthesis	10 min	Knowledge consolidation	Review and integration

2.4.2. Unit Implementation Details

The intervention was implemented through two sequential units, each carefully structured to optimize resource use while ensuring effective learning:

Table 2 outlines the detailed implementation of teaching units in electrochemistry across the two sequential modules of the intervention. It categorizes the instructional activities into four teaching phases for both the spontaneous transformations (6 hours) and forced transformations (6 hours) units, specifying the core concepts addressed, resources utilized, and specific activities conducted during each phase.

Table 2. Implementation of teaching units in electrochemistry

Teaching phases	Unit 1: Spontaneous transformations (6h)	Unit 2: Forced transformations (6h)
Pre-class preparation	Study of electrochemical cell fundamentals and electrode potentials using digital/ print materials and teams platform	Study of electrolysis principles and non-spontaneous reactions using digital/ print materials, and structured guides
In-depth discussion (25 min)	• Core concepts: Electrochemical cells, electrode potentials, polarity and battery principles • Resources: Wall charts and previous session notes	• Core concepts: Electrolysis principles, industrial applications • Resources: Wall charts and industrial process diagrams
Practical demonstration (25 min)	• Activities: Daniell cell assembly, voltage measurements and battery systems analysis • Resources: Laboratory equipment, and measurement tools	• Activities: Water electrolysis, sodium chloride electrolysis • Resources: Electrolysis apparatus, and indicators
Collaborative work (60 min)	• Focus: Problem-solving, calculations, and industrial applications • Resources: Application worksheets, and wall charts	• Focus: Industrial process analysis, and efficiency calculations • Resources: Application worksheets, and wall charts
Synthesis (10 min)	• Purpose: Knowledge consolidation, and preparation for the next session • Resources: Summary materials	• Purpose: Integration of theoretical and practical knowledge • Resources: Review materials

2.5. Traditional Approach (Control Group)

The traditional teaching applied to the control group was structured into seven sessions totalling 12 hours, distributed as follows:

- Electrochemical cells: Four sessions (6 hours) devoted to theoretical presentation, practical demonstrations, and guided exercises.
- Forced transformations: Three sessions (6 hours) including lectures, electrolysis demonstrations, and problem-solving sessions.

Each session followed a classic pedagogical structure: A review of previous concepts, the introduction of new notions, practical demonstration, and application exercises. This approach aimed to provide a solid basis for comparison to evaluate the effectiveness of the experimental method.

2.6. Evolution of the Approach

The iterative refinement of the pedagogical intervention between academic years (2021/2022 and 2022/2023) focused on two key dimensions: physical environment optimization and pedagogical strategy enhancement.

2.6.1. Physical Environment Optimization

Initial classroom layouts featured fixed laboratory benches which impeded collaborative interactions. Based on student feedback, we removed obstructive benches and repurposed unused whiteboards as mobile collaborative tools. These were strategically positioned to enable flexible group configurations, transforming the traditional classroom into an adaptable learning environment conducive to collaborative work.

2.6.2. Pedagogical Strategy Enhancement

Concrete adjustment centred on student engagement helped us refine our approach during implementation. To better immerse participants in the important ideas and practical applications of their work, for example, collaborative work sessions were lengthened from 60 to 75 minutes. We instituted predetermined roles, like "explainer" and "questioner" to organize peer interactions and direct group reflection toward specific topics.

Wall charts were redesigned with an intuitive color code (red for oxidation processes, blue for reductions, and black for standard notations), simplifying the distinction between reaction mechanisms while preserving scientific rigor. Visual innovation also played a central role in this process. We considered student feedback and cut pre-class videos to 10-15 minutes. This length helped students focus the most.

Students' suggestions during our pilot phase informed these straightforward changes which led to discernible gains in both academic achievement and self-assessed comprehension. Our pedagogical approach is designed to thrive even in contexts with limited resources and they show this flexibility.

2.7 Data Collection and Measurement Instruments

We employed two main measurement instruments to evaluate our pedagogical innovation's effectiveness within the Moroccan educational context. First, we used a modified version of the Student Evaluation of Educational Quality (SEEQ) questionnaire (Marsh, 1982) adapted to the local context and validated for cultural appropriateness. The questionnaire's internal reliability was confirmed with a Cronbach's alpha coefficient above 0.83 for all aspects, focusing on learning effectiveness, student engagement, and implementation feasibility.

