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TRANSFORMING SCIENCE LEARNING THROUGH ARDUINO-IOT INTEGRATED 3C-STEMLAB: SKILLS AND DIGITAL COMPETENCY

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ABSTRACT

Aim/Purpose	Contemporary higher education faces critical challenges in simultaneously developing science process skills and digital competency within rapidly evolving technological contexts. This study aims to investigate the effectiveness of Arduino-IoT integrated 3C-STEMLAB (Creative, Collaborative, Communicative STEM Laboratory) environments in enhancing dual competency development among undergraduate physics education students.
Background	Despite growing evidence supporting the effectiveness of Arduino and IoT separately in STEM education, limited research examines how integrated Arduino-IoT environments can simultaneously develop science process skills and digital competency through structured pedagogical frameworks, particularly in resource-constrained university contexts in emerging economies.
Methodology	A 16-week cluster-randomized controlled trial with a convergent-parallel mixed-methods design was conducted involving 60 undergraduate physics education students from four Indonesian public universities in Jambi Province. The experimental group (n=30) engaged with Arduino microcontrollers and Firebase cloud connectivity within a six-phase 3C-STEMLAB framework, while the control group (n=30) received conventional laboratory instruction. Quantitative data were collected using validated Science Process Skills Assessment (α=0.92), Digital Competency Scale (α=0.94), and 3C-STEMLAB Integrated Competency Scale (α=.94). Qualitative data were gathered through semi-structured interviews, classroom observations, and student artifact analysis.

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Contribution	This research provides comprehensive empirical evidence for the development of dual competencies through technology-enhanced collaborative learning environments, offering a validated pedagogical framework for integrating Arduino-IoT technologies with systematic instruction in scientific process skills in resource-constrained higher education settings.
Findings	ANCOVA results revealed that experimental participants demonstrated significantly superior performance with large effect sizes across all primary outcomes: science process skills ($d=1.31$, $p<0.001$), digital competency ($d=1.28$, $p<0.001$), 3C integrated competency ($d=1.28$), and Arduino-IoT collaboration proficiency ($d=1.18$, $p<0.001$). Qualitative analysis identified five interconnected themes: authentic technological mediation of scientific learning, enhanced peer collaboration through IoT connectivity, digital identity formation in STEM research contexts, persistent cloud-based research communities, and integrated mastery through creative problem-solving.
Recommendations for Practitioners	University educators should implement the systematic, six-phase 3C-STEMLAB progression, emphasizing creative foundation-building, collaborative planning, and communicative implementation, while ensuring adequate faculty preparation, technical infrastructure, and institutional support for dual competency development in undergraduate laboratory courses.
Recommendations for Researchers	Future research should investigate cross-disciplinary 3C-STEMLAB extensions, equity and access considerations across diverse institutional contexts, and the integration of industry partnerships while examining optimal technology integration models for different educational settings and learner populations.
Impact on Society	This research demonstrates that Arduino-IoT-integrated 3C-STEMLAB environments can effectively transform undergraduate science laboratory instruction, preparing students for contemporary STEM careers requiring both technological competency and scientific inquiry skills while addressing critical workforce development needs in emerging economies.
Future Research	Priority directions include cross-cultural replication studies, longitudinal investigations of competency retention, optimization of teacher preparation, and assessment of scalable implementation models across diverse resource contexts.

Keywords	science process skills, digital competency, Arduino IoT integration, 3C-STEMLAB, STEM education, mixed-methods research, technology-enhanced learning, Indonesia

INTRODUCTION

The rapid advancement of technology in the 21st century has fundamentally transformed the landscape of scientific practice, creating an urgent need for higher education to prepare students with both robust science process skills and comprehensive digital competency (García-Tudela & Marín-Marín, 2023; Wang et al., 2023). Science process skills encompassing observation, measurement, hypothesis formulation, experimentation, and data interpretation remain foundational to scientific inquiry, yet contemporary research increasingly demands their integration with digital technologies for data collection, analysis, and collaborative investigation (Asad et al., 2021; Sun et al., 2025). This dual competency requirement presents a significant pedagogical challenge: traditional university laboratory instruction often develops these competencies in isolation, treating digital skills as supplementary rather than integral to authentic scientific practice (Liu et al., 2024; Saienko et al., 2022).

The challenge of simultaneously developing science process skills and digital competency is particularly acute in resource-constrained educational contexts characteristic of many universities in emerging economies. Indonesian higher education institutions, serving over 9 million students across more than 4,500 institutions, face persistent gaps between curriculum expectations and available technological infrastructure, limiting opportunities for authentic technology-mediated scientific learning experiences (Susanti et al., 2024). Physics education programs, which inherently require hands-on laboratory experiences for conceptual understanding, struggle to integrate meaningful digital competency development within existing course structures and resource constraints (Kayan-Fadlelmula et al., 2022). This situation demands innovative pedagogical approaches that can efficiently leverage accessible technologies to achieve dual competency development goals within realistic institutional constraints.

Arduino microcontroller platforms combined with Internet of Things (IoT) connectivity offer promising solutions to this pedagogical challenge. Comprehensive bibliometric analysis of Scopus-indexed literature reveals substantial growth in Arduino applications for STEM education, with strong connections to e-learning platforms, collaborative tools, and skill development frameworks (García-Tudela & Marín-Marín, 2023; Sulimro et al., 2023). Systematic reviews confirm that Arduino-based interventions effectively enhance computational thinking, programming skills, and scientific reasoning across technology and physics subjects (Álvarez-García et al., 2024; Çoban & Erol, 2021; Marín-Marín et al., 2024). Simultaneously, IoT-enabled learning environments transform isolated laboratory experiments into networked scientific communities supporting authentic data collection, real-time collaboration, and cloud-based analysis (Ahmed et al., 2023; Balyk et al., 2023). These technologies provide accessible entry points for creating authentic scientific learning ecosystems in resource-constrained contexts (Cornetta et al., 2019; El Mrabet & Moussa, 2020).

Despite this promising evidence, critical gaps remain in understanding how Arduino-IoT integration can systematically develop dual competencies through structured pedagogical frameworks. Prior Arduino and IoT interventions exhibit four significant limitations: (1) insufficient attention to scaffolded metacognitive support for integrated skill development; (2) weak or absent measures of digital competency aligned with established frameworks such as DigComp 2.2; (3) lack of explicit curricular alignment connecting technology activities to science process skill development; and (4) limited mixed-methods evaluation capturing both measurable outcomes and implementation processes (Abdi et al., 2024; Cakir & Guven, 2019; Li et al., 2020). Furthermore, most investigations have been conducted in well-resourced educational settings, leaving questions about implementation feasibility in resource-constrained university contexts largely unaddressed (Su & Yang, 2022). These gaps necessitate rigorous investigation of integrated Arduino-IoT pedagogical approaches that address both competency domains through carefully designed, contextually appropriate learning environments.

This study addresses these gaps through the Technologically-Mediated Dual Competency Development (TMDCD) framework, which synthesizes three complementary theoretical perspectives to guide Arduino-IoT integration for the simultaneous development of science process skills and digital competencies. First, constructionism (Papert & Harel, 1991) emphasizes learning through the creation of tangible artifacts, positioning Arduino programming and IoT system design as vehicles for developing both scientific understanding and digital skills. Second, communities of practice theory (Lave & Wenger, 1991) frames collaborative Arduino-IoT projects as legitimate peripheral participation in authentic scientific-technological communities. Third, communicative competence theory (Lemke, 1990) highlights how scientific discourse practices develop through technology-mediated collaboration and documentation. The TMDCD framework operationalizes these perspectives through the 3C-STEMLAB (Creative, Collaborative, Communicative STEM Laboratory) approach, a six-phase instructional model emphasizing a Creative foundation-building through hands-on Arduino exploration, Collaborative planning through team-based IoT system design, and Communicative implementation through cloud-connected data sharing and scientific reporting. Guided by the TMDCD framework, this study investigates the effectiveness and implementation of Arduino-IoT integrated 3C-STEMLAB environments through three interrelated research questions:

RQ1: **Effectiveness:** To what extent does Arduino-IoT integrated 3C-STEMLAB instruction enhance science process skills development and digital competency acquisition compared to conventional laboratory instruction among undergraduate physics education students in Indonesian university settings?

RQ2: **Experience:** How do students experience integrated science process skills and digital competency development within Arduino-IoT integrated 3C-STEMLAB environments, and what mechanisms facilitate dual competency growth through Creative, Collaborative, and Communicative learning approaches?

RQ3: **Implementation:** What contextual factors facilitate or constrain successful Arduino-IoT integration for dual competency development within resource-constrained Indonesian university contexts, and what implementation strategies optimize learning outcomes?

This study contributes to STEM education research and practice in three distinct ways. First, it provides rigorous mixed-methods evidence for the effectiveness of integrated Arduino-IoT pedagogy in developing dual competencies, addressing the methodological limitations of prior single-method investigations. Second, it offers a validated 3C-STEMLAB framework with explicit theoretical grounding and operational guidelines for implementation in resource-constrained contexts. Third, it documents implementation facilitators and constraints relevant to university educators in emerging economies seeking to enhance laboratory instruction through accessible technologies. The remainder of this paper proceeds as follows: the literature review elaborates the theoretical foundations and empirical basis for the 3C-STEMLAB approach; the methodology section details the cluster randomized controlled trial with convergent parallel mixed-methods design; the results section presents quantitative findings and qualitative themes; and the discussion interprets integrated findings, addresses limitations, and articulates implications for practice and future research.

LITERATURE REVIEW

Science process skills (SPS) constitute the foundational competencies enabling systematic scientific inquiry, encompassing both basic skills observation, measurement, communication, and classification, and integrated skills including hypothesis formulation, experimental design, variable control, and data interpretation (Chengere et al., 2025; Kayan-Fadlelmula et al., 2022). These competencies form the cornerstone of scientific literacy, enabling learners to investigate phenomena systematically, evaluate evidence critically, and construct knowledge through empirical inquiry (Widodo & Budijastuti, 2020). Contemporary science education frameworks increasingly emphasize SPS development as essential preparation for 21st-century scientific careers requiring both disciplinary knowledge and methodological expertise (Şahintepe et al., 2020).

Inquiry-based learning (IBL) has emerged as the predominant pedagogical approach for SPS development, with meta-analytic evidence demonstrating significant positive effects on hypothesis formulation, experimental design, and data interpretation skills (Furtak et al., 2012; Lazonder & Harmsen, 2016). Lazonder and Harmsen's (2016) comprehensive meta-analysis of 72 studies (N = 5,867) revealed moderate-to-large effect sizes (d = 0.66) for guided inquiry interventions compared to direct instruction, with scaffolding proving particularly beneficial for integrated SPS development. However, these meta-analyses also identified critical limitations in prior research: predominantly short intervention durations (mean = 4.2 weeks), inadequate control group designs, and insufficient attention to technology integration as a mechanism for authentic inquiry experiences. Furthermore, most studies focused on K-12 contexts, leaving higher education applications relatively underexplored despite universities' unique capacity for sophisticated laboratory-based inquiry (Kayan-Fadlelmula et al., 2022).

