



ARDUINO-SUPPORTED STEM LEARNING IN PHYSICS TEACHER EDUCATION: DEVELOPMENT OF PROFESSIONAL COMPETENCIES

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ABSTRACT

This study examines Arduino-supported STEM education as a pedagogical approach for developing selected professional competencies of future physics teachers and explores its relevance to technology-enhanced physics teacher education. A two-phase quantitative design combined a systematic review and meta-analysis with an empirical comparative study. Eighteen empirical studies from Web of Science, Scopus, and Google Scholar were synthesized using standardized mean differences in Comprehensive Meta-Analysis 4.0. The empirical phase involved 60 future physics teachers in three Arduino-supported formats: Project-Based Learning, Inquiry/Research-Based Learning, and Laboratory/Experimental Learning. Professional competence was assessed across research competence, engineering and design thinking, practical action skills, and theory–practice connection. Group differences were analyzed using Jamovi and Welch's ANOVA. The meta-analysis showed a positive overall effect of Arduino-supported interventions, with variation across educational contexts. In the empirical phase, the Project-Based Learning group obtained the highest professional-competency scores. Meta-regression showed that instructional format did not significantly moderate the overall effect. Arduino-supported STEM activities may provide a useful context for linking physics concepts with inquiry, engineering design, experimentation, and practical problem solving. The empirical findings are limited to the four assessed competency dimensions and the specific study context. Further research with validated instruments, stronger designs, and broader samples is needed. The study also presents a wind-energy instructional model that integrates Arduino technology, experimental physics, and engineering-oriented STEM activities for future physics teacher preparation.

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Keywords: STEM education; Arduino technology; future physics teachers; professional competence; project-based learning; meta-analysis

INTRODUCTION

The rapid advancement of digital technologies, artificial intelligence, and engineering innovations is reshaping the competencies required in contemporary teacher education. Preparing future physics teachers therefore involves not only disciplinary knowledge but also research, engineering, digital, and problem-solving competencies

that support technology-enhanced teaching and learning. This educational direction is broadly consistent with Sustainable Development Goal 4 (Quality Education), particularly its emphasis on improving the quality of education and strengthening teacher preparation. It can also be viewed as aligning with the innovation-oriented dimensions of SDG 9 (Industry, Innovation and Infrastructure), especially those related to technological development, research, innovation, and digital connectivity, rather than as a direct contribution

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to the goal itself. In this context, strengthening future physics teachers' capacity to use digital and engineering technologies is an important dimension of contemporary, technology-enhanced teacher education (Miao & Cukurova, 2024).

Recent educational reforms emphasize that future teachers should have interdisciplinary competencies that integrate scientific inquiry, engineering design, computational thinking, programming, and experimental practice. Within this context, STEM education has become one of the most effective approaches for developing creativity, critical thinking, collaboration, and innovation among future teachers. Moreover, the increasing integration of artificial intelligence into education further highlights the importance of strengthening digital literacy alongside professional teaching competencies (Abdulayeva et al., 2025).

Among the technologies supporting STEM-oriented physics education, the Arduino open-source microcontroller platform has attracted considerable attention because it enables students to design interactive experiments, collect real-time data, automate measurements, and develop engineering projects. These activities effectively connect theoretical physics concepts with authentic engineering practice. Previous studies show that Arduino improves laboratory instruction, boosts students' motivation to learn, and increases the accuracy of computer-controlled experiments (Akimkhanova et al., 2020). It has also been successfully applied to develop engineering skills and interdisciplinary learning among future teachers (Aliksieieva & Babych, 2018).

A growing body of research has confirmed the educational value of Arduino-supported STEM learning. Anisimova et al. (2020) reported significant improvements in future teachers' research and project-design competencies through STEM and STEAM activities, whereas Gör-gülü Arı & Meço (2021) demonstrated positive effects on creativity, programming ability, and engineering thinking. Likewise, Arduino-based laboratory activities improve conceptual understanding through automated data acquisition and real-time visualization (Chaudry, 2020; Buj & Revuelta, 2021). Arduino-based physical computing approaches also contribute to students' coding literacy and computational thinking (Chung & Lou, 2021). Furthermore, a recent meta-analysis by Jang (2024) confirmed that Arduino-based educational programs produce significant positive effects on academic achievement, motivation, and learning engagement. Likewise, Pacala et al. (2025) reported that Arduino-based STEM edu-

cation effectively supports teachers' professional development, although evidence related to pre-service physics teachers remains limited. In Kazakhstan, Abdrakhmanova et al. (2025) emphasized the importance of integrating innovative STEM technologies into teacher education, while Polatuly et al. (2026) demonstrated that Arduino effectively supports experimental learning and practical verification of theoretical physics concepts.

Despite these advances, several important research gaps remain. First, previous studies have mainly focused on isolated outcomes such as academic achievement, programming literacy, engineering skills, or learning motivation. Second, most empirical research has focused on school students or engineering undergraduates, while relatively little attention has been devoted to the professional preparation of future physics teachers (Ojeogwu & Mumba, 2026). Third, existing studies rarely evaluate the integrated development of professional competencies that combine pedagogical knowledge, experimental competence, engineering thinking, and digital literacy. Similarly, Rehman et al. (2025) reported that STEM teacher professional development research has primarily focused on technological knowledge and instructional practices, with limited attention to integrated competency development. In addition, empirical evidence regarding Arduino-supported STEM education in the context of physics teacher preparation in Kazakhstan remains limited.

To address these gaps, this study proposes an Arduino-supported STEM instructional model specifically designed for future physics teachers. Unlike previous research that primarily examined individual educational outcomes, the proposed approach integrates inquiry-based learning, engineering design, programming, digital technologies, and collaborative problem-solving into a unified competency-oriented instructional framework.

This study's novelty lies in developing and empirically examining an Arduino-supported STEM learning model designed to integrate research, engineering, practical, and theory-practice competencies in future physics teacher education. By combining a systematic literature review, meta-analysis, and an empirical comparative study, the research brings together broader evidence on Arduino-supported STEM learning with findings obtained from a specific physics teacher education context. The broader relevance of the study is supported by meta-analytic evidence showing positive outcomes of Arduino-supported STEM learning across a range of educational contexts,

although effect sizes varied among studies. These findings suggest that the instructional challenges addressed in this study—connecting physics concepts with inquiry, engineering design, experimentation, and practical problem solving—are not specific to Kazakhstan but are also relevant to broader discussions in physics and STEM teacher education internationally. At the same time, the empirical component was conducted within a single national and institutional context, and its findings should therefore not be generalized directly to other teacher-education systems. Rather, the proposed Arduino-supported STEM model may be considered a context-specific example with potential relevance for similar physics teacher education settings, subject to further validation across different countries, curricula, and institutional contexts.