Our second instrument was an electrochemistry knowledge assessment, structured as pre-test and post-test, which included multiple-choice questions, calculation problems, and short-answer questions. This assessment tool was validated by local chemistry experts and aligned with national curriculum standards to ensure contextual relevance. The content covered fundamental electrochemical concepts while incorporating applications relevant to local industrial contexts. Data collection was conducted over two academic years (2021-2023). In 2021/2022, among 94 participating students, 34 (57.6%) of the experimental groups responded to the satisfaction questionnaire. The 2022/2023 academic year saw an improved response rate with 23 out of 32 students (71.9%) in the experimental group completing the satisfaction survey. Knowledge assessments achieved 100% completion rates across both years. Quality assurance measures included bilingual validation (French-Arabic), pilot testing with local students, and expert review by Moroccan teachers. All instruments were administered under standardized conditions with clear instructions provided in languages to ensure reliable data collection within our resource-constrained setting.

Table 3. Student satisfaction questionnaire adapted from SEEQ: Evaluation before and after the pedagogical intervention

Aspect evaluated	Question	Possible answers				
		Very poor	Poor	Moderate	Good	Very good
Learning	1. I found this unit intellectually stimulating and challenging. 2. I learnt something that I consider valuable. 3. My interest in the subject increased as a consequence of this unit. 4. I have learnt and understood the contents of this unit.					
Enthusiasm	5. The teacher was enthusiastic about teaching the course. 6. The teacher was dynamic and energetic in conducting the course. 7. The trainer succeeded in making the lessons enjoyable. 8. The teacher's style of presentation held your interest during class.					
Organization	9. The teacher's explanations were clear. 10. course materials were well prepared and explained clearly. 11. Proposed objectives agreed with those actually taught so you knew where the course was going. 12. Teacher gave lectures that facilitated taking notes.					
Group interaction	13. Students were encouraged to participate in class discussions. 14. Students were invited to share their ideas and knowledge. 15. Students were encouraged to ask questions and were given satisfactory answers. 16. Students were encouraged to express their own ideas and question the teacher.					

Table 3 presents the multi-dimensional satisfaction questionnaire adapted from Marsh's SEEQ methodology. This assessment tool measures four critical aspects of pedagogical effectiveness: conceptual learning, teacher engagement, structural organization, and collaborative interaction. Each dimension contains four targeted questions evaluated on a standardized 5-point Likert scale complemented by open-ended response options that capture qualitative perspectives on the intervention's impact. This comprehensive instrument provides quantitative metrics and rich descriptive insights into students' experiences with the resource-optimized teaching approach in electrochemistry.

Strengths and weaknesses (open-ended response):

25. Indicate the characteristics of this teacher/unit that helped you most in your learning.

26. Indicate the characteristics of this teacher/unit that should be improved as a priority.

27. Use this additional space to clarify any of your answers or add any other comment.

Table 4 details the supplementary assessment instrument developed to evaluate specific elements of the combining flipped classroom and mutual learning approach. The first section examines how this methodology affects student motivation, theoretical understanding, and problem-solving capabilities compared to traditional teaching methods. The second section assesses the effectiveness of frugally developed educational resources, particularly focusing on video content clarity and wall chart utility. This targeted evaluation provides specific insights into which elements of the resource-efficient intervention most effectively support electrochemistry learning in the Moroccan educational context.

Table 4. Additional questionnaire on the combined flipped classroom/peer instruction methodology and educational resources

Aspect evaluated	Questions	Possible answers				
		I strongly disagree.	I disagree.	Not sure	I agree.	I strongly agree.
Combined methodology of flipped classroom and peer instruction	17. This methodology increased my motivation to study this subject. 18. This methodology allowed me to learn theoretical concepts. 19. This methodology allowed me to learn how to solve practical problems. 20. In general, I think the combination of flipped classroom and peer instruction allows for better learning than the traditional methodology (based on in-class presentations by the teacher).					
New materials	21. The explanations given in the videos were clear and easy to understand. 22. The use of wall charts was useful for exchanging ideas and presenting issues.	Very poor	Poor	Intermediat	Good	Very good
	23. The video content was well structured. I always knew where I was and where the course was going. 24. In general, I had to pause the videos and replay certain fragments.	I strongly disagree.	I disagree.	Not sure.	I agree.	I strongly agree.

2.8. Data Analysis

Our analytical approach, using RStudio (2024.04.2) was designed to evaluate the effectiveness and sustainability of our pedagogical innovation in resource-constrained settings. The statistical analysis proceeded in three phases.

First, we assessed intervention impact through paired t-tests for within-group changes and independent t-tests for between-group comparisons (significance levels: $*p < 0.05$ and $**p < 0.01$). Cohen's d was used to calculate effect sizes (Cohen, 1988) with values of 0.2, 0.5, and 0.8 indicating small, medium, and large effects respectively. For Table 6, Cohen's d was calculated to compare pre-test scores between the two academic years (2021/2022 vs 2022/2023) while for Table 8, it was used to compare the experimental and control groups.