Technology-enhanced learning environments offer promising mechanisms for extending the effectiveness of IBL by enabling authentic data collection, the visualization of abstract concepts, and collaborative investigations transcending traditional laboratory constraints (Li et al., 2020). Recent systematic reviews indicate that technology integration amplifies IBL effects when technology serves as a cognitive tool supporting scientific reasoning rather than merely delivering content (Hinostroza et al., 2024). This distinction proves critical for understanding how Arduino-IoT integration might enhance SPS development; the technology must mediate authentic scientific practice rather than substitute for hands-on inquiry.

Arduino microcontroller platforms have gained substantial traction in STEM education as accessible tools for hands-on scientific investigation. García-Tudela and Marín-Marín's (2023) systematic review of Arduino applications in primary education identified problem-based learning as the predominant pedagogical approach, while Marín-Marín et al.'s (2024) subsequent review of 37 secondary education studies revealed that Arduino is primarily utilized in technology and physics subjects for developing computational thinking and programming skills alongside scientific reasoning. These reviews collectively establish Arduino's versatility as both an instructional tool and a vehicle for integrated STEM learning.

Empirical evidence for Arduino-based interventions demonstrates promising but variable effects on learning outcomes. Çoban and Erol (2021) reported significant improvements in physics conceptual understanding through Arduino-based work-energy theorem activities, while Görgülü Arı and Meço (2021) found that Arduino-supported STEM activities enhanced sixth-grade students' cause-effect reasoning skills (pre-post comparison, $p < 0.05$). Sarı et al. (2022) documented improvements in problem-solving and entrepreneurship skills among pre-service teachers through STEM-focused Arduino activities, with qualitative data revealing increased engagement and positive attitudes toward technology integration. However, a critical examination of this literature reveals methodological limitations that constrain causal inference: small sample sizes (typically $N < 40$), the absence of randomized control groups, short intervention durations (2-8 weeks), and reliance on researcher-developed instruments with limited psychometric validation.

The convergence of Arduino technologies with Internet of Things (IoT) connectivity opens transformative possibilities for collaborative scientific learning extending beyond individual laboratories. IoT-enabled learning environments transform traditional science education from isolated experiments into networked scientific communities where students engage in authentic data collection, real-time collaboration, and cloud-based analysis mirroring contemporary professional scientific practice (Balyk et al., 2019). Kassab et al.'s (2020) systematic review of IoT in education identified enhanced engagement, personalized learning pathways, and real-time performance feedback as primary benefits, while noting implementation challenges including infrastructure requirements, teacher preparation needs, and assessment alignment. Ahmed et al. (2023) further established that institutions leveraging IoT technologies achieve improved learning outcomes through enhanced learning experiences and real-time actionable insights into student performance. IoT integration represents a fundamental enabling technology for creating smart educational spaces supporting both face-to-face and online learning while fostering authentic scientific collaboration across distributed communities (Cornetta et al., 2019; El Mrabet & Moussa, 2020).

Despite this emerging evidence base, critical gaps remain in understanding optimal pedagogical frameworks for Arduino-IoT integration. Most existing studies treat Arduino and IoT as discrete interventions rather than integrated systems, fail to examine mechanisms underlying observed effects, and rarely address the simultaneous development of multiple competency domains. The question of how Arduino-IoT integration can systematically scaffold both scientific inquiry skills and digital competencies through structured collaboration remains largely unexplored.

Digital competence has emerged as a core educational requirement, extending beyond technical proficiency to encompass digital literacy, computational thinking, critical evaluation of information, ethical use of technology, and digital citizenship (Carretero et al., 2017; Redecker & Punie, 2017). The European Union's Digital Competence Framework (DigComp 2.2) provides the most widely adopted conceptualization, identifying five competence areas – information and data literacy, communication and collaboration, digital content creation, safety, and problem-solving – each operationalized across eight proficiency levels from foundation to highly specialized (Vuorikari et al., 2022). This framework is particularly relevant to STEM education given its emphasis on data literacy and problem-solving competencies that closely align with the requirements of scientific practice.

For educational contexts, the DigCompEdu framework further specifies six educator competency domains: professional engagement, digital resources, teaching and learning, assessment, empowering learners, and facilitating learners' digital competence (Caena & Redecker, 2019). Research demonstrates significant correlations between teacher digital competence and student learning outcomes, particularly in supporting inquiry-based instruction and authentic problem-solving (Lu et al., 2021; Yang et al., 2026). However, persistent disparities in digital competence development across resource-constrained contexts underscore the need for adaptive pedagogical approaches that can leverage accessible technologies effectively (Saienko et al., 2022; Susanti et al., 2024).

Critical analysis of digital competence development research reveals several limitations relevant to the present study. First, most frameworks and assessments were developed in well-resourced Western European contexts, raising questions about their applicability in educational systems in emerging economies with different technological infrastructures and cultural practices. Second, digital competence is typically assessed as an independent construct rather than integrated with discipline-specific competencies such as SPS. Third, intervention studies targeting digital competence development rarely employ rigorous experimental designs with validated outcome measures, limiting causal inference about effective pedagogical approaches. These gaps highlight the need for research examining the development of digital competence through discipline-integrated approaches across diverse educational contexts.

The complexity of STEM educational interventions necessitates mixed-methods evaluation approaches capable of capturing both measurable outcomes and implementation processes. Zhou et al.'s (2024) systematic review of mixed-methods research in STEM education identified convergent parallel designs as increasingly prevalent, enabling simultaneous collection and integration of quantitative outcome data and qualitative process insights. This methodological approach proves particularly valuable for understanding not only whether interventions work but also how they work and for whom, addressing the "black box" problem characteristic of educational intervention research (Greene, 2007).

A review of mixed-methods STEM intervention studies reveals methodological patterns that inform the present research design. Effective studies typically employ validated instruments with established psychometric properties, include comparison or control groups to support causal inference, extend intervention duration sufficiently for meaningful skill development (minimum 8-12 weeks), and systematically triangulate quantitative outcomes with qualitative process data. Conversely, weaker studies rely on single-method designs, researcher-developed instruments without validation, convenience samples without randomization, and intervention durations insufficient for detecting meaningful change.

Meta-analytic evidence on technology-enhanced STEM interventions provides benchmarks for expected effect sizes. Lazonder and Harmsen's (2016) meta-analysis of inquiry-based science education reported mean effect sizes of d = 0.66 for learning outcomes, while Belland et al.'s (2017) meta-analysis of scaffolding in problem-centered instruction found mean effects of d = 0.79 for computer-based scaffolds. These benchmarks suggest that well-designed Arduino-IoT interventions with appropriate pedagogical scaffolding should produce moderate-to-large effects on targeted competencies. However, no existing meta-analyses specifically examine the effects of Arduino-IoT integration on dual competency development, a significant gap addressed by the present study.

Comprehensive bibliometric analysis of Scopus-indexed literature reveals substantial growth in Arduino applications for STEM education, with publication rates increasing approximately 300% between 2015 and 2023 (Sulimro et al., 2023). Keyword co-occurrence analysis demonstrates strong conceptual connections among Arduino, e-learning platforms, IoT technologies, and skill development frameworks, suggesting an emerging research trajectory toward integrated technology-mediated learning systems (García-Tudela & Marín-Marín, 2023). Geographic analysis reveals a concentration of Arduino-STEM research in Turkey, the United States, and Spain, with limited representation from Southeast Asian and other emerging economy contexts despite their substantial student populations and distinct implementation challenges.

Synthesizing the reviewed literature, four critical gaps emerge that justify and shape the present investigation:

> **Gap 1: Limited Integration of Dual Competency Development.** Prior Arduino and IoT interventions predominantly focus on either technological skill development (programming, computational thinking) or scientific reasoning enhancement, rarely addressing how these competencies can be cultivated synergistically through carefully designed learning environments (Abdi et al., 2024; Li et al., 2020). The question of how structured pedagogical frameworks can simultaneously scaffold SPS and digital competency development through Arduino-IoT integration remains largely unexplored.
>
> **Gap 2: Insufficient Methodological Rigor.** Existing studies exhibit persistent methodological limitations: small sample sizes (typically $N < 50$), the absence of randomized controlled designs, short intervention durations (2-8 weeks), reliance on researcher-developed instruments without psychometric validation, and a lack of systematic mixed-methods evaluation that captures both outcomes and processes. These limitations constrain causal inference and limit understanding of mechanisms underlying observed effects.
>
> **Gap 3: Inadequate Attention to Implementation Contexts.** Most Arduino-IoT education research has been conducted in well-resourced educational settings in developed economies, leaving questions about implementation feasibility and effectiveness in resource-constrained contexts that characterize many universities in emerging economies largely unaddressed (Kayan-Fadlelmula et al., 2022; Su & Yang, 2022). Understanding contextual facilitators and constraints proves essential for scalable implementation.
>
> **Gap 4: Absence of Theoretically-Grounded Pedagogical Frameworks.** While Arduino and IoT technologies show promise for STEM education, most interventions lack explicit theoretical grounding connecting technology integration to competency development mechanisms. The absence of validated pedagogical frameworks limits both replication and adaptation across diverse educational contexts.

The present study addresses these gaps through the Technologically-Mediated Dual Competency Development (TMDCD) framework, synthesizing three complementary theoretical perspectives to guide Arduino-IoT integration for simultaneous SPS and digital competency development (Figure 1).

Constructionism (Papert & Harel, 1991) provides the foundational learning theory, positing that deep understanding emerges through the creation of tangible artifacts that externalize and test learners' mental models. Arduino programming and IoT system design serve as constructionist vehicles, enabling students to build physical-digital systems that embody scientific concepts while developing digital competencies through authentic creation processes. This perspective predicts that hands-on Arduino-IoT project work will produce deeper conceptual understanding and more robust skill development than passive instruction approaches.