Accordingly, this study aims to examine the educational outcomes associated with Arduino-supported STEM learning in preparing future physics teachers and to compare professional competency scores across Project-Based Learning, Inquiry/Research-Based Learning, and Laboratory/Experimental Learning formats. In addition, the study investigates whether instructional format contributes to variation in the effectiveness of Arduino-supported STEM interventions and considers the potential relevance of this approach for technology-enhanced physics teacher education beyond the specific national context in which the empirical study was conducted.

In recent years, pedagogical research has widely discussed using Arduino technology in STEM education. In particular, the educational potential of the Arduino platform has been demonstrated in developing programming skills, computational thinking, and interdisciplinary connections. Marín-Marín et al. (2024) conducted a systematic review of studies focused on developing programming and computational thinking through Arduino at the secondary education level and found that this technology enhances students' algorithmic thinking, problem-solving abilities, and digital literacy.

One key direction in STEM education is interdisciplinary integration. In a study with pre-service chemistry teachers, Morais et al. (2025) found that STEM-based instruction strengthens connections among physics, chemistry, and technology, fostering integrated thinking among future educators. These findings indicate that using the Arduino platform in a STEM environment can also help develop interdisciplinary competencies among future physics teachers.

Studies in biology education have also observed the effectiveness of Arduino technology in teacher education. Nawawi & Dafrita (2022) note that STEM learning materials integrated with Arduino deepen future biology teachers' scientific understanding and develop their experimental and research skills. This conclusion demonstrates the potential of Arduino-based STEM materials as a universal pedagogical tool.

Project-based programming activities in STEM education significantly influence students' motivation to learn. Nurbekova et al. (2020) showed that learning programming through project-based learning increases students' interest and promotes the development of self-directed learning skills. In this regard, the Arduino platform is considered an effective tool for implementing such project-based tasks.

STEM education's motivational potential has also been demonstrated in short-term educational programs. Md Rashid et al. (2026) investigated the outcomes of a short-term STEAM festival designed for female students and found that participation in practical, creative, and collaborative activities significantly improved students' attitudes toward STEM subjects and increased their motivation to learn. Their findings further indicate that STEM activities enhance students' confidence in engaging with technological and engineering tasks. Likewise, Arduino-based short-term projects and practical workshops may foster professional interest and positive attitudes toward STEM teaching among future physics teachers.

Recent studies also highlight the role of Arduino-based STEM programs in developing social and communication skills. Oh (2025) showed that a STEM program using Arduino contributes to students' collaborative problem-solving, teamwork, and cooperation skills. These findings are particularly relevant for fostering soft skills, which are essential for future teachers' professional activities.

STEM project-based learning has also proven effective in improving students' problem-solving abilities and digital literacy. Serevina et al. (2026) investigated the implementation of STEM project-based learning in teaching circular motion and reported significant improvements in students' problem-solving performance and their ability to utilize digital data effectively. Their findings suggest that solving authentic physics problems through project design, measurement, and mathematical analysis facilitates deeper conceptual understanding. This evidence supports using Arduino sensors to measure motion parameters,

collect experimental data, and perform mathematical analyses to strengthen future physics teachers' experimental and analytical competencies.

Analyzing modern trends in physics education, Prahani et al. (2025) emphasize the importance of technology-based instruction in developing 21st-century skills. The researchers note that digital and engineering platforms such as Arduino enable innovative teaching methods in physics education and help enhance the professional competencies of future teachers.

The contribution of digitally integrated project-based physics resources to sustainable development has also attracted increasing scholarly attention. Khaeruddin et al. (2025) demonstrated that contextual project-based physics resources integrated with digital technologies enhance students' critical thinking skills while supporting Sustainable Development Goal 4 (Quality Education). Such resources encourage students to solve authentic real-world problems using physics principles, thereby strengthening their ability to apply scientific knowledge and make evidence-based decisions. Similarly, Arduino-supported STEM instruction can promote sustainable physics education through contextualized and project-based learning activities.

The relationship between STEM education and the Sustainable Development Goals has also been explored through integrating local knowledge and cultural contexts. In their systematic review, Rosyidah et al. (2025) concluded that combining indigenous knowledge with STEM education enhances students' scientific literacy, environmental responsibility, and understanding of sustainable development issues. The authors emphasized that such integration contributes directly to achieving SDG 4. To prepare future physics teachers, Arduino projects addressing local challenges such as energy conservation, environmental monitoring, efficient water resource management, and air quality measurement may further strengthen the social and sustainability dimensions of STEM education.

In addition, artificial intelligence tools in physics education have become increasingly relevant. Anbu (2025) highlights that integrating digital and intelligent tools into physics teaching expands teachers' professional capabilities. In this context, the Arduino platform can serve as a tool that works effectively alongside other digital technologies used in STEM environments.

The importance of the maker education approach in teacher training is also increasing. Quintana-Ordorika et al. (2024) found that implementing maker pedagogy increases future

teachers' motivation and improves their level of technology acceptance. As a key element of the maker environment, the Arduino platform enables practical and creative learning activities.

Technology-integrated models based on project-based learning also play an important role in future teachers' professional preparation. A systematic review conducted by Rahmawati et al. (2020) demonstrated that technology-integrated project-based learning enhances professional competencies, research skills, and reflective abilities among future educators. The Arduino platform is an appropriate tool for implementing project-based learning in the STEM context.

Salazar (2023) also emphasizes the effectiveness of using Arduino technology in developing STEM competencies. The study shows that open-source hardware and software tools based on Arduino contribute to the comprehensive development of students' STEM competencies. This highlights the scientifically grounded need to systematically integrate Arduino technology into the professional training of future physics teachers.