A mixed ANOVA examined group effects, time effects, and their interaction across both academic years with marginal R^2 quantifying the intervention's overall impact to evaluate long-term effectiveness. Standard deviation comparisons and response rate analyses provided insights into the innovation's accessibility and equity aspects, crucial considerations for educational development initiatives.

Results visualization using MATLAB produced comparative histograms illustrating the intervention's progressive impact, facilitating assessment of its potential for sustainable implementation in similar resource-constrained educational settings.

2.9. Ethical Considerations

Institutional Review Board Statement: This study was conducted under official authorization from the Regional Academy of Education and Training of Fez-Meknes, Morocco, approved on December 30, 2021 (Ref. No. S/4824/2021). This authorization issued within the framework of the Ibn Khaldoun research program funded by Morocco's National Center for Scientific and Technical Research (CNRST), explicitly permits conducting surveys with students and implementing experimental pedagogical approaches in classrooms. The research was conducted in accordance with the ethical principles of the Declaration of Helsinki. All participants were fully informed about the study's purpose and objectives before their involvement. Written informed consent was obtained from all participants.

Data collection through questionnaires was conducted anonymously to protect participants' privacy and confidentiality. The study design ensured that participants' rights, dignity and well-being were prioritized throughout the research process.

3. RESULTS

Our analysis examines three hypotheses regarding our pedagogical innovation in resource-constrained settings. The results, collected over two academic years (2021/2022 and 2022/2023) demonstrate both immediate impact and progressive improvement in our local educational context. All statistical analyses were performed using a significance threshold of $\alpha = 0.05$.

3.1. Satisfaction and Learning Outcomes (H_1)

Our first hypothesis predicted significant improvements in learning, enthusiasm, organization, and group interaction. Using the validated SEEQ questionnaire (Cronbach's alpha > 0.83), we measured these dimensions on a 5-point Likert scale (1 = very poor to 5 = very good).

Analysis of responses supports this hypothesis, showing significant improvements across all measured dimensions (see Table 5).

Table 5. Comparative results of the combined pedagogical intervention (2021-2023)

Aspects	Year	Pre-test M(SD)	Post-test M(SD)	t(p)	Cohen's d (2021/22 vs 2022/23)
Learning	2021/2022	3.10(0.15)	4.29(0.11)	-13.79(0.0008) **	1.84
	2022/2023	3.18(0.13)	4.43(0.04)	-21.86(0.0002) **	
Enthusiasm	2021/2022	3.62(0.30)	4.65(0.18)	-13.92(0.0008) **	0.6
	2022/2023	3.86(0.32)	4.75(0.15)	-9.41(0.0025) **	
Organization	2021/2022	3.24(0.28)	4.24(0.23)	-10.03(0.0021) **	1.37
	2022/2023	3.63(0.33)	4.48(0.09)	-4.97(0.0157) *	
Group interaction	2021/2022	3.13(0.19)	4.62(0.13)	-29.00(0.0001) **	1.32
	2022/2023	3.47(0.14)	4.75(0.05)	-15.96(0.0005) **	

Note: *p < 0.05, **p < 0.01.

Learning outcomes demonstrated substantial improvement across both academic years ($p < 0.01$). In 2021/2022, learning scores progressed from 3.10 (SD = 0.15) to 4.29 (SD = 0.11) with even stronger results in 2022/2023, reaching 4.43 (SD = 0.04). The large effect size (Cohen's d = 1.84) between pre-test scores of both years indicates significant enhancement in student preparation and engagement with the learning process.

Student enthusiasm showed consistent positive development throughout the study period. Starting from a baseline of 3.62 (SD = 0.30) in 2021/2022, scores increased to 4.65 (SD = 0.18), further improving to 4.75 (SD = 0.15) in 2022/2023 ($p < 0.01$). The moderate effect size (d = 0.60) suggests steady improvement in student motivation and engagement with the learning process.

Organizational aspects demonstrated significant enhancement from initial levels of 3.24 (SD = 0.28) to 4.24 (SD = 0.23) in 2021/2022 ($p < 0.01$) with continued improvement reaching 4.48 (SD = 0.09) in 2022/2023. The large effect size (d = 1.37) indicates substantial refinement in implementation structure and delivery methods.

Group interaction showed the most dramatic improvement with the strongest initial effect ($t = -29.00$, $p < 0.001$). Scores progressed markedly from 3.13 (SD = 0.19) to 4.62 (SD = 0.13) in 2021/2022, reaching an impressive 4.75 (SD = 0.05) in 2022/2023. The large effect size (d = 1.32) reflects considerable enhancement in collaborative learning practices between academic years.

3.2. Evolution of Effectiveness (H_2)

The second hypothesis concerned improvement over time. Our analysis of this evolution combines quantitative metrics and student responses to provide a comprehensive view of the intervention's development.