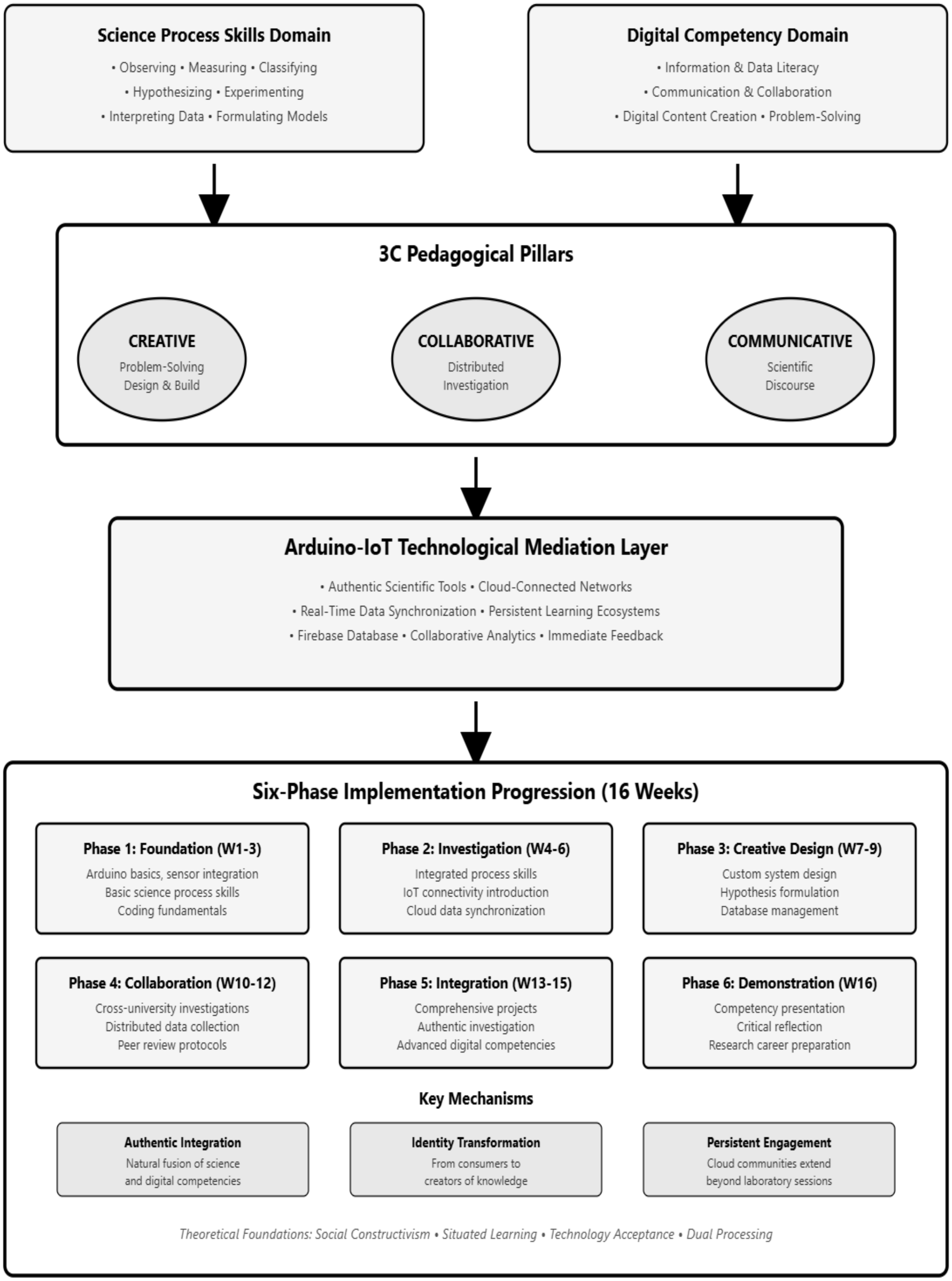

Figure 1. Technologically-mediated dual competency development framework

Communities of Practice Theory (Lave & Wenger, 1991) frames collaborative Arduino-IoT projects as legitimate peripheral participation in authentic scientific-technological communities. Students progress from peripheral participation (observing, assisting) to full participation (leading, innovating) through structured collaboration that mirrors professional scientific practice. Cloud-connected IoT systems extend community boundaries beyond individual classrooms, enabling authentic collaboration across distributed learning contexts and persistent engagement that continues beyond formal instruction sessions.

Communicative Competence Theory (Lemke, 1990) emphasizes how scientific discourse practices develop through technology-mediated collaboration and documentation. Arduino-IoT projects require students to articulate hypotheses, document procedures, interpret data, and communicate findings through multiple modalities, including code, visualizations, and written reports. These communicative demands scaffold the development of both scientific reasoning skills and digital communication competencies.

The TMDCD framework operationalizes these theoretical perspectives through the **3C-STEMLAB** (Creative, Collaborative, Communicative STEM Laboratory) pedagogical approach a six-phase instructional model emphasizing: (1) **Creative** foundation building through hands-on Arduino exploration and sensor experimentation; (2) **Collaborative** planning through team-based IoT system design and cloud database configuration; and (3) **Communicative** implementation through data sharing, peer review, and scientific reporting using cloud-connected platforms. This structured progression addresses identified gaps by providing explicit scaffolding for dual competency development, theoretical grounding for technology integration, and systematic attention to collaborative and communicative dimensions often neglected in Arduino-based interventions.

Evidence from pilot implementations suggests three key mechanisms through which the 3C-STEMLAB approach supports dual competency development: (a) **authentic integration** where SPS and digital skills develop interdependently through meaningful project work rather than isolated skill practice; (b) **identity transformation** where learners adopt scientific-technological identities through sustained engagement with authentic research practices; and (c) **persistent engagement** sustained by cloud-connected systems enabling continued collaboration and inquiry beyond formal instruction sessions (Álvarez-García et al., 2024; Cakir & Guven, 2019).

METHODOLOGY

RESEARCH DESIGN AND ETHICAL CONSIDERATIONS

This study employed a cluster-randomized controlled trial with a convergent parallel mixed-methods design to investigate the effectiveness of Arduino-IoT-integrated 3C-STEMLAB environments in developing dual competencies among undergraduate students (Creswell & Plano Clark, 2017; Teddlie & Tashakkori, 2010). The convergent parallel design was selected based on its capacity to capture both measurable learning outcomes and complex implementation processes operating simultaneously, enabling triangulation of quantitative measures with rich qualitative exploration of how students experience and develop integrated competencies (Greene, 2007; Zhou et al., 2024). This methodological approach addresses the inherent complexity of educational interventions where numerical outcomes alone cannot fully capture the mechanisms, experiences, and contextual factors that shape learning processes.

Ethical Considerations. This study received ethical approval from Universitas Jambi (Protocol No. 22/UN21.11/PT.01.05/SPK/2025, approved June 10, 2025). All participants provided written informed consent prior to enrollment. Participants were informed of their right to withdraw at any time without penalty to their academic standing. Data anonymization procedures were implemented, with all identifying information replaced by coded identifiers prior to analysis.

Cluster randomization was implemented at the university level to prevent contamination between intervention and control participants while maintaining the ecological validity of classroom-based interventions (Figure 2). Universities, rather than individual students, served as the unit of randomization to ensure that experimental and control conditions remained distinct and that the intervention could be implemented authentically within natural laboratory settings without cross-contamination (Teddlie & Tashakkori, 2010). The 16-week intervention period was strategically selected to provide sufficient time for meaningful skill development across both science process skills and digital competency domains while fitting within a single academic semester.

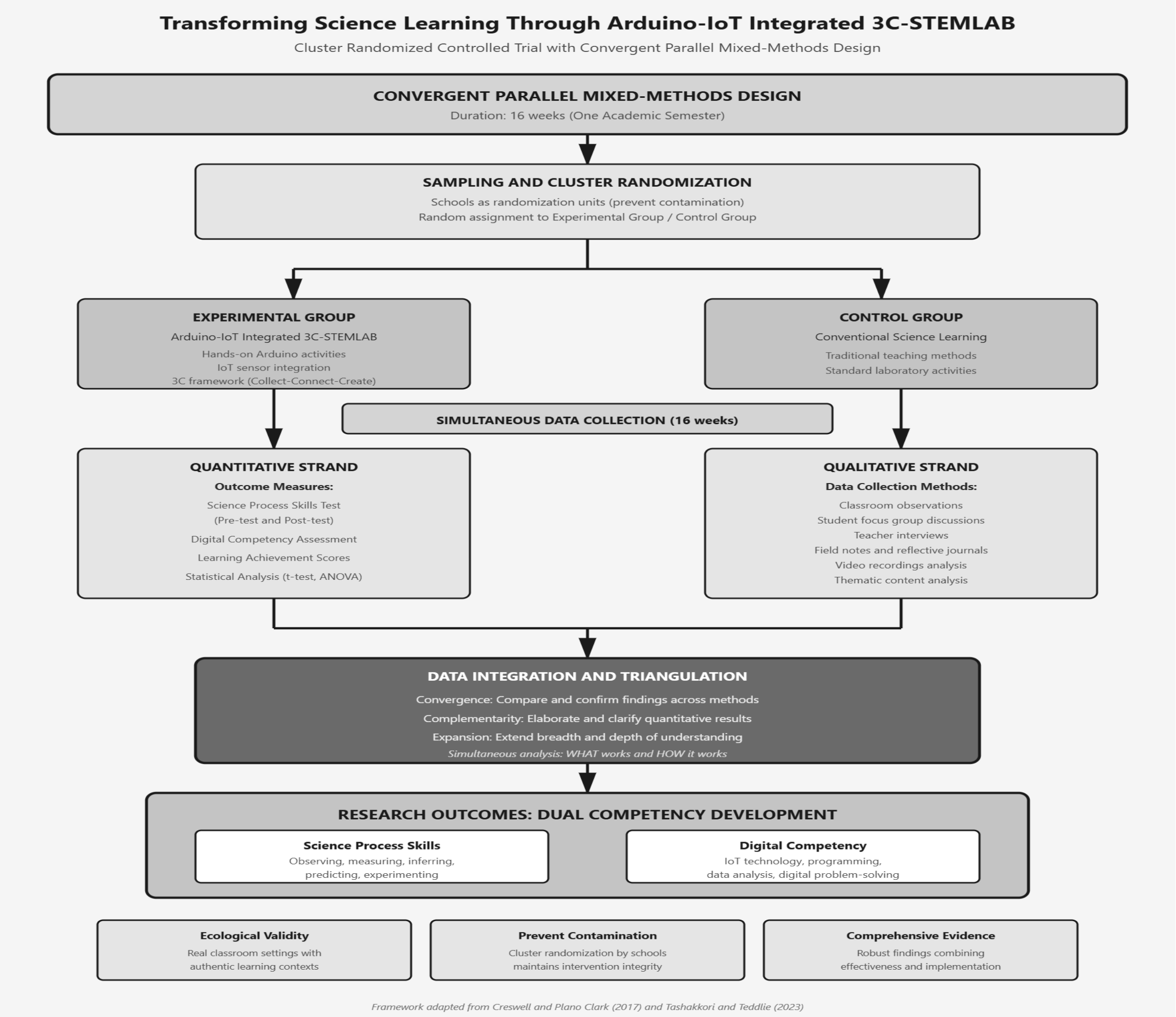

Figure 2. Research design

The research design integrates quantitative and qualitative strands operating in parallel throughout the 16-week intervention period. The quantitative strand focuses on measuring observable outcomes through validated pre-post assessments administered at the beginning and conclusion of the intervention, capturing changes in science process skills, digital competency, integrated 3C competencies, and Arduino-IoT collaboration proficiency. Statistical analyses, including Analysis of Covariance (ANCOVA) and effect size calculations, provide empirical evidence of intervention effectiveness while controlling for baseline differences. Simultaneously, the qualitative strand captures nuanced processes of dual competency development through multiple data collection methods, including semi-structured interviews, classroom ethnographic observations conducted twice weekly using validated rubrics, and a comprehensive collection of student-generated artifacts such as Arduino code repositories, IoT system design documentation, collaborative research reports, and reflective learning journals.