Overall, the reviewed literature demonstrates that Arduino-supported STEM education contributes to the development of computational thinking, programming skills, learning motivation, inquiry competencies, engineering design skills, problem-solving abilities, digital literacy, collaboration, and critical thinking. These approaches have also been shown to support teacher education, maker education, interdisciplinary integration, and progress toward the Sustainable Development Goals.

Although previous studies generally report positive outcomes associated with Arduino-supported STEM learning, the magnitude of these outcomes varies considerably across educational settings, student populations, and instructional designs. One factor that remains insufficiently understood is how instructional format explains this variation. Arduino has been implemented through project-based, inquiry-oriented, laboratory-based, robotics, maker, and other hands-on approaches; however, existing studies have typically examined these formats separately rather than comparing their outcome patterns within a common analytical framework.

This limitation is particularly evident in physics teacher education. While previous research has shown the potential of Arduino-supported activities to develop programming, problem-solving, engineering, experimental, and computational skills, limited empirical evidence directly compares Project-Based Learning, Inqui-

ry/Research-Based Learning, and Laboratory/Experimental Learning among future physics teachers. Consequently, it remains unclear whether instructional format systematically contributes to differences in outcomes in Arduino-supported STEM learning or whether positive effects are observed across formats.

Addressing this gap requires both a broader synthesis of existing evidence and a focused comparison within physics teacher education. Therefore, the present study first examines the overall effect of Arduino-supported STEM learning and tests instructional format as a potential moderator through meta-regression. It then compares professional competency scores among future physics teachers participating in Project-Based Learning, Inquiry/Research-Based Learning, and Laboratory/Experimental Learning formats. This approach provides a direct transition from the identified gap to the study's research questions.

In the present study, professional competence is operationally defined through four dimensions that can be directly assessed within Arduino-supported STEM activities: (1) research competence, including the ability to formulate research questions, plan experiments, and interpret data; (2) engineering and design thinking, including the ability to construct and evaluate Arduino-based solutions; (3) practical action skills related to the use of sensors, tools, and experimental procedures; and (4) theory–practice connection, referring to the ability to apply and explain physics concepts in practical STEM tasks. Programming and digital technologies are instructional resources that support these competencies, not separate outcome variables. Similarly, sustainability is treated as a broader educational context and potential implication rather than a directly measured competency.

Accordingly, this study addresses the following research questions: (1) What is the overall effect of Arduino-supported STEM learning on students' learning and competency outcomes? (2) Does instructional format moderate the effectiveness of Arduino-supported STEM learning? (3) Do professional competency scores differ among future physics teachers across PjBL, Inquiry-Based, and Laboratory-Based learning formats?

METHODS

The study employed a two-phase quantitative research design. Phase 1 involved a systematic literature review and meta-analysis conducted in accordance with PRISMA 2020 to synthesize

empirical evidence on Arduino-supported educational interventions (Page et al., 2021). Phase 2 consisted of an empirical comparative study involving future physics teachers exposed to three Arduino-supported STEM instructional formats: Project-Based Learning, Inquiry/Research-Based Learning, and Laboratory/Experimental Learning. The two phases complemented each other: the meta-analysis provided a broader evidence base, while the empirical phase examined instructional-format differences within the specific context of physics teacher education.

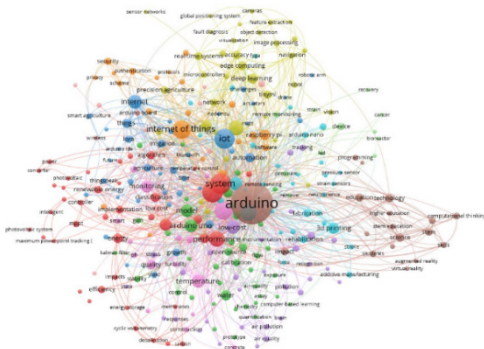
A systematic literature review formed the study's theoretical and methodological basis and identified the pedagogical potential of Arduino-supported STEM project-based learning in training future teachers. The international databases Scopus, Web of Science, and Google Scholar were used to search for scientific publications. The search process included scientific works published between 2016 and 2026.

To identify publications in accordance with the research topic, the following keywords in English were used: “STEM education”, “Arduino”, “physics education”, “pre-service physics teachers”, “professional competence”, “project-based learning”, “engineering competence”, “experimental skills”, and “meta-analysis”. To make the search results more specific, these terms were combined in various combinations using Boolean operators. As an example of the main search query, the combination (“Arduino” AND “STEM education”) AND (“pre-service teacher” OR “physics teacher”) AND (“professional competence” OR “experimental skills”) was used.

A primary bibliographic search was conducted using Scopus and Web of Science databases. Google Scholar was used to identify additional research papers, find full-text publications, and perform a reverse search of the reference lists of selected articles. This search strategy allowed us to systematically identify research papers directly related to the use of Arduino technology in STEM education, the development of professional competence of future physics teachers, and the effectiveness of project-based learning.

Studies for inclusion in the meta-analysis were selected according to predefined inclusion and exclusion criteria. The selection process considered experimental or quasi-experimental studies using Arduino or similar microcontroller platforms, STEM or STEAM, project-based, research-based, and engineering learning. In addition, studies had to provide statistical indicators (mean, standard deviation, and number of participants) needed to calculate effect size and

The VOSviewer analysis does not replace the systematic review's main selection procedure. It was used as an additional bibliometric method to demonstrate the thematic structure of the literature (Figure 1).



To compare the results of studies, the standardized mean difference (Cohen's d) was calculated using Equation (1):

Standard Error (SE) indicates how accurately the sample mean (Mean) estimates the true

population mean. The Shapiro–Wilk normality test examines whether the data follow a normal distribution. This test is a necessary prerequisite for applying parametric statistical methods (ANOVA). In this study, the test was conducted to determine the distribution characteristics of the professional competency indicators of future physics teachers.

The Welch one-way analysis of variance (Welch ANOVA) is a parametric method used to compare the mean values of three or more independent groups.

The empirical phase was conducted at Akhmet Yassawi University during the 2025–2026 academic year. The study included 60 undergraduate students enrolled in the Physics Teacher Education program. Participants were third-year students with a mean age of 19 years. Participants were recruited using convenience

sampling from students enrolled in the relevant course during the study period. All eligible students were informed about the study's purpose and procedures and were invited to participate.

