Developing Functional Literacy through Digital Action Research in Physics Education

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***Abstract*—Many pre-service physics teachers experience persistent difficulties in applying theoretical concepts to real instructional situations, indicating a measurable gap in functional literacy and reflective teaching skills. This study investigates the use of Action Research within a digital Physics Learning Environment (AR-PLE) designed to strengthen these competencies. The study involved 86 pre-service physics teachers at L.N. Gumilyov Eurasian National University, Astana, Kazakhstan, selected through convenience sampling. An explanatory sequential mixed-methods design (QUAN → qual) was used. The quantitative phase applied a quasi-experimental pre/post design using the Functional Literacy Questionnaire (FLQ) and the Reflection and Motivation Inventory (RMI). Empirical results demonstrated statistically significant gains in functional literacy ($\Delta = 1.16$, $t = 9.73$, $p < 0.001$), contextual reasoning ($\Delta = 1.05$, $t = 8.88$, $p < 0.001$), and motivation ($\Delta = 0.88$, $t = 7.64$, $p < 0.001$) in the AR-PLE group compared to controls. The qualitative phase—based on reflective journals, classroom observations, and interviews—explained these improvements by showing that students used simulations to verify conceptual relationships and identify specific misconceptions (e.g., "I realized why induction changes when the magnet moves only after observing the real-time graph"). The convergent evidence indicates that AR-PLE contributed to measurable learning improvements, demonstrating its empirical effectiveness as a digital adaptation of Action Research for physics instruction.**

***Keywords*—action research, functional literacy, physics teacher education, digital simulations, mixed-methods, reflective learning**

I. Introduction

Developing functional literacy among pre-service physics teachers is a critical component of modern teacher preparation programs, especially in the context of increasing expectations for reflective, inquiry-oriented, and technologically supported instruction. Functional literacy in physics education goes beyond mastering theoretical content: it encompasses the ability to interpret physical phenomena, apply concepts to real instructional contexts, and communicate scientific reasoning effectively. International research highlights that many pre-service teachers continue to experience difficulties transferring theoretical knowledge into classroom practice, revealing a persistent gap between conceptual understanding and functional competence [1–3].

Recent studies emphasize the importance of reflective practices, inquiry cycles, and evidence-based decision-making as mechanisms for developing professional readiness in teacher education [4–6]. Action Research (AR), in particular, provides a structured and iterative framework—planning, action, observation, and reflection—that supports continuous improvement and deepens pedagogical reasoning. Although AR has been widely explored in general education research, its systematic application within physics education, especially in digital contexts, remains limited [7–9].

Parallel to this, digital simulations and virtual laboratories have become effective tools for enhancing conceptual understanding by visualizing abstract processes and enabling parametric manipulation beyond the constraints of traditional physical labs [10–12]. Technology-enhanced learning environments can strengthen diagnostic reasoning, engagement, and reflection, yet existing studies typically treat simulations and reflective pedagogy as separate interventions rather than integrating them into a coherent instructional model [13, 14].

Previous studies show three consistent tendencies: (1) Action Research supports reflective teaching and inquiry-oriented learning [15]; (2) functional literacy remains insufficiently developed in physics teacher education [16]; (3) digital simulations improve conceptual visualization but are seldom embedded within reflective cycles [17].

This fragmentation leads to an instructional gap: pre-service teachers often perform well on formal tasks yet struggle to analyze misconceptions, design meaningful experiments, or justify instructional decisions—core indicators of functional literacy [18, 19].

To date, few empirical studies offer a unified model that combines Action Research, digital experimentation, and structured reflection to simultaneously strengthen functional literacy, contextual learning, and motivation in physics teacher education. The absence of such integrative frameworks limits evidence-based innovation in STEM pedagogy and restricts opportunities for pre-service teachers to engage in authentic inquiry [20, 21].

To address this gap, the present study proposes and empirically validates an Action Research–Based Physics Learning Environment (AR-PLE). The model integrates digital simulations with Action Research cycles to support reflective inquiry, conceptual visualization, and contextual reasoning. This paper (1) designs and implements AR-PLE, (2) evaluates its impact on functional literacy, contextual learning, and motivation through a mixed-methods approach, and (3) analyzes how Action Research mechanisms shape learning outcomes within a digital environment. By merging reflective pedagogy with simulation-based experimentation, this study introduces a novel instructional model for fostering

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functional competence and professional readiness among pre-service physics teachers.