3.2.1. Quantitative Analysis of Progress

A comparison of post-test scores between years (2021/2022 vs 2022/2023) using Cohen's d revealed strong effect sizes in learning (d = 1.84) and organization (d = 1.37) with group interaction also showing substantial enhancement (d = 1.32). The moderate effect size for enthusiasm (d = 0.60) likely reflects the already high scores achieved in the first year. The consistent reduction in standard deviations from 2021/2022 to 2022/2023 (e.g., from 0.11 to 0.04 for learning) indicates increasing uniformity in student outcomes.

3.2.2. Student Engagement and Satisfaction Evolution

Survey responses reveal a progressive enhancement in student engagement and satisfaction with the methodology, as comprehensively illustrated in Figure 1. The visualization demonstrates the marked improvement in student responses across key developmental aspects between the two academic years, providing clear evidence of the intervention's growing effectiveness.

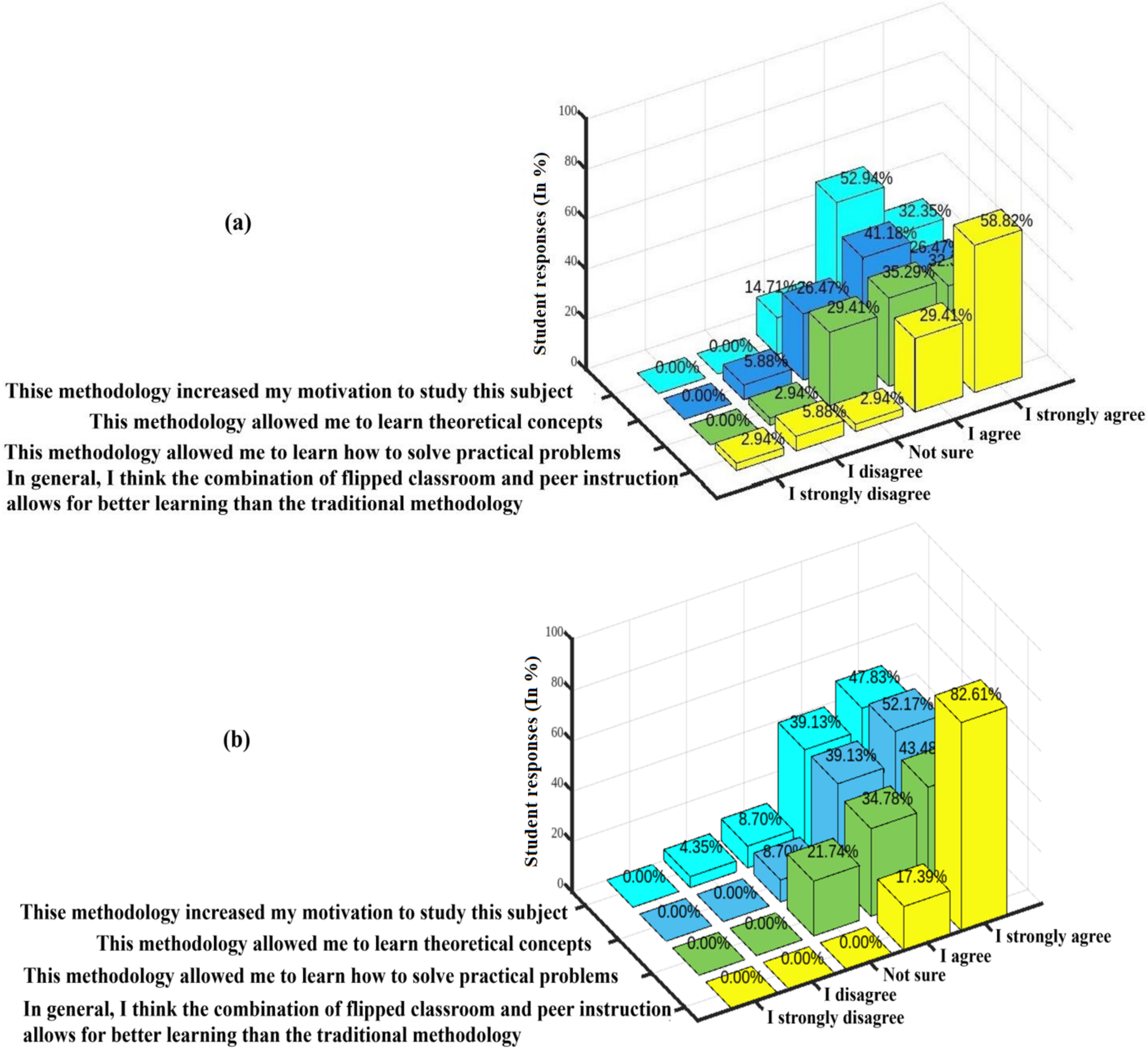

Figure 1. Evolution of student response to pedagogical innovation (2021-2023).