RESULTS AND DISCUSSION

Table 1 systematizes and presents learning- and competency-related outcomes associated with Arduino-supported educational interventions for future physics teachers in the STEM education process.

These studies examine the implementation of Arduino-based project-based and inquiry-oriented learning strategies, the application of interdisciplinary STEM integration approaches, and practices that combine digital, engineering, and programming technologies with pedagogical practice.

Table 1. Results of the Content Analysis of Scientific Research

Title of the article	Results	Title of the publication and publication date
Effects of a block-based Arduino robotics course on computational thinking skills and STEM career interests of Vietnamese students.	Students who completed the Arduino robotics course showed significant improvement in components of computational thinking, such as algorithmic thinking, problem modeling, and logical decision-making (Dat et al., 2025).	Eurasia Journal of Mathematics, Science and Technology Education, 21(6). (2025)
A meta-analysis of the effects of Arduino-based education in Korean primary and secondary schools in engineering education.	Educational programs using Arduino technology showed a moderate positive effect on students' academic achievement and engineering thinking abilities (E. Lee, 2020).	European Journal of Educational Research (2020)
Effects of STEM-focused Arduino practical activities on problem-solving and entrepreneurship skills.	Project-based tasks implemented through Arduino were shown to enhance students' analytical thinking, practical decision-making abilities, and innovative initiatives (Sari et al., 2022).	Australasian Journal of Educational Technology (2022)
A new application in biology education: Development and implementation of Arduino-supported STEM activities.	Practical activities based on Arduino technology demonstrated the potential to effectively link theoretical knowledge with practical application (Görgülü Arı & Meço, 2021).	Biology (2021)
Arduino-based fine particulate matter STEM program: Enhancing problem-solving and collaboration in a post-pandemic blended high school setting.	Arduino technology was found to strengthen students' collaboration skills and practical research culture (Oh, 2025).	Frontiers in Psychology (2025)
Impact of Arduino-Based STEM Education on Cognitive Domain Level of Mechanics and Scientific Creativity.	Arduino enables the simultaneous development of content knowledge and creative competencies in physics education (Çoban & Erol, 2025).	LUMAT (2025)
STEM Teaching Materials Integrated With Arduino Science Journal For Biology Prospective Teachers.	STEM learning materials integrated with Arduino increased students' research engagement and facilitated the integration of subject knowledge with practical activities (Nawawi & Dafrita, 2022).	JURNAL PENDIDIKAN SAINS (JPS), (2022)

The Effect of Arduino-Based E-STEM Education on Students' Entrepreneurial Skills and STEM Attitudes.	Using Arduino in STEM environments contributes to students' personal and professional orientation (Topcubaşı & Tiryaki, 2023).	Journal of Science Learning (2023)
Arduino-based real-time data acquisition systems: boosting STEM career interest.	Using real-time data collection systems through Arduino increased students' interest in STEM-related professions (Prabowo et al., 2024).	International Journal of Evaluation and Research in Education (2024)
Influences of Arduino and Algodoo-Based Mechanics Teaching on Achievement.	Integrating Arduino and the Algodoo platform into teaching positively affected academic achievement in the mechanics section of physics (Çoban & Erol, 2025).	Necatibey Eğitim Fakültesi Elektronik Fen ve Matematik Eğitimi Dergisi (2025)
The effect of project-based Arduino educational robot applications on students' computational thinking skills and their perception of basic STEM skill levels.	Project-based Arduino robotic activities significantly improved students' computational thinking levels and understanding of STEM skills (Karaahmetoğlu & Korkmaz, 2019).	Participatory Educational Research (2019)
Exploring Students' Hands-On Performance, Attitudes, and Usability with Arduino Modular Boards.	Using Arduino modular boards improved students' hands-on skills, attitudes toward technology, and system usability (Tselegkaridis & Sapounidis, 2024).	Information (Switzerland), (2024)
Çevrimiçi Arduino Programlama Öğretiminde Bağlılık ve Özyeterlilik Algısı.	An online Arduino programming course increased students' engagement in the learning process and their programming self-efficacy (Uysal & Ocak, 2023).	Akademik Açı (2023)
Designing Arduino instruction for novice agriculture students: effects on interest, self-efficacy, and knowledge.	An Arduino learning program enhanced interest, self-efficacy, and knowledge levels among novice students (Johnson et al., 2022).	Applied Engineering in Agriculture (2022)
Analyzing the effects of Arduino applications on students' opinions, attitude, and self-efficacy in programming class.	Using Arduino in programming courses improved students' attitudes toward the subject and their self-confidence (Arslan & Tanel, 2021).	Education and Information Technologies (2021)
The Effect of a Design Thinking-based Maker Education Program on the Creative Problem Solving Ability of Elementary School Students.	A design thinking-based maker program improved creative problem-solving abilities among primary school students (S. Lee et al., 2019).	Journal of The Korean Association of Information Education (2019)
Infusion Fluid Monitoring System Using Arduino Microcontroller and Internet of Things (IoT) to Increase Work Efficiency of Nurses in Hospital.	The effectiveness of Arduino technology in applied engineering environments has been demonstrated (Swedarma et al., 2023).	Nursing and Health Sciences Journal (NHSJ), (2023)
Arduino Destekli Robotik Kodlama Etkinlikleri ile İlkokul Sınıf Doğal Afetler Konusunun Öğretimi.	Arduino-supported robotic coding activities improved academic achievement and attitudes toward technology among primary school students (GÜVEN & ÖZÜNEL, 2023).	Ege Bilimsel Araştırmalar Dergisi (2023)

The content analysis results indicate that Arduino-based project-based, inquiry-oriented, and hands-on learning activities significantly improve students' computational thinking, prob-

lem-solving, modeling, and experimental skills, while also strengthening their interest in engineering and scientific careers (Figure 2).

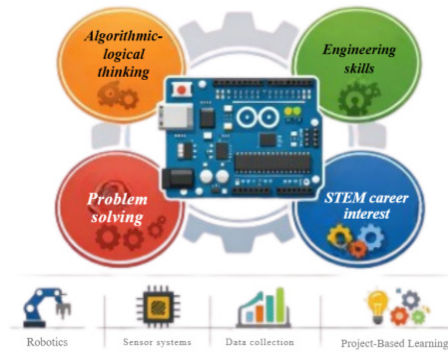


Figure 2. Professional Competency Components of Arduino-based STEM Education

By enabling real-time data collection, sensor-based systems, and robotics applications, Arduino technology effectively integrates theory with practice and fosters an engineering design culture through problem identification, prototyping, experimentation, and result analysis. Overall, these findings suggest that Arduino technology can serve as an effective tool for developing future physics teachers' subject, research, digital, and engineering competencies.

