MODESTUM EURASIA Journal of Mathematics, Science and Technology Education, 2026, 22(6), em2848
ISSN:1305-8223 (online)
OPEN ACCESS Literature Review https://doi.org/10.29333/ejmste/18710

Learning physics with microcontrollers: A systematic review of empirical research

Besnik Saramati [1,2,3*], Andrej Vidak [4], Vanes Mešić [1]

[1] Faculty of Science, University of Sarajevo, Sarajevo, BOSNIA AND HERZEGOVINA
[2] Department of Paramedical Subjects, Faculty of Medicine, University of Prishtina "Hasan Prishtina", Pristina, KOSOVO
[3] Oncology Clinic, University Clinical Center of Kosova, Pristina, KOSOVO
[4] Faculty of Chemical Engineering and Technology, University of Zagreb, Zagreb, CROATIA

Received 06 March 2026 ▪ Accepted 19 May 2026

Abstract

This systematic review synthesizes 38 peer-reviewed empirical studies (January 2010-December 2025) on microcontroller use in physics education, following preferred reporting items for systematic reviews and meta-analyses procedures and searches in Scopus and ERIC. It describes how platforms such as Arduino, ESP32, Atmega328, and Micro:bit potentially support development of laboratory skills and may facilitate learning of mechanics, thermodynamics, electromagnetism and optics. These low-cost programmable devices most often facilitate learning through automated, high-frequency data collection and real-time visualization, allowing students to observe transient phenomena and connect measurements to conceptual models. Instructions are typically inquiry and project-based, with students building sensor systems, troubleshooting, and developing computational and experimental reasoning. Across studies, motivation and engagement frequently improve, and some report gains in conceptual understanding and laboratory problem-solving. Different barriers include limited teacher training, time constraints, calibration/debugging difficulties, and resource and maintenance demands. Future studies should prioritize longitudinal research and scalable teaching models to support sustained classroom integration.

Keywords: microcontrollers, Arduino, ESP32, Atmega328, Micro:bit, physics education

INTRODUCTION

Increasing technological progress has given educators new opportunities to support students in learning and discovering phenomena that are difficult to understand through traditional instruction alone. Modern technologies can make scientific phenomena easier to understand by facilitating the collection and visualization of real-time data in different representations. In physics education, such educational technologies are especially relevant because learning physics requires active intellectual engagement with phenomena, and learning is often most productive when it begins with physical experience, followed by measuring, and interpreting events in authentic contexts (Kircher et al., 2015; Redish, 2004).

Microcontrollers and Their Use in Education

A widely used family of educational technologies that supports experience-based learning is programmable embedded hardware, such as microcontrollers (e.g., Arduino, ESP32, and Micro:bit). Microcontrollers are small programmable devices intended mainly for connecting with sensors and actuators, facilitating measurement and control processes that convert physical inputs into recorded outputs. Microcontrollers can function as low-cost experimental systems and are typically optimized for robust sensor interfacing and real-time acquisition. When it comes to microcontrollers in education, Arduino has become one of the most accessible examples because it combines open-source hardware and software with a large ecosystem of compatible sensors and a

✉ besniksaramati@gmail.com **(*Correspondence)** ✉ vidak.andrej@gmail.com ✉ v.mesic@pmf.unsa.ba

Contribution to the literature

- The review shows that microcontrollers support physics learning mainly by enabling real-time visualization, multiple synchronized representations, automated high-frequency data acquisition, low-cost portable experimentation, and learner agency within experimentally grounded computational work.
- The review clarifies that reported cognitive gains are context-dependent and appear strongest when microcontroller-based activities are carefully scaffolded, conceptually focused, and connected to interpretation rather than mere device construction.
- The review identifies key implementation challenges, including calibration and debugging demands, limited instructional time, equipment maintenance, and insufficient teacher support. It also highlights the need for more sustained and longitudinal research.

relatively low barrier for classroom experimentation (Kubínová & Šlégr, 2015; Uzal, 2022). This is significant in an educational context because microcontrollers establish a direct connection between phenomena and their representations. Sensors measure physical quantities, while the microcontroller samples and processes these signals, allowing for real-time visualization of measurements during experimental activities. These configurations can supplant manual timing and logging with automated data acquisition, thereby augmenting the feasibility of experimentation within conventional classroom limitations and permitting increased time for interpretation and discussion (Çoban, 2020a, 2020b; Moya, 2018). Across classroom and laboratory implementations, microcontroller-based activities repeatedly rely on real-time feedback and visualization to make evolving relationships more intelligible during the experiment itself. In many designs, learners can observe how quantities change and relate through live graphs and immediate feedback, making abstract relations more concrete as the phenomenon develops (Galeriu, 2018; Pusch et al., 2021; Sukmak & Musik, 2022). A second common feature is the use of multiple synchronized representations, such as sensor streams, numerical readouts, real-time graphs, and the underlying acquisition code. This setup helps measurements, models, and interpretations work together and fits with theoretical ideas about how people learn from multiple external representations (Ainsworth, 2006; Kuan et al., 2016). In addition, automated and high-frequency sampling can reveal fast dynamics and subtle temporal patterns (e.g., oscillation traces or thermal transients) that are often missed with manual tools, while improving procedural consistency and repeatability for model testing and uncertainty reasoning (Galeriu, 2018; Mendes et al., 2023).