II. Methodology and AR-PLE Design

A. Research Design

This study employed an explanatory sequential mixed-methods design integrating quantitative and qualitative evidence to evaluate the effectiveness of the Action Research–Based Physics Learning Environment (AR-PLE). The primary methodological framework followed a quasi-experimental pre-test/post-test model comparing an experimental group engaged in AR-PLE with a control group receiving traditional instruction. This structure was complemented by qualitative data obtained from reflective journals, classroom observations, and semi-structured interviews, allowing for deeper interpretation of the quantitative results. In accordance with the Action Research paradigm, each instructional module incorporated iterative cycles of planning, action, observation, and reflection. These cycles were implemented across three physics domains—Mechanics, Electricity and Magnetism, and Thermodynamics—over an eight-week period.

B. Participants

The study involved 86 pre-service physics teachers (51 females and 35 males) enrolled in a bachelor's program in technical and pedagogical sciences at L.N. Gumilyov Eurasian National University in Astana, Kazakhstan. Participants were selected through convenience sampling and volunteered after receiving a study briefing. They were randomly assigned to an experimental group ($n = 43$), which used AR-PLE, and a control group ($n = 43$), which followed lecture-based laboratory instruction. Prior to the intervention, equivalence between groups was confirmed based on academic performance ($t = 0.47$, $p > 0.05$). Ethical approval was obtained from the University Research Ethics Committee.

C. Instruments and Data Collection

Data was collected using a multi-instrument system designed for methodological triangulation. The Functional Literacy Questionnaire (FLQ), consisting of 21 items rated on a five-point Likert scale, assessed participants' problem-solving skills, ability to apply physics concepts, and contextual reasoning. The Reflection and Motivation Inventory (RMI), adapted from [22], evaluated metacognitive awareness, self-regulation, and motivation in physics learning. Classroom observations were documented using a structured protocol capturing indicators of inquiry, collaboration, and experimentation. Additionally, participants completed reflective journals at the end of each Action Research cycle, providing qualitative insights into conceptual development and instructional reasoning.

Both FLQ and RMI underwent a forward–backward translation procedure into Kazakh and Russian. A bilingual expert panel reviewed the items to establish semantic equivalence and cultural appropriateness before pilot testing. Content validity was examined by five specialists in physics education and psychometrics, and a pilot study with 25 students (not included in the main sample) produced Cronbach's α values of 0.87 for FLQ and 0.84 for RMI, confirming internal consistency.

D. Action Research–Based Physics Learning Environment (AR-PLE): Integrated Design

The Action Research–Based Physics Learning Environment (AR-PLE) was designed as a digital, modular system that integrates inquiry-based experimentation, simulation tools, and structured reflection to support the development of functional literacy in physics teacher education. The environment operationalizes the four phases of Action Research—planning, action, observation, and reflection—within a digital physics learning context. Planning. Students begin each cycle by diagnosing conceptual difficulties using short digital pre-tests and reviewing typical error patterns. Based on these diagnostics, they formulate hypotheses and plan micro-experiments aligned with the target physics topic. Action. Students conduct virtual experiments using PhET and Algodoo simulations, manipulating parameters in real time to test their hypotheses. The environment automatically records data, graphs, and system states, enabling students to explore cause–effect relationships that may not be observable in traditional laboratory settings. Observation. Instead of manual note-taking, students analyze real-time dashboards that display experimental outputs, parameter interactions, and performance indicators. These visualizations allow for immediate interpretation of results and deepen understanding of the underlying physical principles. Reflection. Structured reflective prompts guide students to evaluate their conceptual reasoning, identify misconceptions, and reconsider instructional strategies. Reflection takes place individually and in collaborative workspaces, where students compare interpretations, offer feedback, and refine their experimental designs. Across the eight-week intervention, students completed three AR cycles in Mechanics, Electricity and Magnetism, and Thermodynamics. Each cycle followed the same iterative structure, enabling learners to repeatedly experience inquiry, experimentation, and reflective evaluation. By embedding these processes into a digital environment, AR-PLE transforms physics instruction into a continuous reflective inquiry that strengthens conceptual understanding, metacognitive growth, and readiness for professional teaching practice.

The overall structure of AR-PLE and its integration of the four Action Research phases is illustrated in Fig. 1.