Meta-analysis not only describes the conclusions of individual studies but also statistically integrates their results, allowing for evidence-based conclusions. This method increases the reliability of research findings and enables the development of generalized conclusions regarding the effectiveness of a particular pedagogical or scientific intervention. The data obtained from the scientific literature were compiled and presented in a tabular format (Table 2).

Table 2. Data from Scientific Literature

No	Author Name	Std Diff Means	Std Error
1	Dat et al. (2025)	0.76	0.25
2	E. Lee (2020)	0.587	0.045
3	Sarı & Yazıcı (2020)	2.635	0.38
4	Görgülü Arı & Meço (2021)	2.27	0.6
5	Oh (2025)	1.66	0.35
6	Çoban & Erol (2025)	0.25	0.18
7	Nawawi & Dafrita (2022)	1.395	0.222
8	Topcubaşı & Tiryaki (2023)	2.27	0.42
9	Prabowo et al. (2024)	1.6	0.23
10	Çoban & Erol (2025)	2.33	0.36
11	Karaahmetoğlu & Korkmaz (2019)	0.29	0.18
12	Tselegkaridis & Sapounidis (2024)	1.88	0.319
13	UYSAL & OCAK (2023)	0.456	0.352
14	Johnson et al. (2022)	0.698	0.103
15	Arslan & Tanel (2021)	0.527	0.101
16	S. Lee et al. (2019)	0.402	0.114
17	Swedarma et al. (2023)	1.55	0.664
18	Güven & Özünel (2023)	3.76	0.383

The results of the studies included in the meta-analysis were processed using Comprehensive Meta-Analysis 4.0, and the corresponding

statistical conclusions were obtained. During data integration, a Funnel Plot was constructed to assess potential publication bias (Figure 3).

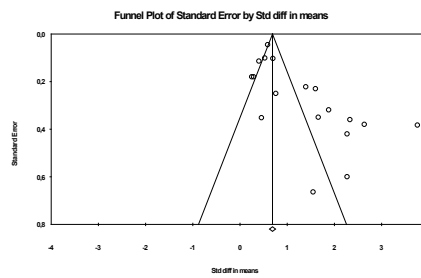


Figure 3. Funnel Diagram based on Collected Scientific Data

This diagram illustrates the distribution of effect sizes relative to their standard errors in the studies included in the meta-analysis. The distribution pattern of the points in the Funnel Plot

allowed assessment of the consistency of the meta-analysis results and the possible level of publication bias (Table 3).

Table 3. Results of the Assessment of Publication Bias

Method	Indicator	p-value	Interpretation
Begg & Mazumdar	Kendall's $\tau = 0.085$	0.312 (1-tailed)	No publication bias detected
Egger test	Intercept = 1.26	0.214 (1-tailed)	No small study effect observed
Trim & Fill	ES: 0.92 $\rightarrow$ 0.88	-	Effect size virtually unchanged
Fail-safe N	1480	-	Result reasonably stable

To detect publication bias, several statistical procedures were applied, including the Begg and Mazumdar rank correlation test, Egger's regression test, the Duval and Tweedie Trim and Fill method, and the Fail-safe N statistic. The Begg and Mazumdar test showed no statistically significant relationship between effect size and standard error ($p > 0.05$), suggesting no publication bias.

According to the Egger test, the intercept value was not statistically significant ($p > 0.05$), indicating that the small-study effect was not observed. The Trim and Fill method showed only minimal changes in effect size, indicating that publication bias did not substantially affect the

meta-analysis results. Furthermore, the high Fail-safe N value indicates that the results are reliable and stable.

Overall, the combined results confirm the absence of publication bias in the meta-analysis and show that the conclusions are scientifically well founded.

The meta-analysis examining the development of future physics teachers' professional competencies through Arduino technology in STEM education demonstrated the high effectiveness of this instructional approach. According to the aggregated results, the average effect size was $d = 1.27$, with a 95% confidence interval ranging from 0.99 to 1.56 (Figure 4).

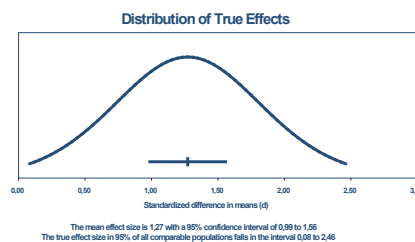


Figure 4. Distribution of True Effects

This value indicates that Arduino-based STEM instruction has a very strong practical effect on the development of professional competencies among future physics teachers. According to the model describing the distribution of true effects, in 95% of comparable populations the true

effect size lies between 0.08 and 2.46, indicating that this effect is stable across diverse educational contexts rather than limited to individual cases. The results are visually presented in a Forest plot (Figure 5).

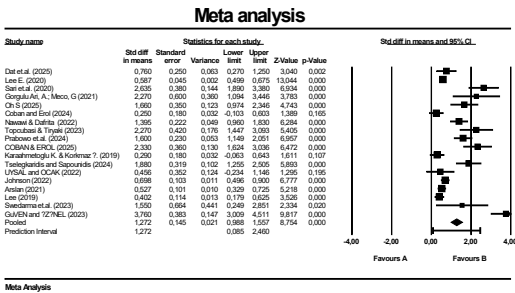


Figure 5. Graphical Representation of Meta-Analysis Results from Data

The Forest plot (Figure 5) compares effect sizes across the 18 included studies alongside their combined overall effect, showing confidence intervals, effect direction, and the level of heterogeneity among studies.

The meta-analysis included 18 empirical studies using standardized mean difference (d) as the effect size measure; given the diversity of educational contexts, a random-effects model was applied.

The Z-test confirmed that the effect size was significantly different from zero ($Z = 8.75$, $p < 0.001$).

