SCIENCE HUB REVIEW
2026
Volume 1
Issue 2
www.sciencehubreview.uz
ILMIY ELEKTRON JURNAL

Development of Collaborative and Communicative Competences through Interdisciplinary Physics Education: Analyzing Electromagnetic Induction and Bioelectromagnetic Effects on Ocular Systems

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Abstract

This study investigates an integrated pedagogical methodology designed to develop collaborative and communicative competences among undergraduate physics students while addressing real-world applied physics problems. Conducted at the Department of Physics, Higher School of Natural Sciences Pedagogy, Jizzakh State Pedagogical University, the research involved a controlled pedagogical experiment with 124 second-year students. The framework leveraged problem-based learning (PBL) focused on the core engineering dynamics of Faraday's Law of Induction alongside an innovative interdisciplinary application: investigating the bioelectromagnetic effects of induced electric currents on ocular physiology (magnetophosphenes and thermal lens changes). The results demonstrated a statistically significant enhancement in students' scientific communication and team-based peer defense mechanics. Quantitative evaluation proved an increase of over 54% in collaborative indicators and an empirical academic ovet-performance of 38% compared to traditional standalone instructional methods. This framework bridges the gap between pure classical physics and practical biomedical risk modeling in contemporary STEM fields.

Keywords

Electromagnetic induction, Collaborative competence, Communicative competence, Bioelectromagnetism, Ocular physics, Interdisciplinary STEM, Jizzakh State Pedagogical University.

Introduction

Modern higher education engineering and physics paradigms demand a rapid shift from classical passive instruction towards active, competence-based framework models. In traditional physics settings, complex mathematical topics like electromagnetism often induce severe cognitive blockages due to their high degree of mathematical abstraction. The physical phenomena underlying electromagnetic induction involve multi-dimensional vector spaces, dynamic surface fields, and temporal variations. Mastering

these concepts requires a robust synthesis of technical aptitude and contextual interpretation [1].

Concurrently, professional environments seek graduates who possess strong technical capabilities alongside highly refined interpersonal soft skills. Collaborative competence refers to the operational capability to distribute analytical burdens, share intellectual responsibility, and operate cohesively within diverse scientific teams. Communicative competence represents the explicit ability to articulate precise physical arguments, defend empirical hypotheses, and translate complex mathematical equations into logical conceptual models [2].

To achieve these professional milestones, this research introduces an interdisciplinary problem-based learning (PBL) module. Instead of keeping students focused solely on theoretical induction loops, the curriculum requires laboratory teams to collaboratively study the physiological and biomedical impacts of electromagnetic induction. Specifically, the module analyzes the induction of secondary electric currents within human ocular systems exposed to time-varying magnetic fields. This synthesis forces students to communicate across disciplinary boundaries (physics, mathematics, and biophysics), building deep conceptual mastery alongside exceptional interpersonal capabilities [3]

Methodology

2.1. Research Design and Demographics. The controlled pedagogical experiment was systematically deployed during the academic period at Jizzakh State Pedagogical University. The sample population comprised N = 124 undergraduate physics students enrolled within the Faculty of Physics at the Higher School of Natural Sciences Pedagogy. The cohort was symmetrically split into two research groups:

- Control Group (CG, n = 61): Instructed through traditional deductive lectures and conventional individualistic laboratory exercises.

- Experimental Group (EG, n = 63): Instructed utilizing the newly developed interdisciplinary, collaborative problem-based learning curriculum.

2.2. Fundamental Physics Framework and Equation Modeling. The core mathematical and collaborative curriculum was structured around Faraday's Law of Induction and Maxwell's differential field configurations. Student teams were tasked with evaluating the generation of electromotive force (EMF) inside continuous media. The fundamental physical equation analyzed across all groups is represented by Faraday's Law:

$$\varepsilon_i = - d\Phi / dt \quad (1)$$

Where the total magnetic flux (Φ) passing through a given surface area is calculated via the surface integral of the magnetic B-field vector:

$$\Phi = \iint_S B \cdot dA \quad (2)$$

To model spatial variations and understand how time-dependent magnetic fields induce localized circular electric fields within biological tissues, students applied Maxwell's curl equation:

$$\nabla \times E = - \partial B / \partial t \quad (3)$$

2.3. Interdisciplinary Biological Extension: Ocular Induction Modeling. To expand communicative boundaries, student teams were presented with an advanced biophysical problem: calculating the exact biological impact of low-frequency magnetic

exposure on the human eye. When an individual is exposed to time-varying magnetic fields (e.g., around high-voltage equipment or medical MRI scanners), internal eddy currents are induced within the conductive vitreous humor and retina of the eye. This gives rise to two distinct phenomena which the teams had to analyze mathematically and defend verbally:

1. Magnetophosphene Thresholds: Retinal cells are stimulated non-thermally by weak induced electric fields, producing artificial light sensations known as magnetophosphenes. Students modeled the threshold induced current density (J) required to trigger phosphenes using the electrical conductivity of ocular tissue ($\sigma \approx 0.52$ S/m) and the frequency of the field (f), defined by the biological induction relationship:

$$J = \sigma \cdot E_{induced} = \sigma \cdot (\pi \cdot r \cdot f \cdot B_{max}) \quad (4)$$

Where r represents the mean radius of the human ocular globe (approximately 11–12 mm). Teams had to determine safe operating thresholds for technicians based on international safety guidelines.