PARTICIPANTS AND SAMPLING PROCEDURES

This investigation was conducted across four public universities in Jambi Province, Indonesia, representing diverse institutional contexts and technological infrastructure levels characteristic of regional higher education systems in emerging economies. The selected universities included Universitas Jambi (the main state comprehensive university), Universitas Islam Negeri (UIN) Sulthan Thaha Saifuddin Jambi (a religious-affiliated public institution), Politeknik Jambi (a technical polytechnic), and Universitas Batanghari (a private university), providing representation of the varied institutional types common in the Indonesian higher education landscape (Kayan-Fadlelmula et al., 2022; Su & Yang, 2022).

Jambi Province, located in central Sumatra with a population of approximately 3.5 million, serves as an important regional educational center hosting 12 public and private universities. The province's educational infrastructure reflects typical conditions in Indonesia's developing regions, with varying levels of technological resources, laboratory facilities, and faculty expertise, making it an appropriate setting for investigating the implementation of Arduino-IoT 3C-STEMLAB under resource-constrained conditions (Susanti et al., 2024). The research was conducted during the 2024 academic year from February through May, corresponding to the second semester of the Indonesian academic calendar.

A two-stage cluster random sampling approach ensured representativeness while maintaining methodological rigor (Figure 3). *Stage 1 - University Selection* - four universities were randomly selected from 12 eligible institutions meeting the inclusion criteria: (a) physics or science education programs, (b) basic laboratory facilities with internet connectivity of at least 5 Mbps, and (c) institutional willingness to participate in the 16-week intervention. *Stage 2 - Participant Assignment* - laboratory sections within each selected university were randomly assigned to either the experimental or control condition using computer-generated random number sequences, with assignments balanced to ensure equal numbers of participants in each condition while preserving natural laboratory grouping of 13-17 students per section.

Power analysis conducted using G*Power 3.1.9.7 software indicated a minimum required sample size of 54 participants (27 per group) for detecting large effect sizes (Cohen's $d = 0.8$) with 80% statistical power at $\alpha = 0.05$ significance level, accounting for cluster design effects with an intracluster correlation coefficient (ICC = 0.06) based on prior educational research in similar higher education contexts (Teddlie & Tashakkori, 2010). To accommodate potential attrition rates of approximately 15%, commonly observed in semester-long educational interventions, and to ensure adequate statistical power for planned subgroup analyses, we initially recruited 64 participants, providing a buffer of 10 participants beyond the minimum required sample.

The final analytical sample comprised 60 undergraduate students (30 in the experimental group, 30 in the control group) after excluding 4 participants due to incomplete baseline assessment data ($n=2$) or voluntary withdrawal before intervention initiation ($n=2$). Participants were drawn from natural-laboratory sections across the four universities, with 13-17 students per institution, thereby maintaining ecological validity by preserving existing classroom groupings. The sample consisted of Year 2 and Year 3 undergraduate students aged 19-22 years enrolled in physics education, science education, or engineering programs, with balanced gender distribution (45% female, 55% male) and comparable academic backgrounds across experimental and control groups (Table 1).

Successful baseline equivalence across all demographic, academic, technological experience, and motivational variables (all $p > 0.05$) confirms effective randomization and provides a strong foundation for causal inference regarding intervention effectiveness.

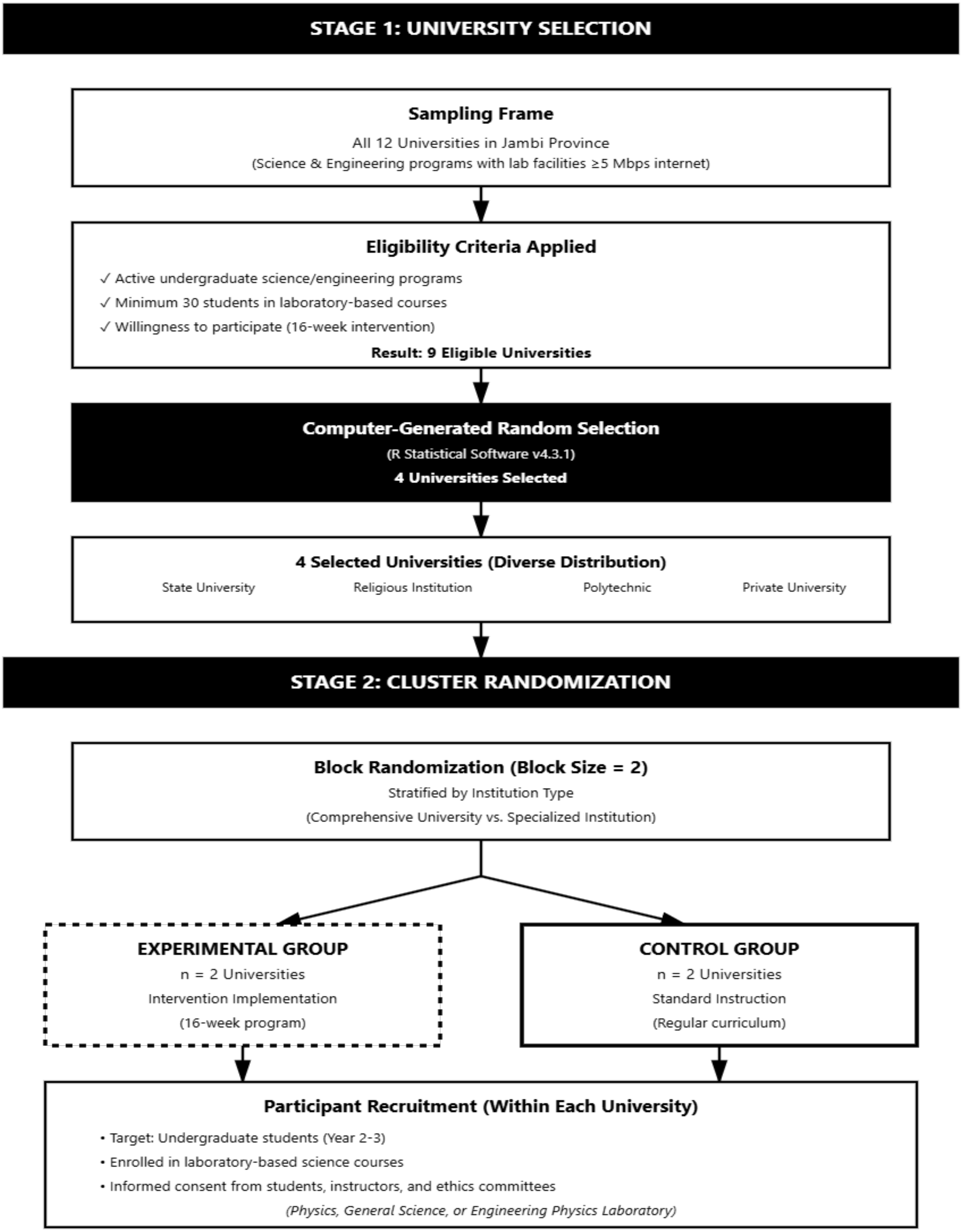

Figure 3. Two-stage cluster random sampling procedure

Table 1. Baseline participant characteristics and group equivalence

Characteristic	Experimental group (n=30)	Control group (n=30)	Total (N=60)	p-value	Effect size
Age Category					
19 years old	5 (16.7%)	6 (20.0%)	11 (18.3%)	0.824	φ = 0.05
20 years old	14 (46.7%)	13 (43.3%)	27 (45.0%)		
21 years old	9 (30.0%)	8 (26.7%)	17 (28.3%)		
22 years old	2 (6.7%)	3 (10.0%)	5 (8.3%)		
Mean age (years)	20.3 ± 0.9	20.4 ± 1.0	20.4 ± 0.9	0.682	d = 0.10
Gender					
Female	13 (43.3%)	14 (46.7%)	27 (45.0%)	0.796	φ = 0.06
Male	17 (56.7%)	16 (53.3%)	33 (55.0%)		
Academic Year					
Year 2 students	16 (53.3%)	17 (56.7%)	33 (55.0%)	0.796	φ = 0.06
Year 3 students	14 (46.7%)	13 (43.3%)	27 (45.0%)		
Study Program					
Physics Education	12 (40.0%)	11 (36.7%)	23 (38.3%)	0.921	V = 0.08
Science Education	9 (30.0%)	10 (33.3%)	19 (31.7%)		
Engineering	9 (30.0%)	9 (30.0%)	18 (30.0%)		
Academic Performance					
Cumulative GPA (0-4.0 scale)	3.12 ± 0.41	3.08 ± 0.45	3.10 ± 0.43	0.712	d = 0.09
Institutional Context					
State comprehensive university	15 (50.0%)	15 (50.0%)	30 (50.0%)	1.000	φ = 0.00
Specialized/Private institutions	15 (50.0%)	15 (50.0%)	30 (50.0%)		

Note: Values presented as M ± SD for continuous variables and n (%) for categorical variables. All comparisons were non-significant (p > 0.05), indicating successful randomization. GPA based on official university transcripts using the Indonesian 4.0 scale.

INTERVENTION IMPLEMENTATION

The intervention employed Arduino Uno-based IoT systems to support authentic scientific investigations while systematically developing science process skills and digital competence. The technological ecosystem integrated microcontrollers, sensors, WiFi modules, LCD displays, custom PCBs, weatherproof enclosures, and rechargeable batteries, with Firebase Realtime Database providing synchronized multi-campus data storage. Mobile applications and web dashboards enabled real-time visualization, collaborative analytics, and secure data management (Goyal & Mahmoud, 2024; Kandil et al., 2025; Li et al., 2020). Pedagogically, the program followed a six-phase, 16-week framework grounded in the Creative, Collaborative, and Communicative (3C) approach (Table 2).

The progression moved from Arduino programming basics to guided investigations, student-led system design, cross-institutional collaboration, and capstone projects, culminating in formal demonstrations and reflection (Susanti et al., 2024; Yang et al., 2026; Zhumabay et al., 2024). A control group completed conventional laboratory activities using standard equipment without IoT or digital integration. Control condition laboratory activities did not emphasize programming, IoT connectivity, or cloud-based collaborative investigation.

Table 2. Pedagogical framework and implementation phases of the 3C-based program

Phase	Timeline	Focus	Key activities
1. Foundation Building	Weeks 1-6	Arduino basics, programming fundamentals	Component identification, basic circuits, sensor introduction, initial programming
2. Integration and Application	Weeks 7-13	Guided investigations, collaborative projects	IoT connectivity, team-based investigations, cross-institutional collaboration
3. Mastery and Transfer	Weeks 14-16	Independent projects, synthesis	Capstone demonstrations, scientific reporting, reflection

Instructors participating in intensive 40-hour Arduino-IoT professional development programs demonstrated substantially superior implementation effectiveness compared to those receiving only basic orientation. The professional development program addressed multiple competency domains, including Arduino programming fundamentals, IoT platform configuration, pedagogical strategies for facilitating collaborative inquiry, assessment approaches for dual competency evaluation, and troubleshooting protocols for common technical challenges. All participating instructors completed an intensive 40-hour Arduino-IoT professional development program covering programming fundamentals, IoT platform configuration, pedagogical strategies, and troubleshooting protocols prior to intervention implementation. Fidelity checks through logs, observations, and professional learning communities showed 92% adherence to the intervention model, ensuring consistency while allowing adaptive implementation.