Note: (a) Academic year 2021/2022 results.
(b) Academic year 2022/2023 results.

This figure illustrates the marked enhancement in student responses between academic years, focusing on key developmental aspects. The 2021/2022 academic year showed initial adoption levels with theoretical concept understanding at 67.65%, problem-solving capabilities at 67.65%, and methodology preference at 88.23%. Student motivation to study the subject demonstrated particularly strong results, with 85.29% of students reporting increased motivation (32.35% strongly agree and 52.94% agree). The 2022/2023 results showed even more impressive outcomes with theoretical concept understanding increasing dramatically to 91.30%, problem-solving capabilities improving to 78.26%, and methodology preference reaching complete acceptance at 100%. Student motivation continued to strengthen with 86.96% of students reporting increased motivation to study (47.83% strongly agree and 39.13% agree) representing a notable improvement from the previous year.

3.2.3. Educational Materials Effectiveness

A detailed analysis of educational materials between academic years 2021/2022 and 2022/2023 presented in Table 6 and visualized in Figure 2 reveals significant improvements in the evaluation of educational materials. The comprehensive assessment data demonstrates notable progress in three of the four evaluated aspects with particularly strong gains in video clarity and wall chart effectiveness.

Table 6. Comparative evolution of educational materials (2021-2023): Questions 21-24 from the SEEQ modified questionnaire.

Evaluated aspects	2021/2022		2022/2023		Evolution
	Mean score	Positive eval. (%)	Mean score	Positive eval. (%)	Points %
Wall charts (Q21)	4.56	91.2	4.79	97.0	+5.85
Video clarity(Q22)	4.08	78.2	4.21	85.3	+7.07
Video structure(Q23)	4.22	87.0	4.15	84.4	-2.57
Video replay(Q24)	3.96	73.9	4.03	76.5	+2.56

Note: Mean scores calculated on a 5-point Likert scale (1 = very poor to 5 = very good).
Positive evaluation represents the cumulative percentage of "good" and "very good" responses.

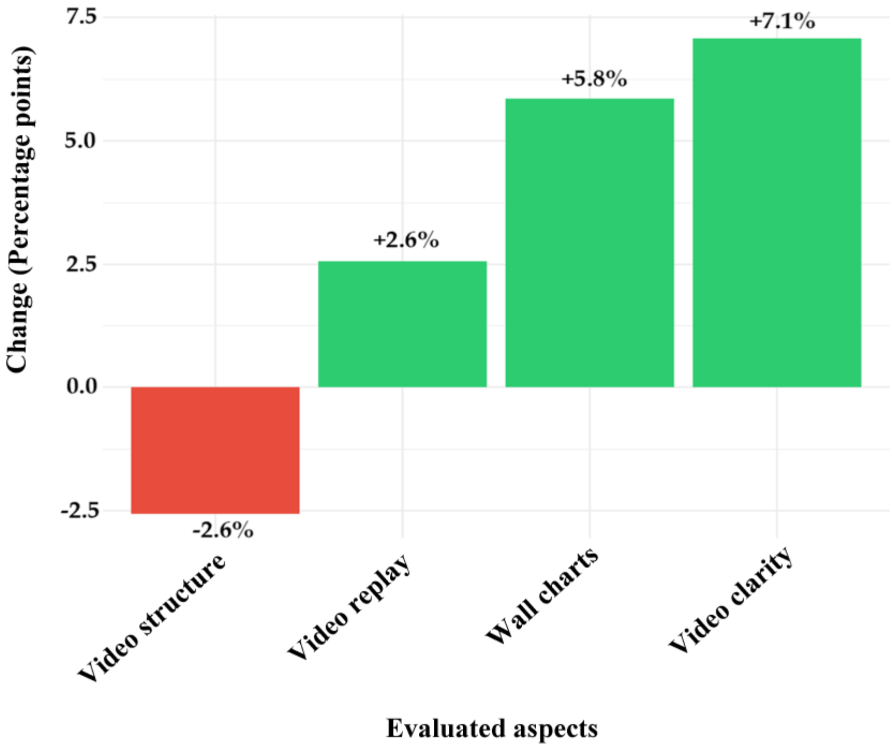

Figure 2. Evolution of positive evaluations between 2021/2022 and 2022/2023.

A detailed analysis of educational materials between academic years 2021/2022 and 2022/2023 (see Table 6 and Figure 2) shows significant changes in the evaluation of educational materials. The data reveals improvement in three out of four evaluated aspects of the educational materials.