2. Thermal Power Absorption (SAR): High-frequency or high-intensity induction triggers localized heat dissipation inside the crystalline lens. Because the eye lacks extensive vascularization to dissipate heat efficiently, excessive induced power deposition (Specific Absorption Rate - SAR) can accelerate microstructural proteins degradation, potentially leading to cataract formation. The SAR value induced in the ocular tissue was derived using the following formulation:

$$SAR = (\sigma \cdot |E_{induced}|^2) / (2 \cdot \rho) \quad (5)$$

Where ρ represents the mass density of the ocular vitreous structure ($\rho \approx 1000$ kg/m³). Working in teams, students had to evaluate whether a given magnetic flux density poses an immediate ophthalmological risk.

2.4. Laboratory Hardware and Cooperative Interventions. The Experimental Group carried out collaborative investigations utilizing specialized laboratory setups. These included multi-turn induction coils, automated digital data loggers, computer-linked signal generators, and dual-trace digital oscilloscopes. Structurally, the intervention followed a rigid cooperative protocol:

1. Heterogeneous Team Allocation: Teams of four were formed combining varied academic performance profiles, forcing advanced students to articulate concepts to peers.

2. Structured Jigsaw Specialization: Using the Jigsaw approach, each team member was designated as the primary investigator for a single sub-variable: one managed magnetic field frequency, another handled loop geometry, the third calculated biological tissue conductivity, and the fourth estimated SAR and thermal limits.

3. Peer-Argumentative Defense Seminars: Teams were required to collectively defend their mathematical models and safety assessments against critiques from opposing groups, directly stimulating argumentation skills.

Results

3.1. Quantitative Competence Tracking. Prior to and following the pedagogical intervention, both cohorts were rigorously evaluated using a standardized multi-kriterial rubrics matrix. This matrix measured the Collaboration Index (I_col), the Communication Index (I_com), and Academic Physics Performance on a standard scale ranging from 1.00 to 4.00.

Evaluation Metric	Group	Pre-test Mean	Post-test Mean	Net Shift (%)
Collaborative Index (I_col)	CG	2.41	2.55	+5.8%
	EG	**2.38**	**3.68**	**+54.6%**
Communicative Index (I_com)	CG	2.28	2.44	+7.0%
	EG	**2.31**	**3.58**	**+55.0%**
Academic Physics Grade	CG	2.75	2.92	+6.1%
	EG	**2.71**	**3.74**	**+38.0%**

Table 1. Comparative competence shifts and academic grading matrices between cohorts.

3.2. Quantitative Ocular Safety Results from Student Projects. During the interdisciplinary projects, the Experimental Group analyzed specific safety scenarios based on equations (4) and (5). Students calculated that at a common power frequency of f = 50 Hz, the minimum threshold magnetic flux density required to cause magnetophosphenes in human eyes is approximately B_max = 10 mT. Their models confirmed that while industrial induction heaters can easily cross this threshold, standard household appliances remain entirely safe. Furthermore, they proved that at extreme high-frequency induction fields (f > 10 MHz), an induced electrical field of E = 100 V/m leads to localized thermal energy absorption exceeding safe limits, showing how prolonged exposure can lead to cataract formation due to protein denaturation. This practical application gave students a tangible sense of the value of physics in occupational health.

3.3. Statistical Significance Verification. To confirm that the observed gains in the Experimental Group were a direct result of the pedagogical intervention rather than random chance, an independent two-sample t-test was conducted using the following formula:

$$t = (\bar{X}_1 - \bar{X}_2) / \sqrt{((s_1^2 / n_1) + (s_2^2 / n_2))} \quad (6)$$

The statistical analysis yielded a calculated t-value of t_calc = 4.12. This significantly exceeds the critical t-value of t_crit = 1.98 at a significance level of α = 0.05. This mathematically proves that the interdisciplinary collaborative methodology is highly effective for student development.

Discussion

The experimental results gathered at Jizzakh State Pedagogical University demonstrate that embedding real-world biophysical problems within classical physics education significantly enhances learning outcomes. Traditional physics instruction often isolates concepts, leading students to view electromagnetic induction purely as an abstract mathematical exercise. However, when students were tasked with modeling induced currents within human ocular systems, the abstract nature of Maxwell's equations instantly transformed into a concrete, tangible challenge [4].

From a cognitive perspective, forcing students to collaborate on topics like magnetophosphenes and cataract risks required them to clarify their thoughts before

sharing them with the team. To solve Equation 4 and Equation 5, team members had to discuss biological conductivity, vector alignments, and thermodynamic limits. This peer-to-peer dialogue forces cognitive reorganization, directly driving the rapid development of communicative competence. Additionally, dividing responsibilities for calculating thermal effects and electrical thresholds successfully built collective accountability. This shift disproves the common misconception that collaborative activities slow down academic progress; rather, it accelerates deep conceptual understanding [5].

Conclusion

Implementing a collaborative, interdisciplinary teaching methodology in the 'Electromagnetic Induction' chapter at Jizzakh State Pedagogical University successfully achieved its goals. The approach led to a 54% improvement in teamwork dynamics and communication skills, alongside a 38% increase in conceptual physics exam scores. By analyzing the practical effects of induced fields on ocular structures, students gained a deeper understanding of classical physics alongside vital biophysical risk-assessment capabilities. This model provides an effective, scalable framework for physics departments across Central Asia seeking to elevate engineering and science education to international standards.

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