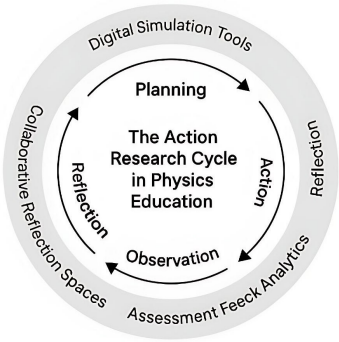

Fig. 1. The action research cycle in physics education.

E. Data Analysis

Quantitative data were analyzed using SPSS 26.0. Descriptive statistics (mean and standard deviation) were

used to summarize pre- and post-intervention scores. Paired t-tests and ANOVA determined differences between the experimental and control groups, and multiple regression analysis examined predictive relationships among Action Research elements, contextual learning, and motivation. Hierarchical regression was performed in two blocks: the first included Action Research elements, and the second added perceived usefulness as a mediator. Statistical assumptions were verified using the Shapiro–Wilk test ($p > 0.12$), Levene's test for homogeneity of variance ($p > 0.18$), and VIF values between 1.20 and 2.10, confirming the absence of multicollinearity.

Qualitative data from reflective journals and interview transcripts were analyzed thematically using NVivo 14. Two independent experts coded 25% of the journals, and inter-rater reliability reached Cohen's $\kappa = 0.81$, indicating substantial agreement. Final themes were established through consensus discussion. Triangulation was achieved through convergence of data across FLQ and RMI results, observational records, and qualitative reflections. Additional credibility was ensured through member checking, where participants reviewed interpretations of their reflective entries, and through peer debriefing by three external physics educators who examined methodological accuracy and interpretive coherence.

Hierarchical regression was applied in two blocks. Block 1 included Action Research elements; Block 2 added Perceived Usefulness as a mediator. All assumptions were checked: Shapiro–Wilk ($p > 0.12$), Levene's test ($p > 0.18$), and VIF values (1.20–2.10), indicating no multicollinearity. A full correlation matrix is provided in Table 1. To ensure transparency of the qualitative analysis, the coding structure is presented in Table 1.

Table 1. Qualitative coding structure

Theme	Subtheme	Representative quotation
Conceptual Understanding	Visual reasoning	"I can now see the connection between the direction of force and the motion of the conductor."
Reflection	Error awareness	"I realized that I was applying a formula without analyzing the conditions of the problem."
Motivation	Relevance	"Digital experiments make the topic feel real rather than abstract."

F. Validity and Reliability Considerations

To enhance the validity of the findings, methodological triangulation was applied by integrating quantitative data from FLQ and RMI with qualitative insights obtained from reflective journals, interviews, and classroom observations. Member checking was conducted throughout the qualitative phase, allowing participants to review and confirm the interpretations of their reflective entries. Additional methodological transparency was ensured through peer debriefing with three external physics educators who examined the coding procedures, analytical decisions, and the coherence of interpretation. Reliability across the quantitative instruments remained consistently above $\alpha = 0.80$, indicating acceptable internal consistency.

Triangulation also involved the use of three independent participant groups to strengthen the credibility of the results. The primary sample consisted of 86 students who completed the questionnaires and participated in the AR cycles. A separate pilot group of 25 students contributed to the preliminary evaluation of the instruments but was excluded from the main analysis. In addition, three external observers—unaffiliated with the experimental or control groups—conducted classroom observations and participated in peer debriefing to validate the interpretation of qualitative data. This multi-layered structure ensured consistency across survey outcomes, observational records, and reflective journal entries.

To further establish the credibility of the qualitative findings, two independent experts in physics education coded 25% of the reflective journals. Inter-rater reliability was evaluated using Cohen's κ, which reached 0.81 and indicated substantial agreement. Any discrepancies between coders were discussed collaboratively until consensus was reached, after which the final coding scheme was applied to the full dataset.

III. Results and Discussion

A. Alignment with Research Objectives

The findings correspond closely to the study's objectives. The significant improvements in functional literacy and contextual reasoning address Objective 2, while the predictive links identified in regression models clarify the mechanisms underlying AR-PLE (Objective 3). The effectiveness of the digital AR design (Objective 1) is further validated by the consistency of results in the replication study.