The most substantial improvement was observed in video clarity (Q22) with a +7.07 percentage point increase in positive evaluations (from 78.2% to 85.3%) and a corresponding improvement in mean score from 4.08 to 4.21. Wall charts (Q21) received the highest evaluations showing an increase of +5.85 percentage points in positive evaluations (from 91.2% to 97.0%) and mean scores rising from 4.56 to 4.79.

Video replay practices (Q24) showed modest improvement (+2.56 percentage points) with mean scores progressing from 3.96 to 4.03. However, video structure (Q23) experienced a slight decline (-2.57 percentage points) in positive evaluations with mean scores decreasing from 4.22 to 4.15.

3.3. Academic Performance Impact (H_3)

Our third hypothesis predicted superior academic performance in experimental groups. Results from both academic years strongly support this prediction through analysis of standardized assessments aligned with the national curriculum.

Table 7. Academic performance comparison 2021/2022

Groups	N	Pre-test M(SD)	Post-test M(SD)	Difference M(SD)	t	p	d
Exp1	29	12.20(2.05)	14.50(4.17)	2.30(4.32)	2.87	0.0077	0.69
Exp2	30	12.09(1.58)	15.31(4.33)	3.22(5.10)	3.45	0.00172	1.03
Control	35	12.36(1.45)	10.10(4.77)	-2.26(4.39)	-3.04	0.0045	-0.56

Table 8. Results of two-way repeated measures ANOVA (2021/2022)

Source of variation	df	F	p-value	Partial η²
Group	2.114	10.86	<0.001	0.16
Time	1.32	4.82	0.036	0.13
Group × Time	2.114	11.63	<.001	0.17

Note: M = mean; SD = Standard deviation; t = Paired t-test value; p = p-value; d = Cohen's d; Partial η² = Effect size

3.3.1. First Year Outcomes (2021/2022)

During 2021/2022, both experimental groups demonstrated substantial gains (see Table 7). The first experimental group (Exp1) showed significant improvement (M = +2.30, SD = 4.32, t = 2.87, p = 0.00770 and d = 0.69), while the second experimental group (Exp2) demonstrated even stronger gains (M = +3.22, SD = 5.10, t = 3.45, p = 0.00172 and d = 1.03). In contrast, the control group exhibited a significant decline (M = -2.26, SD = 4.39, t = -3.04, p = 0.00450 and d = -0.56).

The two-way repeated measures ANOVA (see Table 8) indicated significant main effects for group ($F(2.114) = 10.86$, $p < .001$, $\eta^2 = 0.16$), time ($F(1.32) = 4.82$, $p = .036$, $\eta^2 = 0.13$), and group × time interaction ($F(2.114) = 11.63$, $p < .001$, $\eta^2 = 0.17$). The complete model explained 23.7% of the total variance in student performance.

Table 9. Academic performance comparison 2022/2023

Groups	N	Pre-test M(SD)	Post-test M(SD)	Difference M(SD)	t	p	d
Experimental	32	13.31(3.49)	15.85(2.83)	2.54(4.33)	3.32	0.00233	0.73
Control	34	13.19(2.84)	12.03(3.62)	-1.16(3.74)	-1.81	0.07933	-0.41

Table 10. Results of two-way repeated measures ANOVA (2022/2023)

Source of variations	df	F	p-value	Partial η²
Group	1.62	10.20	0.002	0.14
Time	1.32	2.15	0.152	0.06
Group × Time	1.62	12.03	<.001	0.16

Note: M = Mean; SD = Standard deviation; t = Paired t-test value; p = p-value; d = Cohen's d; Partial η² = Effect size

3.3.2. Second Year Confirmation (2022/2023)

The 2022/2023 results (see Table 9) confirmed the intervention's sustained effectiveness. The experimental group showed significant improvement (M = +2.54, SD = 4.33, t = 3.32, p = 0.00233 and d = 0.73) while the control group showed a non-significant decline (M = -1.16, SD = 3.74, t = -1.81, p = 0.07933 and d = -0.41).

The repeated measures ANOVA for 2022/2023 (see Table 10) revealed significant effects for group ($F(1.62) = 10.20$, $p = .002$, $\eta^2 = 0.14$) and group × time interaction ($F(1.62) = 12.03$, $p < .001$ and $\eta^2 = 0.16$), while the time effect was non-significant ($F(1.32) = 2.15$, $p = .152$ and $\eta^2 = 0.06$). The model accounted for 15.7% of the total variance in student performance. The reduced standard deviation in post-test scores (from 4.17/4.33 in 2021/2022 to 2.83 in 2022/2023) suggests increased consistency in implementation effects.

3.4. Qualitative Analysis of Student Feedback

The thematic analysis of the open questions (Q25-27) drawn from 57 student responses (34 in 2021/2022; 23 in 2022/2023) revealed key changes in the perception of the impact of the intervention. The rich and nuanced testimonies illustrate both the appropriation of the method and its impact on learning.