The Q-test was statistically significant ($Q = 86.97$, $df = 17$, $p < 0.001$), and the I^2 value of 58% indicated moderate-to-substantial heteroge-

neity. Rather than reflecting a weakness of the intervention, this variation suggests that the effectiveness of Arduino-based STEM instruction differs across educational environments, curricula, and implementation formats, depending on factors such as students' prior preparation and the organization of practical activities.

Taken together, these results confirm that Arduino-based STEM instruction has a consistent, statistically robust effect, though its magnitude varies with learning conditions. To identify the sources of this variation, a meta-regression analysis relating effect sizes to study-level moderators — such as content structure, task complexity, and instructional format — was conducted (Table 4).

Table 4. Meta-Regression Results for Assessing the Impact of Teaching Format on the Effectiveness of Arduino-based STEM Teaching

Covariate	Coefficient	Standard Error	95% Lower	95% Upper	Z-value	2-sided P-value
Intercept	1.1495	0.3723	0.4198	1.8791	3.09	0.002
Study: 2	0.1396	0.4278	-0.698	0.978	0.33	0.7442
Study: 3	0.2294	0.477	-0.705	1.1643	0.48	0.6306

Statistics for Model 1

Test of the model: Simultaneous test that all coefficients (excluding intercept) are zero

$Q = 0.23$, $df = 2$, $p = 0.8908$

Goodness of fit: Test that unexplained variance is zero

$\text{Tau}^2 = 0.3492$, $\text{Tau} = 0.5910$, $I^2 = 58\%$, $Q = 86.37$, $df = 15$, $p = 0.0000$

Comparison of Model 1 with the null model

Total between-study variance (intercept only)

$\text{Tau}^2 = 0.2928$, $\text{Tau} = 0.5411$, $I^2 = 58\%$, $Q = 86.97$, $df = 17$, $p = 0.0000$

Proportion of total between-study variance explained by Model 1

R^2 analog = 0,00 (computed value is -0.19)

The overall model showed a high and statistically significant effect of Arduino technology (Intercept = 1.15; $p = 0.002$). Relative to the PjBL reference category, regression coefficients indicated a positive but non-significant change in effect

size for Inquiry/Research-Based Learning ($\beta = 0.14$) and Laboratory/Experimental Learning ($\beta = 0.23$) ($Q = 0.23$; $p = 0.891$).

These results indicate that instructional format does not significantly moderate the ef-

fectiveness of Arduino-based STEM instruction: three formats, confirming their versatility as a methodologically flexible STEM tool (Figure 6).
cognitive, research, and practical skills across all

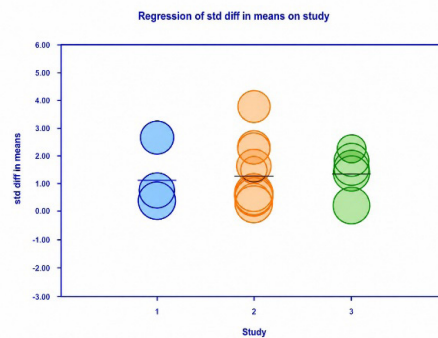


Figure 6. Graphical Representation of Meta-Regression on Effect Sizes of Arduino-based STEM Learning Depending on the Learning Format

Overall, Arduino-based STEM instruction demonstrated the strongest effect within a Project-Based Learning framework, providing the empirical basis for the instructional model presented below.

The wind energy training device is an educational apparatus that enables the experimental investigation of the process of converting wind energy into electrical energy. This device visually demonstrates the operating principles of renewable energy sources, explains the laws of energy transformation, and highlights the importance of environmentally friendly power sources (Ramankulov et al., 2026).

The main objective of the training device is to give students a practical understanding of

the physical principles of wind energy, the engineering mechanisms behind its implementation, and the process of electricity generation through experimental activities. In the device, an artificial airflow acts on the rotor blades, producing mechanical rotational motion. The generator then converts this motion into electrical energy, and dedicated measuring instruments record the resulting voltage and current.

The main structural components are 3D-printed and integrated with accessible electronic components. These include a rotor, fan motor, generator motor, Arduino Nano microcontroller, Hall sensor and magnets, digital voltmeter–ammeter, LCD1602 display, servo tester, battery, breadboard, and connection wires (Figure 7).

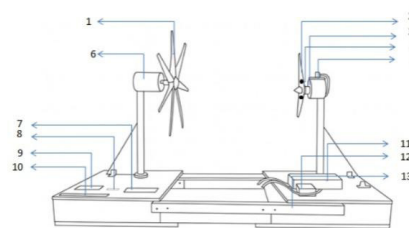


Figure 7. Wind Energy Training Tool

Information:

blade (1,2), fan motor (3), neodymium magnets (4), Hall sensor 3144 (5), generator motor (6), LCD1602 display (7), USB 3.0 cable (8), digital voltmeter-ammeter (9), breadboard (10), battery (11), servo tester ESC Servo CCPM (12), ruler (13)

The fan generating the airflow is mounted in a movable configuration, allowing investigation of the effects of wind speed and direction on generator performance.

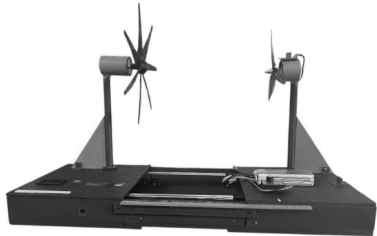
The device follows the STEM education framework. The Science component explores wind kinetic energy, electromagnetic induction, and energy conservation; Technology focuses on data acquisition using Arduino and sensors; En-

gineering develops design and prototyping skills through device assembly and testing; and Mathematics involves data analysis, power calculations, and graphical representation of results.

The wind generator converts the wind's kinetic energy into mechanical rotation and then into electrical energy through electromagnetic induction. By varying the distance between the fan and the rotor, students can simulate different

wind conditions and investigate how they affect electrical power generation.

Based on this STEM learning model, we organized project-based and experimental activities to integrate theoretical knowledge with practical experience while promoting engineering thinking and research skills.



The technical solution of the proposed training device has been registered at the National Institute of Intellectual Property of the Republic of Kazakhstan, and a utility model patent has been granted under the title “Training Device for Wind Energy” (Patent No. 11837, 2026) (Figure 8).