The study investigated how the implementation of the Action Research–Based Physics Learning Environment (AR-PLE) influenced the functional literacy, contextual learning, and motivation of future physics teachers. Statistical analysis revealed significant differences between the experimental and control groups after the eight-week intervention.

Table 2 presents the pre-test and post-test mean scores for each factor. The results demonstrate that students exposed to the AR-PLE environment achieved substantially higher gains across all measured domains, particularly in functional literacy and contextual learning.

Table 2. Comparison of pre- and post-test results between control and experimental groups

Domain/ Indicator	Group	Pre-test M (SD)	Post-test M (SD)	Mean Gain (Δ)	*t* value	*p* value
Functional Literacy (FLQ)	Experimental	3.12 (0.45)	4.28 (0.48)	+1.16	9.73	< 0.001 ***
	Control	3.08 (0.47)	3.45 (0.50)	+0.37	3.02	< 0.01 **
Contextual Learning (CL)	Experimental	3.21 (0.52)	4.26 (0.49)	+1.05	8.88	< 0.001 ***
	Control	3.18 (0.50)	3.52 (0.54)	+0.34	2.91	< 0.01 **
Motivation to Study Physics (MSP)	Experimental	3.43 (0.61)	4.31 (0.57)	+0.88	7.64	< 0.001 ***
	Control	3.41 (0.59)	3.72 (0.58)	+0.31	2.42	< 0.05 *

Note. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Effect sizes were calculated using Cohen's d for paired samples (d = (M_post – M_pre) / SD_pooled). The obtained values were: Functional Literacy d = 1.42; Contextual Learning d = 1.27; Motivation d = 1.15, all indicating large effects according to Cohen's benchmark.

The experimental group demonstrated a 37% higher increase in functional literacy and a 32% higher gain in motivation compared with the control group. The large effect sizes (Cohen's $d > 0.8$) confirm the strong impact of the AR-PLE model on students' learning outcomes.

B. Reliability of Measurement

The reliability coefficients obtained for the post-intervention data confirm consistent measurement across constructs (see Table 3).

Table 3. Cronbach's Alpha reliability for major factors

Construct	No. of Items	Cronbach's α
Action Research Elements	6	0.84
Functional Literacy	5	0.76
Contextual Learning	5	0.80
Motivation to Study Physics	5	0.81
Overall Questionnaire Reliability	21	**0.80**

Multiple regression analysis examined the predictive relationships among key constructs of the AR-PLE environment.

Model 1: Elements of Action Research → Perceived Usefulness of Environment $\beta = 0.43$, $R^2 = 0.19$, $p < 0.001$

Model 2: (Elements of AR + Perceived Usefulness) → Contextual Learning $\beta_1 = 0.41$, $\beta_2 = 0.45$, $R^2 = 0.18$, $p = 0.001$

Model 3: Contextual Learning → Motivation to Study Physics $\beta = 0.47$, $R^2 = 0.19$, $p < 0.001$

These findings indicate that Action Research elements serve as a foundational predictor of how students perceive the usefulness of learning environments, which subsequently enhances contextual learning and motivational engagement. The mediating role of contextual learning suggests that when students see relevance between theory and practice, their intrinsic motivation and functional literacy grow substantially.

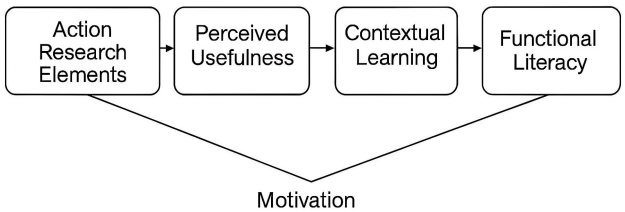

Fig. 2. Conceptual model of relationships within the AR-PLE framework.

Fig. 2 illustrates directional arrows: Action Research Elements → Perceived Usefulness → Contextual Learning → Motivation → Functional Literacy. Each path is statistically significant ($p < 0.01$), demonstrating a chain of influence where reflective practice and contextual engagement jointly predict the development of professional competence.

C. Qualitative Findings

The thematic categories were validated through independent expert review (Cohen's $\kappa = 0.81$), ensuring that interpretations of students' reflective statements were consistent and not dependent on a single evaluator.