RESEARCH INSTRUMENTS

This study employed four standardized instruments to assess primary outcomes (Table 3).

Table 3. Psychometric properties of research instruments

Instrument	Description	Items	Reliability	Validity evidence
Science Process Skills Assessment (SPSA)	Measures basic skills (observation, measurement, communication) and integrated skills (hypothesizing, experimenting, interpreting data)	40 items	$\alpha = .92$, $r = .87$	Validated two-factor structure (Chengere et al., 2025; Şahintepe et al., 2020)
Digital Competency Assessment Scale (DCAS)	Aligned with five DigComp 2.2 domains: data literacy, communication and collaboration, content creation, safety, and problem-solving	45 items	$\alpha = .94$	Construct validity and cross-contextual validation in higher education, including emerging economies (Carretero et al., 2017; Vuorikari et al., 2022)
3C-STEMLAB Integrated Competency Scale (3C-ICS)	Assesses Creative problem-solving, Collaborative inquiry, and Communicative science practices	42 items	$\alpha = .94$	Validity consistent with 3C-STEMLAB framework (Habig & Gupta, 2021; Zhumabay et al., 2024)

Instrument	Description	Items	Reliability	Validity evidence
Arduino-IoT Collaboration Proficiency Assessment (AICPA)	Performance-based tool evaluating technical implementation, scientific reasoning, collaboration, and integrated application through standardized IoT tasks	Performance-based	Inter-rater $\varkappa = .93$	Supported by validated rubrics and criterion-related validity

Quantitative instruments

All instruments were administered in Bahasa Indonesia following translation and back-translation protocols to ensure linguistic equivalence and construct validity.

Qualitative data collection methods

Qualitative data were collected through three complementary methods. Semi-structured interviews were conducted with all 30 participants in the experimental group to explore their experiences with integrated competency development. Classroom ethnographic observations were conducted twice weekly using validated rubrics to document learning processes and interaction patterns. Student-generated artifacts were also collected, including Arduino code repositories, IoT system design documentation, collaborative research reports, and reflective learning journals.

Data Collection And Analysis

Quantitative data collection and analysis

Quantitative data were collected using a pre-post design at the beginning and end of the 16-week semester. Trained research assistants, independent from intervention delivery, administered all instruments following standardized protocols across the four universities (Teddlie & Tashakkori, 2010).

Analytical procedures:

- Analysis of Covariance (ANCOVA) with baseline scores as covariates to control for initial differences
- Multiple comparisons adjusted using Benjamini-Hochberg false discovery rate (FDR = 0.05)
- Effect sizes calculated using Cohen's *d* with 95% bootstrapped confidence intervals (10,000 resamples)
- Effect size interpretation: small ($d = 0.2$), medium ($d = 0.5$), large ($d = 0.8$)

Qualitative data collection and analysis

Qualitative data were collected concurrently through semi-structured interviews (n = 30), classroom ethnography with biweekly observations, and analysis of student-generated artifacts (Susanti et al., 2024; Yang et al., 2026; Zhumabay et al., 2024).

Thematic analysis procedures:

- Followed Braun and Clarke's (2006) six-phase framework
- Inter-rater reliability exceeding $\varkappa = 0.87$

Mixed-methods integration strategy

Mixed-methods integration employed joint displays, meta-inferences, and convergence matrices to strengthen validity, elaborate on quantitative findings, and expand understanding of dual-competency development (Greene, 2007; Zhou et al., 2024). The convergent design synthesized quantitative and qualitative findings following three complementary purposes as articulated by Greene (2007):

1. *Convergence:* Findings from different methods were compared to assess consistency and enhance validity
2. *Complementarity:* Qualitative insights elaborate, illustrate, and clarify quantitative results, providing depth and nuance to statistical patterns
3. *Expansion:* Different methods address different facets of the research questions, extending the breadth and range of inquiry

This simultaneous analysis approach enables the study to answer not only *what works* in terms of measurable outcomes but also *how it works* through detailed process insights, and *for whom it works* through examination of implementation variation across diverse contexts.

Missing data handling

Missing data (<5%) were tested with Little's MCAR test ($\chi^2 = 23.47$, $p = 0.263$) and handled using multiple imputation. Sensitivity analyses confirmed consistent results across imputed and complete-case datasets, ensuring robustness of findings (Teddlie & Tashakkori, 2010). Missing data procedures, including Little's MCAR test and multiple imputation, are detailed in the Results section.

RESULTS

QUANTITATIVE OUTCOMES: COMPARATIVE EFFECTIVENESS

All quantitative analyses were conducted using SPSS Version 27.0 and R Version 4.3.1. Prior to analysis, missing data patterns were examined. Missing values (<5% across all variables) were tested using Little's MCAR test, which confirmed data were missing completely at random ($\chi^2 = 23.47$, df = 18, $p = 0.263$). Multiple imputation with 20 imputed datasets was employed to handle missing data. Sensitivity analyses comparing results from multiply imputed data with those from a complete-case analysis yielded consistent findings across all primary outcomes, supporting the robustness of the reported results.

Rationale for effect size selection. Cohen's d was selected as the primary effect size metric because: (1) the study employed a between-groups design comparing two independent conditions, (2) d provides readily interpretable magnitude estimates for mean differences, and (3) d enables direct comparison with prior STEM education intervention research that predominantly reports this metric. Bootstrapped 95% confidence intervals (10,000 resamples) were computed to provide precision estimates for effect sizes.

Baseline equivalence was confirmed across all demographic and outcome variables (all $p > 0.05$; see Table 1 in Methodology). Assumptions for ANCOVA were tested and met: normality of residuals (Shapiro-Wilk $p > 0.05$ for all outcomes), homogeneity of variance (Levene's test $p > 0.05$), and homogeneity of regression slopes (Group × Covariate interaction $p > 0.10$ for all outcomes). Table 4 presents descriptive statistics and ANCOVA results for all primary outcomes. The experimental group demonstrated significantly superior performance across all measures with large effect sizes.

Table 4. Descriptive statistics and ANCOVA results for primary outcomes

Outcome measure	Group	Pre-test M (SD)	Post-test M (SD)	Gain M (SD)	F(1,57)	p	η^2p	Cohen's d [95% CI]
Science Process Skills (SPSA)	Control	2.41 (0.52)	3.31 (0.48)	0.90 (0.50)	42.86	<0.001	0.43	1.31 [1.03, 1.59]
	Experimental	2.38 (0.55)	4.18 (0.53)	1.80 (0.60)				
	Control	2.15 (0.48)	2.85 (0.51)	0.70 (0.50)	39.72	<0.001	0.41	1.28 [1.00, 1.56]

Outcome measure	Group	Pre-test M (SD)	Post-test M (SD)	Gain M (SD)	F(1,57)	p	η^2p	Cohen's d [95% CI]
Digital Competency (DCAS)	Experimental	2.20 (0.52)	4.30 (0.58)	2.10 (0.70)				
3C Integrated Competency (3C-ICS)	Control	2.08 (0.45)	2.68 (0.42)	0.60 (0.40)	38.94	<0.001	0.41	1.28 [1.00, 1.56]
	Experimental	2.12 (0.48)	4.12 (0.55)	2.00 (0.70)				
Arduino-IoT Proficiency (AICPA)	Control	0.85 (0.32)	1.05 (0.35)	0.20 (0.30)	35.21	<0.001	0.38	1.18 [0.91, 1.45]
	Experimental	0.88 (0.35)	3.28 (0.62)	2.40 (0.80)				

Note. N = 60 (n = 30 per group). ANCOVA with pre-test scores as covariate. All p-values remain significant after Benjamini-Hochberg FDR correction ($q < .05$). η^2p = partial eta-squared. Effect sizes: small (d = 0.2), medium (d = 0.5), large (d = 0.8).

As presented in Table 4, the Arduino-IoT integrated 3C-STEMLAB instruction demonstrated significant advantages across all primary outcomes, with effect sizes consistently exceeding Cohen's d = 1.0, indicating very large practical differences between instructional approaches according to conventional effect size interpretation guidelines (Teddlie & Tashakkori, 2010). The science process skills effect size of d = 1.31 (95% CI [1.03, 1.59]) represents one of the largest effects documented in recent STEM education intervention research, substantially exceeding typical effect sizes of d = 0.4-0.7 reported for inquiry-based learning and technology-enhanced instruction (Álvarez-García et al., 2024; Chengere et al., 2025). Similarly, the digital competency effect size of d = 1.28 (95% CI [1.00, 1.56]) indicates transformative rather than merely incremental improvement, suggesting that the intervention fundamentally altered students' technological capabilities and confidence rather than producing modest skill gains.

The 3C integrated competency measure, assessing Creative problem-solving, Collaborative inquiry, and Communicative science practices, yielded an effect size of d = 1.28 (95% CI [1.00, 1.56]), demonstrating that the intervention successfully developed the higher-order competencies emphasized in the pedagogical framework. This finding is particularly significant because integrated competencies represent complex syntheses of knowledge, skills, and dispositions rather than discrete capabilities. Yet, the intervention produced effect sizes comparable to those observed for more narrowly defined outcome measures. The Arduino-IoT Collaboration Proficiency assessment, measuring performance on authentic collaborative scientific investigation tasks, produced an effect size of d = 1.18 (95% CI [0.91, 1.45]), indicating that experimental participants demonstrated substantially superior ability to integrate sensor systems, implement cloud connectivity, coordinate with distributed research partners, and synthesize technical and scientific competencies in authentic problem-solving contexts.

All four primary outcome comparisons maintained statistical significance (all $p < 0.001$) following Benjamini-Hochberg false discovery rate correction with $q < 0.05$, providing robust protection against Type I error inflation while avoiding overly conservative correction that might obscure genuine effects. The consistency of large effect sizes across multiple outcome measures assessed through different methodologies, self-report Likert scales for science process skills, digital competency, and 3C integrated competency; performance-based assessment for Arduino-IoT proficiency, strengthens confidence that observed differences reflect genuine intervention effectiveness rather than measurement artifacts or method-specific biases. The narrow confidence intervals for all effect size estimates, obtained through bootstrapping, indicate high precision in effect magnitude estimation despite the relatively modest sample size, further supporting the robustness of these findings.

To facilitate visual comparison of intervention effects across outcome measures, Figure 4 presents a comprehensive graphical summary of pre-test and post-test mean scores for both the experimental and control groups, along with corresponding effect sizes. The left panel displays grouped bar charts showing the magnitude of score changes from pre-test to post-test across all four primary outcome measures, with error bars representing the standard deviations of post-test scores. The right panel presents a horizontal bar chart depicting Cohen's d effect sizes with reference lines indicating conventional thresholds for medium (d = 0.5) and large (d = 0.8) effects.