Figure 8. Utility Model Patent for “Training tool for Wind Energy” (No. 11837, Republic of Kazakhstan)

The pedagogical process was organized in four stages. First, students were introduced to the theoretical foundations of wind energy—kinetic energy, energy conservation, and electromagnetic induction—through problem-based discussion of its environmental significance. Second, in an engineering design stage, students studied the device’s components (rotor, generator, Arduino microcontroller) and assembled the system themselves. Third, in an experimental stage, they generated artificial airflow at varying distances from the rotor and recorded the resulting voltage and current in real time via the Arduino display. Finally, in the research stage, students analyzed the collected data, constructed tables and graphs, and concluded the relationship between wind speed and generated energy—developing their analytical and data-processing skills in the process.

To comparatively evaluate the development of professional competencies in future physics teachers through Arduino technology in the STEM education process, the study identified several pedagogical and statistical criteria. The comparative analysis considered the comprehensive nature of professional competence, including research skills, engineering thinking, practical

activities, and the ability to apply theoretical knowledge. The study included 60 future physics teachers. The participants were divided into three groups according to different instructional formats for implementing Arduino technology within the STEM education process:

- Project-Based Learning (PjBL) format - 20 students;
- Inquiry / Research-Based Learning format - 20 students;
- Laboratory / Experimental Learning format - 20 students.

The equal group sizes ensured the accuracy of the comparative statistical analysis and the reliability of the results.

The professional competence of future physics teachers was determined based on the following key criteria in order to comprehensively evaluate the pedagogical effectiveness of using Arduino technology in the STEM education process. These criteria characterize the content of future specialists’ professional training, their readiness for research, engineering, and practical activities, and their ability to apply theoretical knowledge in real educational and experimental contexts (Table 5).

Table 5. Criteria for Assessing the Professional Competence of Future Physics Teachers

No	Professional competence criteria	Evaluation indicators	Evaluation scale
1	Research Competence	pose a research question; plan and conduct an experiment; analyze and interpret data;	0–10 points
2	Engineering and Design Thinking	build a device/model based on Arduino; solve a technical problem; evaluate the effectiveness of a design solution;	0–10 points

3	Practical Action Skills	apply theory in practice; work with tools and sensors; result-oriented action;	0–10 points
4	Theory-Practice Connection	relate physical laws to practical tasks; explain and justify STEM tasks;	0–10 points

The four professional competency criteria were assessed using a common 0–10-point rubric. Assessment was based on observable student performance during Arduino-supported STEM activities, including formulating research questions, conducting and interpreting experiments, constructing Arduino-based models, working with sensors and tools, and applying physics concepts to practical tasks. The course instructor (s) evaluated student work using the same rubric, and the overall professional competency score was calculated as the mean of the four criteria.

The three assessment instruments captured different dimensions of learning, including knowledge, self-reported perceptions, and practical application. Self-reported responses were interpreted as students' perceived attitudes, confidence, or learning experiences rather than as

direct evidence of actual behavior or demonstrated competence. Accordingly, performance-based conclusions were based only on observable student activities and assessed practical outcomes.

Quantitative data were analyzed using Jamovi 2.4. Descriptive statistics, including the mean (M), standard deviation (SD), and standard error (SE), were calculated to compare professional competency across the Project-Based Learning, Inquiry-Based Learning, and Laboratory instructional formats. Data normality was assessed using the Shapiro–Wilk test, confirming the appropriateness of parametric analysis. Differences among instructional formats were examined using one-way ANOVA, with statistical significance set at $p < 0.05$. Table 6 presents descriptive statistics for each instructional format.

Table 6. Descriptive Statistics Results

	Format	N	Mean	SD	SE
Competence	Inquiry	20	8.3	0.66	0.032
	Laboratory	20	7.83	0.166	0.0372
	PjBL	20	8.72	0.210	0.0469

The comparative analysis showed that students who studied in the Project-Based Learning format had the highest level of professional competence ($M = 8.72$). In the Inquiry-Based format,

this indicator was somewhat lower ($M = 8.3$), and in the Laboratory format, professional competence was relatively low ($M = 7.83$) (Figure 9).

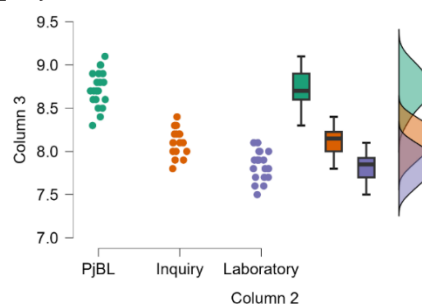


Figure 9. Raincloud Plots

The descriptive statistics indicated that using Arduino technology in the STEM educational process through a project-based learning format is more effective in developing the professional competence of future physics teachers and served as the basis for the analysis of variance in the next stage.

To examine the statistical significance of the differences identified through descriptive sta-

tistics, a one-way analysis of variance (ANOVA) was conducted. In this analysis, the dependent variable was the professional competence score of future physics teachers, while the independent factor was the instructional format (Project-Based Learning, Inquiry-Based Learning, and Laboratory formats).

First, to verify the suitability of parametric statistical methods, we assessed the normality as-

sumption using the Shapiro–Wilk test. The normality test indicated that the data were normally distributed ($W = 0.972$; $p = 0.188$), confirming

the appropriateness of parametric analysis. Table 7 presents the normality test results.

Table 7. Normality Test

	W	p
Competence	0.972	0.188

Note: A low p-value suggests a violation of the normality assumption.

Because the normality condition was met, Welch’s one-way ANOVA was used next to determine whether professional competence levels varied by training format. The results showed a

statistically significant difference in professional competence levels across training formats ($F(2, 37.6) = 109$, $p < 0.001$). The results of the Welch one-way ANOVA are presented in Table 8.

Table 8. Welch ANOVA Results for Professional Competence Indicators by Training Format

	F	df1	df2	p
Competence	109	2	37.6	<.001

Overall, the ANOVA results support that using Arduino technology in Project-Based Learning in STEM education is the most effective pedagogical approach for developing the professional competence of future physics teachers.

The large effect size identified in this study suggests the educational potential of Arduino-supported STEM instruction in developing professional competencies among future physics teachers. Rather than demonstrating the independent causal effect of Arduino itself, the meta-analytic findings indicate positive outcomes associated with its integration into STEM-oriented learning environments. Arduino-based learning tasks enable students to connect theoretical knowledge with practical activities by observing physical phenomena, collecting experimental data using sensors, analyzing results, and developing engineering solutions. As a result, students gain experience applying fundamental physical principles to authentic engineering problems. In the empirical phase of the present study, these outcomes were specifically assessed through research competence, engineering and design thinking, practical action skills, and theory–practice connection.