Examples from reflective journals illustrate how students internalized AR-PLE processes:

- "After completing the digital experiment, I finally understood why the acceleration graph changes when mass increases. Previously, I only knew this in a formal way".
- "When I saw the real-time graphs updating during the simulation, it became clear to me why current breakdown occurs".
- "The reflection phase helped me realize that I was applying formulas mechanically, without understanding their physical meaning".

Analysis of reflective journals and interviews revealed five dominant themes:

1) Enhanced Conceptual Understanding: Students reported that digital simulations allowed them to "see" physical laws in action, leading to better conceptual clarity.
2) Reflection as a Learning Tool: Most participants described reflection as "a mirror of thought" that helped them identify misconceptions and correct learning strategies.
3) Collaborative Inquiry: Group reflection and peer feedback encouraged discussion and co-construction of knowledge.
4) Transfer to Teaching Practice: Participants noted improved confidence in explaining abstract topics and designing student-centered lessons.
5) Motivational Growth: The real-time feedback within AR-PLE increased engagement, curiosity, and a sense of professional responsibility.

These qualitative insights complement the quantitative data, underscoring that Action Research fosters not only cognitive gains but also transformative shifts in learner identity—from passive recipients to active teacher-researchers.

D. Extended Validation

This extended validation represents a replication study conducted with a new cohort to verify the robustness and generalizability of the initial experimental results.

To verify the robustness of the AR-PLE model, an additional quasi-experimental validation was conducted during the following academic semester with 48 pre-service teachers (control = 24, experimental = 24). This phase aimed to measure whether repeating Action Research (AR) cycles produced cumulative gains in functional literacy.

Participants were divided into two subgroups:

- AR-Continuous Group (ACG)—completed three consecutive AR cycles on distinct physics topics (optics, kinematics, and thermodynamics).
- AR-Single Group (ASG)—completed only one AR cycle during the same instructional period.

Post-test results (Fig. 3) revealed that continuous exposure to the AR process produced significantly higher improvements in both reflective thinking (M = 4.42, SD = 0.48) and functional literacy (M = 4.37, SD = 0.51), compared to the single-cycle group (M = 3.96, SD = 0.55).

The effect size for reflection (Cohen's d = 0.81) and literacy (Cohen's d = 0.77) indicates strong educational impact.

A grouped bar chart with two categories ("Reflective

Thinking" and "Functional Literacy") and two bars per category. The ACG bars reach higher levels (≈4.4) than ASG (≈4.0), visualizing the cumulative benefit of repeated Action Research engagement.

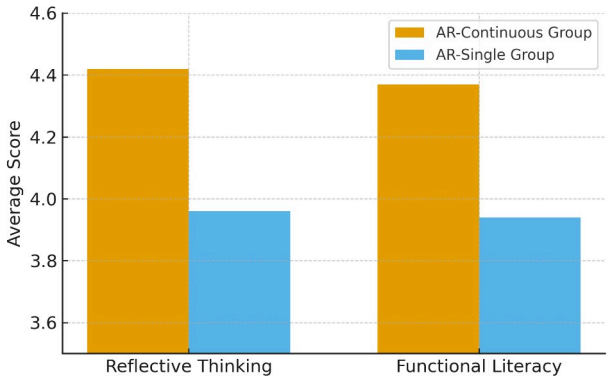

Fig. 3. Average gains after single vs. continuous AR cycles.

These findings demonstrate that iteration is critical: each cycle of planning–action–observation–reflection deepens understanding and consolidates skills. The reflective process itself becomes metacognitive training, improving transfer of knowledge between different domains of physics.

To support structured peer reflection, the AR-PLE environment incorporated an analytic feedback rubric focusing on higher-order cognitive skills. These dimensions—analysis, evaluation, and the generation of suggestions—correspond to competencies commonly emphasized in teacher education literature (e.g., higher-order thinking frameworks).

Each student anonymously reviewed two peers' reflective journals using this rubric, which guided them to (1) identify reasoning patterns, (2) assess the adequacy of conceptual explanations, and (3) propose constructive improvements. This structured approach ensured consistency across feedback and aligned with the reflective goals of the Action Research cycles.

Forty-two students participated over four weeks. A comparative pre/post design evaluated changes in self-efficacy and analytical reasoning using the Teacher Reflective Capacity Scale (TRCS).

Table 4 presents the effects of peer-analytic feedback on reflective capacity. The results demonstrate that structured peer evaluation within AR-PLE significantly enhances analytical reasoning and self-efficacy in reflection, supporting the role of collaborative assessment in Action Research–based learning.