Theme 1: Changes in the learning process

The students described a marked increase in their commitment. In 2021/2022, 18 respondents highlighted a fundamental change in their approach as evidenced by this comment, "I've moved on from rote learning to deep understanding of the mechanisms." In 2022/2023, 15 students expressed a more accomplished mastery as summarised by one, "The interactive simulations have made the abstract concepts of electrochemistry concrete and manipulable."

Theme 2: Development of collaborative learning

Learning group dynamics have been refined between the two cohorts. In 2021/2022, 22 students highlighted the practical benefits of collaborative work, "Explaining a concept to a peer forced me to clarify my own ideas.' In 2022/2023, 19 respondents deepened this reflection, noting, for example, "Disagreements in the group pushed us to confront our reasoning and find stronger solutions."

Theme 3: Refining implementation

The students' suggestions ranged from logistical adjustments to targeted pedagogical improvements. In 2021/2022, 27 mentions concerned operational optimisations (shorten the explanatory videos). In 2022/2023, 16 suggestions were aimed at enhancing the depth of learning, such as this request, "Add animations showing the movement of ions during redox reactions".

Theme 4: Indicators of sustainability

In 2022/2023, 20 students called for the method to be extended to other scientific disciplines, "This approach should be extended to chemical kinetics, organic chemistry, and even mathematics".

We noticed students stopped giving us technical suggestions and started asking for these methods in their other class too, a real sign that our approach had become part of their educational expectations.

4. DISCUSSION

This study examines a systemic pedagogical innovation combining flipped classroom and mutual learning in teaching electrochemistry in Morocco, demonstrating how local innovation can drive sustainable educational development in resource-constrained environments. Recent research has demonstrated that integrating blended learning approaches can enhance both academic performance and student engagement in science education, as evidenced by empirical studies in diverse educational contexts (Alsalhi et al., 2019; Keržič, Aristovnik, Tomaževič, & Umek, 2018). Through systematic analysis of results obtained over two academic years (2021-2023), we assessed three key hypotheses within a dual theoretical framework: the ICAP framework (Chi & Wylie, 2014) guiding our understanding of learning engagement progression and frugal innovation principles (Radjou & Prabhu, 2015) informing our resource-optimization approach.

The evolution of educational materials effectiveness provides particularly compelling evidence supporting our frugal innovation approach. Our analysis reveals significant improvements in educational resource effectiveness, with wall charts achieving exceptional performance (positive evaluations increasing from 91.2% to 97.0%, mean scores rising from 4.56 to 4.79). This success in materials development aligns with research by Aparicio et al. (2017) on the importance of resource adaptation in educational settings. Similarly, video resources demonstrated substantial progress with clarity ratings improving by 7.07 percentage points, supporting Chen and Jones's (2007) findings on the effectiveness of blended learning approaches.

Examining our first hypothesis which predicted significant improvements in learning, enthusiasm, organization, and group interaction, our analysis reveals substantial support across multiple dimensions. The SEEQ questionnaire results (Cronbach's $\alpha > 0.83$) showed significant improvements in all key areas consistent with research by Oliver-Hoyo, Allen, Hunt, Hutson, and Pitts (2004) on active learning environments. The progression from passive to interactive engagement aligns with Lin, Chen, and Liu's (2017) findings on digital learning effectiveness, particularly within our mutual learning framework where students alternate between teaching and learning roles. This is evidenced by the improvement in learning scores from 3.10 (SD=0.15) to 4.43 (SD=0.04) across academic years ($p < 0.01$).

Our second hypothesis, concerning the improvement of intervention effectiveness over time is supported by both quantitative and qualitative evidence. The shift from rote memorization to conceptual understanding demonstrates the successful implementation of Talanquer's (2011) multi-representational chemistry learning framework, where students progressively mastered macroscopic, submicroscopic, and symbolic representations of electrochemical processes. This transformation was particularly evident in student comments about understanding reaction mechanisms rather than merely memorizing equations. Student feedback evolved from operational concerns to sophisticated pedagogical insights reflecting (Arkorful & Abaidoo, 2015) observations on the transformative potential of blended learning approaches.

Our third hypothesis predicting enhanced academic performance in experimental groups was strongly supported by empirical data. Analysis of the 2021/2022 results revealed significant improvements across both experiential groups (Exp1: M = +2.30, SD = 4.32, d = 0.69; Exp2: M = +3.22, SD = 5.10 and d = 1.03), contrasting notably with the control group's performance decline during the same period. These findings align with Freeman et al.'s (2014) meta-analysis on active learning approaches. When we replicated the study in 2022/2023, we observed similar positive outcomes (experimental group: M=+2.54, SD=4.33 and d=0.73), lending further support to Joseph et al.'s (2020) research on flipped classroom efficacy in educational contexts.