The findings are consistent with previous research on technology-enhanced teacher education. Sari & Yazıcı (2020) reported that pre-service teachers demonstrated positive attitudes toward Arduino technology and perceived it as useful for classroom instruction. Similarly, Usembayeva et al. (2024) emphasized the importance of 3D modeling, printing, and STEM technologies for interpreting physics concepts and integrating technological tools into physics education. Berdi et al. (2015) also demonstrated

the relevance of information and telecommunication technologies in preparing future teachers professionally. These studies support the broader role of digital technologies in teacher education. However, in the present empirical study, digital and pedagogical competencies were not assessed as independent outcome variables; therefore, the results are interpreted only in relation to the four directly assessed dimensions of professional competence.

The obtained results can also be considered in relation to project-based learning. Sumarni et al. (2025) demonstrated that Collaborative Ethno-STEAM Enriched Project-Based Learning can support creativity and collaboration among pre-service science teachers. In the present study, Arduino-based STEM activities involved designing engineering solutions, assembling hardware components, developing programs, and analyzing experimental data. The PjBL group showed the highest observed professional competence score in the present sample, suggesting that project-based organization may provide favorable conditions for integrating research, engineering, practical activity, and theoretical knowledge. However, this result is interpreted within the context of the present study and is not considered evidence of the general superiority of PjBL over other instructional formats.

Contemporary STEM education increasingly emphasizes integrating digital technologies with artificial intelligence. Vera et al. (2025) reported that AI-integrated STEM education can support digital competence, innovative thinking, and technological adaptability among pre-service science teachers. From this perspective, Arduino can be viewed as a technological platform that

enables sensor-based data acquisition, real-time processing, and potential integration with intelligent systems. Nevertheless, the present study did not independently measure digital competence and therefore treats it as a contextual feature of the learning environment rather than a direct empirical outcome.

Furthermore, Xing & Qi (2023) demonstrated that interactive technologies can facilitate creativity, collaboration, and professional interaction. In the present study, participants collaboratively planned projects, discussed experimental findings, and made engineering decisions during Arduino-supported STEM activities. These activities demonstrate collaborative learning processes within the instructional environment. However, communication and teamwork were not assessed as outcome variables; therefore, no direct conclusion can be drawn about improvement in these competencies.

This study contributes by linking evidence synthesis with an empirical comparison of instructional formats in the context of future physics teacher education. Methodologically, the study combines a systematic literature review and meta-analysis with an empirical comparative phase, allowing broader patterns in Arduino-supported STEM learning to be considered alongside context-specific evidence. Pedagogically, the study demonstrates how Arduino-based activities can integrate physics concepts, engineering design, experimentation, data analysis, and practical problem solving within a unified learning environment. The wind-energy instructional model further illustrates how these elements can be incorporated into a competency-oriented STEM activity. However, the study's contribution should be understood primarily in relation to the four directly assessed dimensions: research competence, engineering and design thinking, practical action skills, and theory–practice connection.

Several limitations should be considered when interpreting the findings. First, the empirical study used a relatively small sample of 60 future physics teachers from a single university, which limits how far the findings can be generalized to other institutional or national contexts. Second, participants were recruited through convenience sampling, and the comparative design does not provide the same level of causal evidence as a randomized experimental design. Third, professional competence was assessed using a performance-based rubric developed for the present instructional context, and the authors did not establish formal inter-rater reliability or broader psychometric validation. In addition, the

meta-analysis included studies conducted with different student populations, educational levels, outcome measures, and implementation conditions, which may contribute to the observed heterogeneity and require cautious interpretation of the pooled effect. Future research should examine Arduino-supported STEM learning using larger and more diverse samples, validated competency measures, longitudinal designs, and stronger experimental or quasi-experimental procedures. Cross-institutional and cross-national studies would be particularly valuable for determining whether the patterns observed in the present study are reproduced across different teacher-education systems, curricula, and technological infrastructures. The study's broader relevance lies in addressing instructional challenges common in physics teacher education internationally, including the need to connect theoretical physics with inquiry, engineering design, experimentation, and practical problem solving. Nevertheless, because the empirical component was conducted within a single national and institutional context in Kazakhstan, the findings should not be interpreted as universally generalizable. Rather, the proposed Arduino-supported STEM model should be viewed as a context-specific instructional example with potential relevance to similar physics teacher education settings and as a basis for further comparative validation.

CONCLUSION

The findings suggest that integrating Arduino technology into STEM-oriented physics teacher education is associated with positive learning and professional-competency outcomes. The systematic review and meta-analysis of 18 empirical studies indicated an overall positive effect of Arduino-supported educational interventions ($d = 1.27$), particularly for cognitive, research, engineering, and practical learning outcomes. In the empirical phase, students in the Project-Based Learning format showed the highest professional-competency scores among the three instructional groups; however, these results should be interpreted as comparative associations within the specific educational context rather than definitive evidence of causal effectiveness. The meta-regression further indicated that differences among the examined instructional formats were not statistically significant, suggesting that Arduino may be flexibly integrated across different STEM learning approaches.

The Arduino-supported STEM model developed around wind-energy conversion provided

a practical instructional context in which students could connect physics concepts with experimental activities, engineering design, sensor-based measurement, and data analysis. Within the empirical component of the study, professional competence was evaluated through four explicitly defined dimensions: research competence, engineering and design thinking, practical action skills, and theory–practice connection. Accordingly, conclusions regarding broader digital, pedagogical, or sustainability-related competencies should be considered as potential educational implications rather than directly measured outcomes.

Overall, the study provides evidence supporting the potential of Arduino-supported STEM activities as a pedagogical resource for enriching physics teacher education and strengthening the integration of theoretical, experimental, and engineering-oriented learning. The findings may inform the further development of STEM- and project-based components in physics teacher education curricula; however, additional studies using stronger experimental designs, validated competency measures, and broader participant samples are required to establish the effectiveness and long-term contribution of such approaches to sustainable physics teacher education.

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