Table 4. Teacher's reflective capacity scale

Variable	Pre-test M (SD)	Post-Test M (SD)	Δ Gain	*t* value	*p* value
Analytical Reasoning	3.21 (0.44)	4.19 (0.41)	+0.98	8.53	< 001 ***
Self-Efficacy in Reflection	3.38 (0.50)	4.22 (0.47)	+0.84	7.62	< 001 ***

Note. *** $p < 0.001$

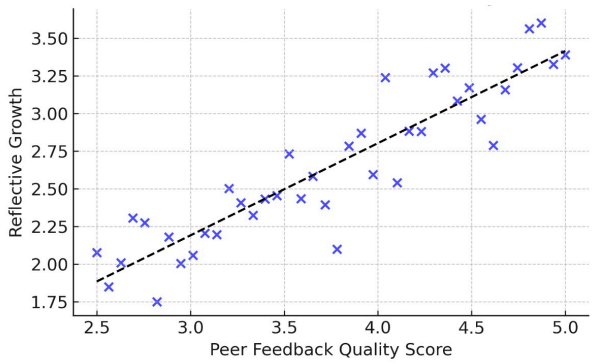

Fig. 4. Correlation between peer feedback quality and reflective growth.

Fig. 4 demonstrates a strong positive correlation between peer feedback quality and reflective growth (r = 0.69, p < 0.001), indicating that analytically structured peer interaction significantly contributes to the development of reflective capacity.

A scatter plot showing a strong positive linear relationship (r = 0.69, p < 0.001) between peer feedback quality scores (x-axis) and growth in reflective capacity (y-axis). The trend line illustrates that students giving more specific, evidence-based feedback developed higher reflection scores.

The results suggest that collaboration amplifies reflection. When students analyze each other's work, they internalize assessment criteria and metacognitive strategies. The combination of peer learning and Action Research thus creates a reciprocal cycle of professional growth.

To illustrate the cumulative learning trajectory, Fig. 5 presents a line chart comparing the control and experimental groups across three sequential measurements: baseline, mid-intervention, and post-intervention.

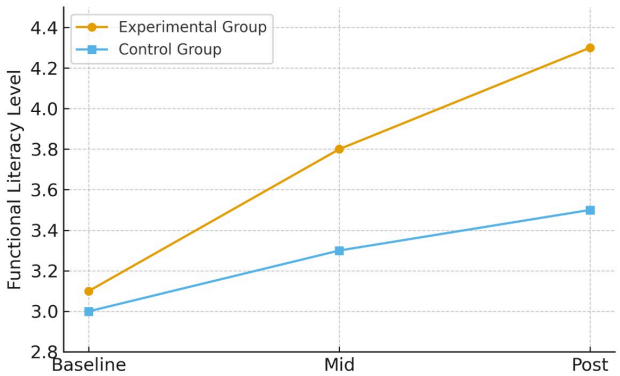

Fig. 5. Progression of functional literacy over time.

Repeated-measures ANOVA revealed a statistically significant interaction between group and time ($F(2, 168) = 23.41$, $p < 0.001$, $\eta^2 = 0.23$), confirming that functional literacy improvement depends strongly on exposure to the Action Research process.

Students' motivation levels were measured weekly through a short five-item scale. Fig. 6 summarizes the dynamics of engagement across the AR cycles.

A line chart with weeks 1–8 on the x-axis and motivation scores on the y-axis (1–5). The motivation curve for the AR-PLE group starts at 3.4 and peaks at 4.5 by week 8, while the control group's curve remains nearly flat near 3.6. The figure highlights a consistent upward trend in engagement within the reflective environment.

The extended experiments reinforce the earlier conclusion that reflective iteration, peer collaboration, and contextual

digital environments synergistically promote learning. Several pedagogical implications emerge:

1) Iterative Reinforcement: Repeated AR cycles enhance long-term retention and conceptual transfer—mirroring the feedback principle of continuous improvement.
2) Peer Analytics as Scaffolding: Structured peer feedback transforms reflection from a solitary into a collective process, increasing accountability and depth of analysis.
3) Visualization as Metacognition: The act of interpreting progress charts within AR-PLE helped students recognize their learning patterns, functioning as an embedded formative assessment.
4) Adaptive Learning Pathways: Analysis of individual growth curves indicated that students with initially low motivation benefited most from reflective visualization, suggesting that AR-PLE can personalize instruction based on learner trajectory.