Complementing these quantitative results, our qualitative analysis provides deeper insights into how students experienced and engaged with this pedagogical transformation. We identified several key patterns in the evolution of learning experiences through thematic analysis of 57 student responses across both academic years. In 2021/2022, 18 students reported transitioning from rote memorization to deeper conceptual understanding with one student noting, "I've moved on from memorizing formulas to understanding why reactions happen." This progression demonstrates the shift from passive to interactive learning modes, validating the ICAP framework's predictions about learning engagement levels.

Collaborative learning emerged as a particularly powerful mechanism for conceptual development. Initial responses in 2021/2022 (22 students) highlighted basic benefits of peer explanation, while by 2022/2023, 19 students reported more sophisticated metacognitive insights. As one student observed, "Group disagreements pushed us to confront our reasoning and find stronger solutions." This evolution supports (Lin et al., 2017) findings on the relationship between collaborative engagement and learning outcomes.

The refinement of student feedback from operational concerns to pedagogical insights (27 mentions in 2021/2022 versus 16 deeper learning suggestions in 2022/2023) demonstrates increasing student investment in their learning process, consistent with Arkorful and Abaidoo's (2015) observations on learner autonomy development. Particularly notable was the spontaneous request from 20 students in 2022/2023 to extend this approach to other scientific disciplines, suggesting successful institutionalization of the innovative practices (Sakti et al., 2023).

The physical transformation of the learning environment played a crucial role in these improvements, exemplifying (Hawkins et al., 2020) recommendations for strategic resource optimization. The evolution from traditional classroom arrangements to flexible, collaborative spaces facilitated deeper engagement as theorized in the ICAP framework. This transformation aligns with Dowling §, Godfrey §, and Gyles's (2003) findings on the importance of adaptable learning environments.

We must acknowledge certain limitations in our work. While our study provided depth in the Fez-Meknes context, it would gain strength with validation in other regions. Akbarov, Gönen, and Aydogan (2018) have indeed emphasized the importance of such geographical diversification. We encountered technical obstacles that occasionally influenced our approach, echoing Keržič et al.'s (2018) observations about infrastructural challenges inherent to blended learning environments. It would also be valuable as suggested by Chikeme et al. (2024) to extend our temporal horizon to better understand long-term concept retention.

Regarding the Moroccan educational landscape, our findings illuminate the potential for systemic innovation despite resource constraints. The successes observed in Fez-Meknes hint at broader application possibilities across the country's diverse educational settings, particularly through the existing GENIE program infrastructure. The more we consider this potential scaling, the more certain critical factors emerge for ensuring effective expansion.

These discoveries have tangible implications for teacher training in constrained environments. To successfully implement this approach, teachers need to develop specific aptitudes—facilitating peer learning isn't innate, nor is managing flexible learning spaces. Our field experience has shown that many teachers need targeted support to shift from lecture-based habits toward interactive, student-centred approaches. Knowing how to manage collaborative environments and adapt educational resources to local realities proves particularly crucial, as highlighted by Hawkins et al. (2020). Without these competencies, it's difficult to envision sustainable implementation of pedagogical innovations in resource-limited contexts.

5. CONCLUSION

Our study in Fez-Meknes yielded two insights for frugal pedagogy in electrochemistry education. First, the integration of flipped classrooms with structured mutual learning generated measurable improvements in both academic performance (experimental groups showing gains of +2.30/+3.22 points in 2021-2022 and +2.54 points in 2022-2023) and student engagement (with learning scores rising from 3.10 to 4.43 and group interaction advancing from 3.13 to 4.75). Second, the success of resource-efficient interventions like our color-coded wall charts achieving 97% positive evaluations from students highlights how locally adapted visual tools can outperform more expensive technological alternatives in resource-constrained educational settings.

Critically, the evolution in student feedback from operational suggestion (shorten the explanatory videos) to sophisticated pedagogical insights (disagreements in the group pushed us to confront our reasoning and find stronger solutions) signals a progression through the ICAP engagement levels from passive to interactive learning modes. Students were spontaneously requesting extension of these methods to other scientific disciplines, demonstrating their investment in the approach to learning.

While our findings underscore the viability of frugal innovation within Morocco's GENIE program, their scalability depends on systemic factors beyond individual classrooms, including proper teacher training in facilitating mutual learning and managing flexible learning spaces. Future research should explore the effectiveness of this approach across diverse educational settings while examining how specific cultural assets and institutional practices influence implementation. Our work demonstrates that transformative pedagogical change doesn't necessarily require extensive financial investment thoughtfully optimized resources can create meaningful learning experiences that advance educational quality and equity in developing contexts.

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Transparency: The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
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