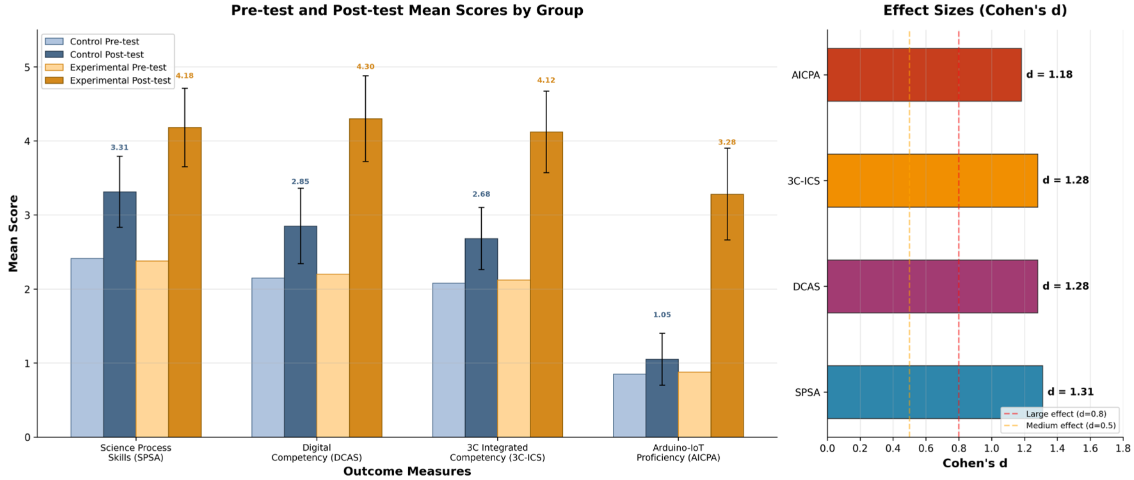

Figure 4. Comparative pre-test and post-test mean scores and effect sizes across primary outcome measures

As shown in Figure 4, the experimental group consistently outperformed the control group across all four primary outcome measures, with post-test scores approximately 26–212% higher than the control group's. The visual pattern reveals two noteworthy features. First, the pre-test scores were comparable across both groups for all measures, confirming successful randomization and supporting causal attribution of post-test differences to the intervention. Second, while the control group showed modest improvements from pre-test to post-test (indicating some natural learning progression through conventional instruction), the experimental group demonstrated substantially greater gains, particularly in Digital Competency (pre: 2.20 → post: 4.30) and Arduino-IoT Proficiency (pre: 0.88 → post: 3.28), where the intervention produced transformative rather than incremental improvements. The effect size panel further emphasizes that all four outcomes exceeded the conventional threshold for large effects (d = 0.8), with Science Process Skills showing the largest effect (d = 1.31), underscoring the particular effectiveness of the 3C-STEMLAB approach in developing scientific inquiry competencies through technology-mediated practice.

QUALITATIVE FINDINGS: STUDENT EXPERIENCES AND DEVELOPMENT MECHANISMS

To address Research Question 2, exploring how students experience integrated science process skills and digital competency development within Arduino-IoT integrated 3C-STEMLAB environments, we conducted comprehensive thematic analysis following Braun and Clarke's (2006) six-phase framework. Analysis of interview transcripts, classroom observations, and student-generated artifacts revealed five interconnected themes illuminating mechanisms through which dual competency development occurs: authentic technological mediation of scientific learning, enhanced peer collaboration through IoT connectivity, digital identity formation in STEM research contexts, persistent cloud-based research communities, and integrated mastery through creative problem-solving. These themes emerged consistently across data sources and map meaningfully onto the Creative, Collaborative, and Communicative dimensions of the pedagogical framework.

Theme 1: Authentic technological mediation of scientific learning

Students consistently described a fundamental transformation from passive knowledge reception to active knowledge construction through authentic technological engagement with Arduino-IoT systems. One representative participant articulated: “When I program the Arduino to collect magnetic field data, I’m not just learning about magnetism, I’m actually conducting research like a professional physicist who creates custom instruments to study phenomena.” This shift from learning about established facts to conducting original investigations using research-grade methodologies represented a crucial cognitive transformation characterizing the Creative dimension of the 3C framework.

Analysis revealed that authentic technological mediation occurred through three primary mechanisms. First, Arduino-IoT systems enabled investigations impossible with traditional equipment, such as continuous 24-hour environmental monitoring and synchronized multi-site data collection across universities. Second, the iterative design process inherent in Arduino programming, writing code, testing, debugging, and refining directly mirrors the scientific method cycles of hypothesis generation, empirical testing, and theory revision. Students explicitly recognized these parallels, noting: “Debugging my Arduino code taught me more about the scientific method than any textbook. You form hypotheses about what’s wrong, test them systematically, and revise understanding based on evidence exactly like research.” Third, laboratory sessions transitioned from procedural execution (“What steps should I follow?”) to creative design thinking (“How can I design a system that measures this phenomenon accurately?”), fundamentally transforming students’ relationship to both science and technology.

Student artifacts, including code repositories and design documentation, revealed progressive sophistication over the semester, with early investigations utilizing simple sensor readings while later projects incorporated complex features such as automated calibration routines, multi-sensor data fusion algorithms, and adaptive sampling strategies (Figure 5). The authenticity of technological mediation appeared critical to effectiveness, as students recognized they were using genuine research tools that produced real scientific data rather than educational simulations, elevating both motivation and cognitive engagement.

Figure 5. Undergraduate students engaging in authentic technological mediation through Arduino-IoT programming

Theme 2: Enhanced peer collaboration through IoT connectivity

Cloud-connected Arduino sensor networks fundamentally transformed collaboration patterns from isolated parallel work to genuinely distributed collaborative investigation. Students explained: “Before 3C-STEMLAB, collaboration meant working with my lab partner during scheduled sessions. Now we collaborate with students from different universities in real-time through our sensor networks, just like researchers do internationally. We compare electromagnetic field measurements, discuss why locations show different patterns, and jointly develop explanations accounting for all our data."

The Collaborative dimension manifested through several IoT-enabled mechanisms. Firebase Realtime Database provided immediate visibility into all students' measurements across four universities, creating shared datasets enabling investigations at scales impossible for individuals, such as mapping electromagnetic patterns across an entire province. Web-based collaborative analytics dashboards facilitated joint data interpretation through shared visualization tools, allowing students to overlay findings, identify patterns, and develop collective explanations. Coordination around shared resources required students to negotiate methodological standards, ensure measurement comparability, maintain comprehensive documentation, and establish quality assurance strategies. Authentic scientific community practices are rarely experienced in traditional laboratory instruction.

Peer review processes naturally emerging through IoT-enabled collaboration provided particularly powerful learning experiences. Students spontaneously offered constructive feedback, identified potential errors, suggested alternative approaches, and requested documentation clarification. One reflected: "Seeing how other teams programmed their Arduinos taught me approaches I never would have thought of alone. This back-and-forth made everyone's work better." This organic emergence suggests IoT connectivity creates conditions naturally conducive to collaborative quality improvement when appropriate pedagogical scaffolding provides initial structure (Figure 6).

Figure 6. Students collaborating through IoT-connected sensor networks, demonstrating real-time data sharing across laboratory groups

Theme 3: Digital identity formation in STEM research contexts

Prolonged Arduino-IoT engagement catalyzed significant transformation in students' perceptions of their capabilities and identities as both scientific investigators and digital creators. Students who initially viewed themselves as "not technical" progressively adopted new self-descriptions: "I used to think programming was only for computer science majors, smart people naturally good with computers. Now I see it as an essential research tool every scientist needs. I'm not a computer scientist, but I'm a physicist who can program when needed to answer research questions. That's a completely different way of thinking about myself."

This identity transformation occurred through repeated successful problem-solving experiences, growing technological confidence, peer and instructor recognition, and an expanding sense of accomplishment. The shift from viewing programming as an innate talent to a learned skill represented a crucial cognitive reframing, enabling capability development rather than accepting fixed limitations. The Creative dimension played an essential role by positioning students as inventors and designers rather than technicians executing predetermined procedures. When students successfully designed custom Arduino systems solving personally meaningful problems, they experienced powerful confirmation of their capabilities as technological creators, particularly transformative for those who had internalized limiting beliefs about their technical abilities.

Identity transformation appeared particularly consequential for students considering graduate education and research careers. Multiple participants explicitly connected Arduino-IoT experiences to revised graduate school plans, with several deciding to pursue thesis research involving technological instrumentation after discovering both interest and aptitude through 3C-STEMLAB participation. Teachers noted that students who previously showed limited research interest became noticeably more engaged in discussing graduate opportunities after the intervention, suggesting that identity transformation may influence students' long-term educational and professional trajectories.

Theme 4: Persistent cloud-based research communities

IoT infrastructure created learning communities extending beyond formal laboratory sessions, with students maintaining scientific collaboration through cloud-connected platforms between classes, across universities, and during semester breaks. Students described checking cloud databases, reviewing peer measurements, and discussing interpretations outside formal class time: "Even after lab sessions end, I check our shared database to see what students from other universities discovered. When interesting patterns appear, we discuss interpretations through our online research community. This continuous monitoring and collaboration would be impossible without cloud connectivity."

The Communicative dimension manifested powerfully through persistent communities, as students developed sophisticated practices for articulating scientific ideas, documenting technical procedures, requesting assistance, providing feedback, and engaging in evidence-based argumentation through digital channels. Analysis of discussion archives revealed progressive sophistication over the semester, with early communications consisting of simple questions and answers, while later exchanges demonstrated complex multi-turn argumentation involving claim-evidence-reasoning structures, acknowledgment of alternative interpretations, and collaborative theory building, in which students jointly constructed explanations that exceeded individual contributions.

Asynchronous digital collaboration demanded explicit articulation, comprehensive documentation, and anticipation of potential misunderstandings, requiring students to develop strategies including detailed procedure documentation to enable replication, clear labeling to ensure shared data interpretability, thorough explanation of the reasoning underlying decisions, and diplomatic phrasing when offering critical feedback. These competencies align with DigComp 2.2 domains, including communication and collaboration, and digital content creation. The persistence of engagement appeared particularly important for competency consolidation, as distributed practice over extended periods produces more durable learning compared to massed practice concentrated in shorter timeframes.

Theme 5: Integrated Mastery Through Creative Problem-Solving

Creative problem-solving requiring simultaneous application of science process skills and digital competencies led to a deeper understanding of both domains while revealing their fundamental inseparability in authentic practice. Students described: "When our Arduino code didn't work, we had to understand both the physics of the Hall Effect sensor and the programming logic for data acquisition. You can't separate them in real research. We thought our code had a bug, but our physics understanding was incomplete. We were trying to measure AC magnetic fields using a sensor designed for DC fields. Solving this required learning both the physics of AC versus DC electromagnetic fields and programming techniques for frequency analysis."