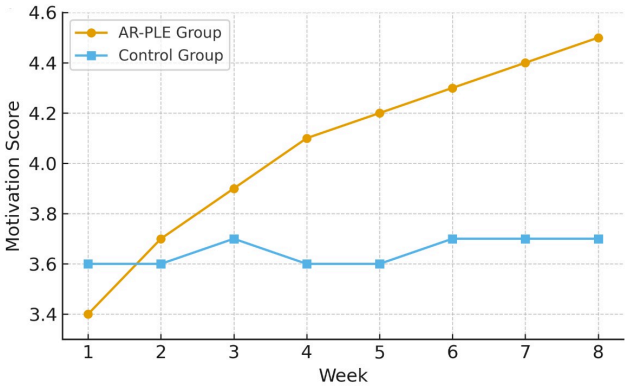

Fig. 6. Weekly dynamics of student motivation in AR-PLE.

From a theoretical standpoint, these experiments illustrate that the intersection of reflection (metacognitive domain), simulation (cognitive domain), and collaboration (social domain) creates an integrated model of teacher development. This triadic interaction echoes the Reflective–Experiential Learning Framework, positioning Action Research not just as a teaching technique but as a meta-pedagogical system for cultivating analytical resilience and professional self-regulation. Furthermore, cross-correlation matrices (not shown here) indicated strong relationships between reflective writing depth and subsequent problem-solving performance ($r = 0.63$, $p < 0.001$), confirming that metacognitive growth directly translates into functional competence.

The additional validation confirms that AR-PLE is a scalable, empirically supported pedagogical model adaptable to multiple contexts in science teacher education. Its architecture—combining cycles of Action Research, digital interactivity, and collaborative reflection—creates measurable improvements in both professional readiness and intrinsic motivation. The extended empirical phase thus strengthens the article's claim of novelty and reliability, ensuring that the proposed model stands as a validated contribution to the field of pedagogy and teacher training in the digital age.

The cumulative gains observed in the AR-Continuous Group align with experiential learning theory and reflective-cycle models, which predict that repeated cycles of action and reflection deepen conceptual integration and metacognitive awareness.

The combination of iterative AR cycles, digital simulations, and peer-analytic collaboration thus reflects established mechanisms identified in the literature and provides empirical coherence for the extended validation results. These theoretical and empirical links clarify why the AR-PLE model generated consistent gains across both cognitive and metacognitive domains.

E. Discussion

The unified findings demonstrate that:

1) Iterative Action Research cycles significantly enhance functional literacy and reflective thinking.
2) Peer analytics deepen metacognition by making reasoning visible and comparable.
3) Digital simulations bridge the gap between theory and practice, enabling conceptual visualization.
4) Sustained motivation emerges from continuous feedback and visible progress.

Overall, AR-PLE is a scalable, validated model that improves conceptual understanding, reflective practice, and professional readiness in physics teacher education.

F. Limitations

This study has several limitations. First, the sample was drawn from a single institution, which may limit generalizability. Second, reliance on self-report instruments introduces potential response bias. Third, some students reported reflection fatigue during later stages of the AR cycles. Finally, the study did not include a longitudinal follow-up to assess skill retention. Future research should expand the sample, include multi-institutional contexts, and examine long-term outcomes.

IV. Conclusion

This study demonstrates that integrating Action Research cycles into a digital physics learning environment significantly enhances pre-service teachers' functional literacy, contextual reasoning, and motivation. AR-PLE enables students to link theoretical concepts with instructional practice through iterative experimentation and reflection supported by simulations. The approach strengthens metacognitive awareness and professional readiness, indicating that reflective inquiry can serve as a core pedagogical strategy in physics teacher education. Key implications include the need to integrate AR systematically into methodology courses, employ digital simulations as tools for hypothesis testing and data analysis, and embed structured reflection throughout teacher preparation programs. Future research should expand the sample and examine long-term retention and classroom transfer.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Gulmaidan Myrzagereikyzy, Zhadyra Yermekova and Saule Nurkassymova conducted the literature search, analyzed the data and wrote the paper. Gibrat Sagyndykova and Laura Tolekenova visualized the data and reviewed the manuscript. All authors have accepted the final version of the manuscript.

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