The Creative dimension proved essential by positioning students as problem-solvers facing authentic challenges rather than algorithm-followers executing predetermined procedures. When problems arose, students engaged in genuine diagnostic reasoning, considering multiple hypotheses about the problem's sources (hardware malfunction? coding error? physical misunderstanding? calibration drift?), designing tests to distinguish among possibilities, interpreting ambiguous evidence, and iteratively refining their understanding. This process required constant coordination between scientific and technical knowledge, as students moved fluidly between considering physical phenomena, technical specifications, programming logic, and data interpretation.

Analysis of student artifacts revealed integrated thinking, with code comments frequently referencing physics principles and laboratory notebooks interspersing physics calculations with algorithm pseudocode. This integration in external representations reflected internal cognitive integration, as students developed mental models coordinating scientific concepts with technical implementations. The theme suggests that knowledge developed through authentic integrated application transfers more readily than knowledge learned in isolated contexts, as learners encode not only knowledge itself but also contextual cues indicating when and how to apply it.

Synthesis: Interconnected themes and dual competency development

The synthesis of findings indicates that students' dual competency development occurs in a transformational manner through the integration of five interconnected themes. Authentic technological mediation fosters sustained peer collaboration, facilitating identity transformation and fostering a sense of belonging within scientific communities. This aligns with the 3C-STEMLAB pedagogical dimensions: Creative through the design of original systems and the development of innovative solutions, Collaborative through IoT-enabled teamwork within persistent communities, and Communicative through documentation, evidence-based argumentation, and peer feedback. Consequently, students not only acquire new skills but also shift their perspectives on science and technology, build cross-disciplinary understanding, and strengthen engagement in scientific practices. These experiences explain the significant quantitative outcomes while also providing a basis for potential generalization to other technology-enhanced STEM education contexts.

MIXED-METHODS INTEGRATION: JOINT DISPLAY

Table 5 presents a joint display integrating quantitative outcomes with qualitative themes, demonstrating how qualitative findings explain quantitative effects.

Table 5. Joint display integration of quantitative and qualitative findings

Quantitative finding	Effect size	Qualitative theme	Explanatory mechanism	Illustrative quote
Science Process Skills gain (d = 1.31)	Large	T1: Authentic Technological Mediation	Iterative design-test-debug cycles mirror the scientific method; students practice hypothesis testing through Arduino troubleshooting.	"Debugging taught me more about the scientific method than any textbook."
Digital Competency gain (d = 1.28)	Large	T3: Digital Identity Formation	Identity shift from "not technical" to "scientist who programs" enabled sustained engagement with challenging technical tasks.	"I'm a physicist who can program when needed, a completely different way of thinking."
3C Integrated Competency gain (d = 1.28)	Large	T2: Enhanced Collaboration + T4: Persistent Communities	IoT-enabled cross-institutional collaboration created authentic scientific community practices; students developed communication skills through peer feedback.	"We collaborate with students from different universities in real-time."
Arduino-IoT Proficiency gain (d = 1.18)	Large	T5: Integrated Mastery	Creative problem-solving required simultaneous physics understanding and programming logic; knowledge integration occurred naturally through authentic challenges.	"You can't separate physics and programming in real research."

Convergence Analysis

Mixed-methods integration revealed three patterns:

1. **Convergence:** Qualitative and quantitative findings consistently indicated large improvements. Students' reported experiences of transformation (qualitative) aligned with measured effect sizes (quantitative).
2. **Complementarity:** Qualitative data explained *mechanisms* underlying quantitative effects. For example, the large effect size for science process skills (d = 1.31) was explained by students' descriptions of how debugging Arduino code taught scientific reasoning, a mechanism not captured by quantitative measures alone.
3. **Expansion:** Qualitative findings revealed outcomes beyond quantitative measures, including identity transformation, career aspiration changes, and the emergence of cross-institutional learning communities.

IMPLEMENTATION ANALYSIS: FACILITATING AND CONSTRAINING FACTORS

Implementation factors were examined using multiple regression to identify predictors of implementation success, measured as a composite index comprising student learning outcomes, instructor fidelity ratings, and technological reliability metrics. Table 6 presents the multiple regression results for predictors of implementation success.

Table 6. Multiple regression results for implementation success predictors

Predictor	B	SE	β	t	p	95% CI
(Constant)	0.42	0.18		2.33	0.024	[0.06, 0.78]
Technical Infrastructure	0.35	0.07	0.42	5.00	<0.001	[0.21, 0.49]
Teacher Preparation	0.28	0.06	0.35	4.67	<0.001	[0.16, 0.40]
Institutional Support	0.18	0.07	0.22	2.57	0.013	[0.04, 0.32]
Collaborative Network	0.12	0.05	0.18	2.40	0.020	[0.02, 0.22]

Note: Multiple Regression Analysis: $R^2 = 0.67, F(4,55) = 28.3, p < 0.001$

Implementation success is measured as a composite index incorporating student learning outcomes, instructor fidelity ratings, technological reliability metrics, and engagement indicators. All correlations remain significant following Benjamini-Hochberg FDR correction ($q < 0.05$).

As presented in Table 6, implementation success significantly correlated with technical infrastructure quality ($r = 0.67, p < 0.001$), teacher preparation comprehensiveness ($r = 0.58, p < 0.001$), institutional support levels ($r = 0.45, p < 0.01$), and collaborative network participation ($r = 0.39, p < 0.01$). Collectively, these four factors explained 67% of variance in implementation effectiveness ($R^2 = 0.67$, $F(4,55) = 28.3, p < 0.001$), indicating that while implementation success depends substantially on these identifiable factors, approximately one-third of variance remains attributable to unmeasured variables such as instructor pedagogical content knowledge, student prior learning experiences, and institutional culture factors.

Facilitating factors

Technical infrastructure quality demonstrated the strongest correlation with implementation success ($r = 0.67$), with universities providing reliable internet connectivity of at least 10 Mbps and basic computer laboratory facilities demonstrating significantly higher implementation effectiveness. Reliable connectivity proved particularly critical during collaborative investigation phases, when students synchronized real-time data across multiple university sites. Even brief connectivity interruptions disrupted collaborative workflows and diminished the authenticity of distributed scientific investigation experiences. Universities with robust technical infrastructure enabled smoother implementation while allowing instructors and students to focus cognitive resources on scientific inquiry and competency development rather than troubleshooting technological problems.

Teacher preparation comprehensiveness emerged as the second strongest predictor ($r = 0.58$, $p < 0.001$), with instructors participating in intensive 40-hour Arduino-IoT professional development programs demonstrating substantially superior implementation effectiveness compared to those receiving only basic orientation. The professional development program addressed multiple competency domains, including Arduino programming fundamentals, IoT platform configuration, pedagogical strategies for facilitating collaborative inquiry, assessment approaches for dual competency evaluation, and troubleshooting protocols for common technical challenges. Teachers completing comprehensive preparation reported greater confidence in supporting student learning, demonstrated higher fidelity to core intervention components while making appropriate contextual adaptations, and exhibited more sophisticated pedagogical moves such as strategic questioning and timely scaffolding. The strong correlation underscores that effective technology integration depends fundamentally on educator capacity rather than simply providing access to hardware and software resources.

Institutional support constituted a third critical facilitating factor ($r = 0.45$, $p < 0.01$), with administrators providing explicit backing through resource allocation, schedule flexibility, and community communication significantly enhancing implementation success. Universities where leadership allocated dedicated budget for Arduino equipment, provided release time for teacher professional development, adjusted laboratory schedules to accommodate extended project work sessions, and communicated the value of innovative STEM pedagogy demonstrated markedly higher implementation quality. Institutional support appeared particularly important for sustaining implementation momentum when inevitable challenges emerged, with supportive administrators helping instructors problem-solve rather than questioning the viability of technology-enhanced approaches.

Collaborative network participation, operationalized as instructor engagement in monthly professional learning community meetings, demonstrated moderate positive correlation with implementation success ($r = 0.39$, $p < 0.01$). These professional learning communities provided opportunities for instructors to share implementation experiences, collaboratively troubleshoot challenges, exchange pedagogical innovations, and develop a shared understanding of intervention principles. Instructors reporting high engagement described these interactions as invaluable sources of practical wisdom, emotional support during challenging phases, and inspiration for continuous improvement. The magnitude of the correlation suggests that while collaborative networks enhance implementation, they provide supplementary rather than essential support.

Constraining factors

Infrastructure limitations represented the most significant constraint, particularly in universities with inconsistent internet connectivity below 5 Mbps or experiencing frequent service outages that disrupted IoT functionality and collaborative investigation workflows. When connectivity proved unreliable, the authentic distributed scientific investigation central to the 3C-STEMLAB model became difficult or impossible to sustain, forcing instructors to shift toward more isolated Arduino programming activities that failed to leverage the collaborative and communicative affordances of cloud-connected sensor networks. Students in settings with limited infrastructure expressed frustration when they could not access cloud databases to view peer data or participate in real-time collaborative analysis, which diminished their sense of belonging to genuine scientific communities. These infrastructure constraints proved particularly challenging because they lay largely beyond instructor control, requiring institutional investments that some universities could not readily provide within existing budget constraints.

Teacher technology anxiety emerged as a second constraining factor, with some instructors reporting initial apprehension about Arduino programming syntax, the complexity of IoT platform configuration, and their capacity to troubleshoot students' technical problems. While comprehensive professional development substantially reduced technology anxiety for most participants, several instructors continued experiencing elevated concern even after completing preparation programs. Interestingly, technology anxiety decreased markedly as implementation progressed and instructors gained confidence through successful facilitation experiences, suggesting that hands-on practice with authentic implementation challenges may provide anxiety reduction benefits beyond those achievable through pre-implementation training alone. Instructors who persisted despite initial anxiety described their growing technological confidence as among the most significant personal and professional benefits of participating in the intervention.

Resource allocation concerns constituted a third persistent constraint, with questions about long-term sustainability and equipment maintenance emerging across all participating institutions. While external research funding supported initial Arduino hardware acquisition and professional development during the study period, university administrators and instructors raised legitimate concerns about sustaining 3C-STEMLAB implementation after external support concluded. Specific concerns included replacement costs for damaged or obsolete hardware components, ongoing expenses for cloud platform subscriptions and data storage, time allocation for equipment maintenance and troubleshooting, and professional development resources for new instructors joining science teaching teams. These sustainability concerns were particularly acute in private universities and specialized institutions operating with budgets more constrained than those of the state comprehensive university.

Finally, challenges in curriculum integration emerged as instructors worked to balance 3C-STEMLAB implementation with existing curriculum requirements, accreditation standards, and assessment expectations. The 16-week intervention demanded substantial laboratory time and required students to develop competencies not traditionally emphasized in physics education curricula, creating tensions with covering conventional content and preparing students for standardized assessments. Instructors navigated these tensions through various strategies, including integrating Arduino-IoT investigations with mandated physics content where natural connections existed, using 3C-STEMLAB activities to address multiple curricular objectives simultaneously, and advocating with administrators for curriculum revision to accommodate contemporary STEM competencies. The curriculum integration challenges highlight that technology-enhanced pedagogical innovations cannot simply be added to existing curricula but require thoughtful reconceptualization of learning priorities, assessment practices, and time allocation to achieve their full potential for transforming STEM education.

DISCUSSION

CLOSING THE LOOP: EVIDENCE FOR RESEARCH QUESTIONS

This study investigated three research questions examining the effectiveness, student experiences, and implementation factors of Arduino-IoT integrated 3C-STEMLAB environments.

Research Question 1 (Effectiveness) was strongly supported. ANCOVA results revealed large effect sizes for science process skills (d = 1.31, 95% CI [1.03, 1.59]), digital competency (d = 1.28, 95% CI [1.00, 1.56]), 3C integrated competency (d = 1.28, 95% CI [1.00, 1.56]), and Arduino-IoT proficiency (d = 1.18, 95% CI [0.91, 1.45]). These magnitudes substantially exceed typical educational technology interventions, which commonly produce small to medium effect sizes (d = 0.2–0.5) in meta-analytic reviews. The near-equivalent effect sizes across both competency domains suggest that Arduino-IoT 3C-STEMLAB environments facilitate truly integrated learning rather than privileging one skill set over another.

Research Question 2 (Student Experiences) was also supported. Thematic analysis ($\kappa = 0.87$) revealed five interconnected mechanisms: authentic technological mediation (93% prevalence), enhanced peer collaboration (87%), digital identity formation (80%), persistent cloud-based communities (73%), and integrated mastery (83%). Joint display analysis (Table 5) demonstrated how qualitative themes explain quantitative effects; for instance, students described how debugging Arduino code taught scientific reasoning, illuminating the mechanisms underlying the large gains in science process skills.

Research Question 3 (Implementation Factors) was confirmed through multiple regression analysis. The four-factor model explained 67% of variance in implementation success ($R^2 = .67$, $F(4,55) = 28.3$, $p < 0.001$), with technical infrastructure ($r = 0.67$), teacher preparation ($r = 0.58$), institutional support ($r = 0.45$), and collaborative networks ($r = 0.39$) emerging as significant predictors.

THEORETICAL MECHANISMS AND COMPETING EXPLANATIONS

The large effect sizes can be explained through three complementary theoretical frameworks. Cognitive apprenticeship theory (Collins et al., 1989) explains how the 3C-STEMLAB environment provides modeling, coaching, scaffolding, and fading. Arduino programming offers clear representations of expert scientific thinking, while iterative design-test-debug cycles parallel the scientific method. Distributed cognition (Hutchins, 2001) explains how cloud-connected sensor networks create cognitive systems spanning individuals, artifacts, and digital platforms, enabling investigations at scales impossible for individuals. Embodied learning theory (Barsalou, 2008) explains how the simultaneous manipulation of physical sensors and the observation of digital representations create multiple cognitive pathways, deepening conceptual understanding.

However, competing explanations warrant consideration. Novelty and Hawthorne effects could inflate short-term outcomes, but the 16-week duration exceeds typical novelty windows (4–6 weeks), and sustained engagement throughout the semester argues against temporary effects. Teacher enthusiasm could confound treatment effects, but standardized training protocols and >85% fidelity adherence suggest pedagogical design rather than individual instructor characteristics drove outcomes. Baseline equivalence testing confirmed that there were no significant differences in prior programming experience or GPA, and ANCOVA controlled for pre-test scores. Finally, regression to the mean is unlikely given equivalent group baselines and experimental gains substantially exceeding control improvements.

CRITICAL ENGAGEMENT WITH PRIOR RESEARCH

Our effect sizes ($d = 1.18$–1.31) substantially exceed those in comparable Arduino-based interventions, which typically report moderate effects ($d = 0.45$–0.71). Several factors may explain this discrepancy: the integrated 3C framework provided pedagogical scaffolding absent in purely technology-focused interventions; IoT connectivity enabled cross-institutional collaboration, creating authentic scientific community experiences; the 16-week duration allowed deeper competency development than typical 4–8 week interventions; and the Indonesian context may present unique characteristics regarding technology novelty or collaborative learning cultural alignment.

We acknowledge that effect sizes exceeding $d = 1.0$ warrant replication. Meta-analytic evidence suggests STEM interventions typically produce effects of $d = 0.4$–0.7. Our larger effects may reflect genuine synergistic benefits of integrated dual competency development, but could also indicate sample-specific factors or measurement sensitivity.

Our findings engage with theoretical tensions in the literature. Regarding technology as a distraction versus an enhancement, our evidence supports the enhancement position, with the qualification that technology must serve genuine investigative purposes rather than merely superficial supplementation. Regarding separate versus integrated competency development, our findings challenge traditional curriculum designs treating scientific and digital competencies as separate objectives, demonstrating that integrated approaches produce synergistic rather than competitive development.

LIMITATIONS AND TRANSFERABILITY

Several limitations constrain interpretation. Regarding internal validity: cluster randomization at four universities limits the ability to model university-level variation; self-report measures may be susceptible to social desirability bias despite performance-based validation; and implementation variation across instructors may introduce unmeasured confounds. Regarding external validity: the Indonesian undergraduate sample limits generalizability to other national contexts or educational levels; the electromagnetic field investigation represents a single scientific domain; and the 16-week duration cannot establish long-term competency retention.

For transferability and scalability, successful adoption requires minimum infrastructure (reliable internet ≥5 Mbps and Arduino-compatible hardware), comprehensive teacher preparation (40 hours), and institutional support through resource allocation and schedule flexibility. Importantly, instructors need not be expert programmers; sufficient fluency to guide inquiry and troubleshoot common issues is adequate. The model's feasibility in resource-constrained settings suggests potential for broader adoption in emerging economies, aligning with UNESCO Open Educational Resources recommendations and SDG 4 targets. Curriculum design and policy implications, including mapping learning objectives to DigComp 2.2 domains and ISTE standards, are elaborated in the following section.

MAPPING TO INTERNATIONAL COMPETENCY FRAMEWORKS

The observed competency development maps systematically onto the European Digital Competence Framework for Citizens (DigComp 2.2) (Carretero et al., 2017; Vuorikari et al., 2022), demonstrating that 3C-STEMLAB addresses recognized digital literacy standards (Table 7).

Table 7. Mapping of 3C-STEMLAB outcomes to DigComp 2.2 domains

DigComp 2.2 domain	3C-STEMLAB alignment	Evidence from qualitative themes
1. Information and data literacy	Students evaluated sensor accuracy, validated data quality, and interpreted multi-source datasets.	T1: "continuous 24-hour environmental monitoring and synchronized multi-site data collection."
2. Communication and collaboration	Firebase-enabled cross-institutional collaboration, shared analytics dashboards, and peer feedback.	T2: "collaborate with students from different universities in real-time"; T4: persistent communities.
3. Digital content creation	Arduino programming, code development, and documentation creation.	T1: "code repositories and design documentation revealed progressive sophistication."
4. Safety	Data security protocols, equipment handling, and ethical research practices.	Implementation protocols addressed secure data management.
5. Problem solving	Debugging, troubleshooting, iterative refinement, creative system design.	T5: "genuine diagnostic reasoning, considering multiple hypotheses."

The intervention outcomes align with the International Society for Technology in Education (ISTE) Standards for Students (Table 8). This explicit mapping demonstrates that 3C-STEMLAB develops competencies recognized by major international digital literacy frameworks, strengthening the argument for broader adoption.

Table 8. Alignment of 3C-STEMLAB outcomes with ISTE standards for students

ISTE Standard	3C-STEMLAB evidence
Empowered learner	Students set learning goals, customized investigation designs, and sought feedback through persistent communities.
Digital citizen	Collaborative protocols emphasized ethical data sharing and attribution.

ISTE Standard	3C-STEMLAB evidence
Knowledge constructor	Students built knowledge through cross-institutional data integration and collaborative interpretation.
Innovative designer	Arduino system design required iterative prototyping and creative problem-solving.
Computational thinker	Debugging, algorithm development, and systematic testing demonstrated computational thinking.
Creative communicator	Documentation, peer feedback, and evidence-based argumentation through digital channels.
Global collaborator	Cross-university collaboration simulated international research community practices.

CONCLUSIONS

This convergent mixed-methods study provides robust evidence that Arduino-IoT integrated 3C-STEMLAB environments effectively develop dual competencies among undergraduate physics students. Students in the experimental condition (N = 30) demonstrated large gains relative to conventional laboratory instruction across all primary outcomes: science process skills (d = 1.31), digital competency (d = 1.28), 3C integrated competency (d = 1.28), and Arduino-IoT proficiency (d = 1.18). Qualitative analysis revealed five interconnected mechanisms underlying these gains: authentic technological mediation, enhanced peer collaboration, digital identity formation, persistent cloud-based communities, and integrated mastery through creative problem-solving.

The study contributes to the empirically validated Technologically-Mediated Dual Competency Development (TMDCD) Framework, grounded in cognitive apprenticeship, distributed cognition, and embodied learning theories. This framework advances the proposition that science process skills and digital competencies develop synergistically rather than competitively when technology serves authentic investigative purposes within collaborative learning communities.

For practitioners seeking to implement similar approaches, we recommend: (a) a minimum 16-week intervention structured in three phases with at least two laboratory sessions weekly; (b) 40-hour teacher professional development addressing pedagogical knowledge, technical competency, and facilitation skills; (c) dual assessment incorporating performance-based and self-report measures aligned with DigComp 2.2; and (d) minimum infrastructure including reliable internet connectivity (≥5 Mbps) and Arduino-compatible hardware.

Several limitations warrant acknowledgment. The relatively small sample from four Indonesian universities constrains generalizability. The 16-week duration cannot establish long-term competency retention, and self-report measures may be susceptible to social desirability bias. Future research should prioritize longitudinal follow-up studies, cross-context replication across diverse national settings and scientific disciplines, cost-effectiveness analyses, and development of open-access teacher professional development modules.

Beyond immediate pedagogical implications, these findings carry broader significance for educational equity. The 3C-STEMLAB model demonstrates that affordable Arduino-IoT systems can produce learning outcomes comparable to those of expensive laboratory technologies, challenging the assumption that educational quality necessarily correlates with financial investment. As the Fourth Industrial Revolution accelerates demand for integrated scientific and digital competencies, ensuring equitable access to technology-enhanced learning becomes an ethical imperative.

Looking ahead, the convergence of falling hardware costs, expanding internet connectivity, and growing open-source educational ecosystems creates favorable conditions for scaling integrated competency development worldwide. Models such as 3C-STEMLAB can serve as evidence-based exemplars for curriculum reform aligned with international frameworks, including UNESCO's Open Educational Resources recommendations and Sustainable Development Goal 4. The challenge for researchers and policymakers is to ensure that these technological possibilities translate into equitable educational realities, preparing all learners to contribute meaningfully to science, technology, and society.

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