The educational significance of microcontrollers extends beyond merely achieving "better measurements." A persistent educational theme is learner agency: students are able to construct circuits, choose sensors, adjust parameters, and iteratively enhance configurations based on data analysis, transitioning activities from inflexible "cookbook" methods to inquiry practices that mirror genuine experimental work (Bouquet et al., 2017). This agency also supports learning in authentic contexts beyond school laboratories because low-cost and portable setups make it possible to connect physics to everyday phenomena and field-like settings (Gkiolmas et al., 2020; Moghimi-Araghi, 2025). Finally, microcontroller-based work naturally integrates IT skills with laboratory practice, since students implement acquisition logic in code, manage sampling decisions, calibrate sensors, debug hardware and software interactions, making the measurement process more transparent and supporting computational and experimental reasoning within a single workflow (Bulus & Basaran, 2019; Kuan et al., 2016).

Learning Theories That Are Relevant to Microcontroller-Based Physics Education

Theories pertinent to reasoning about learning through technology-enhanced visualizations are also applicable to microcontroller-based physics education. Constructivist theory posits that effective learning necessitates active engagement and collaborative interaction among students (Papert, 1980; Piaget, 1970; Vygotsky, 1978), and in the context of physics education, it is imperative that students directly encounter physical phenomena (Kolb, 1984). Microcontroller-based laboratories exemplify these principles by allowing students to design, construct, and program measurement systems that produce real-time data from genuine physical phenomena. Students engaged in the iterative design of circuits, debugging of code, and analysis of sensor data undergo the full experiential learning cycle, which includes concrete experience, reflective observation, abstract conceptualization, and active experimentation (Kolb, 1984).

According to cognitive load theory (Sweller, 1988), working memory is limited and can become overloaded, which impedes learning. Well-designed Arduino laboratories manage cognitive demands by positioning related information spatially close, breaking complex projects into scaffolded modules, and employing block-based programming to reduce syntax complexity (Sweller et al., 2011).

Mayer's (2014) cognitive theory of multimedia learning describes how multimedia elements can be combined effectively: the multimedia principle states that people learn better from words and pictures than from words alone. Microcontroller-based setups, together with a host device (computer/tablet/ smartphone) and appropriate software, can combine words, images, animations, and real-time data streams, for example, circuit-assembly demonstrations and textual guidance alongside live graphing synchronized with concurrent sensor measurements. According to the principle of spatial contiguity, people learn better when words and pictures are close together than when they are far apart (Mayer, 2014). In microcontroller environments, tablets can display live acceleration data positioned alongside falling objects or cooling curve graphs displayed near physical sensor apparatus.

Theories of embodied and grounded cognition assert that cognitive processes are rooted in sensory-motor activities and particular contexts (Wilson, 2002). When students physically interact with Arduino-based accelerometers, oscillating systems, and temperature sensors while monitoring real-time data, they establish a closed sensorimotor loop between cognition and action. This active participation fosters a deeper, more intuitive comprehension than mere passive observation.

The theory of distributed cognition asserts that cognition is distributed across internal human minds, external cognitive artifacts, and groups of people (Hutchins, 1995), and in Arduino laboratories, the computational system externalizes intermediate results, allowing students to focus cognitive effort on interpretation and design improvement.

Microcontroller-based physics education may also facilitate learning by presenting physical measurements through multiple representations. Ainsworth (2006) identifies three ways multiple representations support learning: by allowing complementary information, by limiting interpretation, and by constructing more profound understanding.

Social semiotics ultimately views meaning-making as a social practice shaped by semiotic resources in specific contexts (Kress & Van Leeuwen, 2006). Social semiotics suggests that when students experiment in teams, they utilize microcontrollers as shared semiotic resources code, hardware, and data, to negotiate and co-construct meaning about physical phenomena. This perspective frames physics learning as a collaborative social practice where understanding emerges from the group's collective interaction with these technological tools.

The above-mentioned theoretical frameworks collectively demonstrate that microcontroller-based physics laboratories are intellectually enriching and socially relevant settings for developing a profound understanding of physics and 21st century problem-solving abilities.

Previous Systematic Reviews, Bibliometric Studies, or Meta-Analyses

In **Table 1** we present a summary of 13 articles, consisting of several major systematic reviews, meta-analyses, and bibliometric studies on the use of different microcontroller platforms (especially Arduino, ESP32) in physics and STEM education for the period from 1 October 2020 to 31 August 2025. While systematic reviews and bibliometric analyses concerning microcontrollers in education are increasingly prevalent, a limited number concentrate specifically on physics education, and those that do often fail to address the entirety of physics domains equitably (e.g., Fauza et al., 2023; Monteiro et al., 2022; Neto et al., 2021). The reviews summarized in **Table 1** show substantial variability in the number of included studies, which is primarily driven by differences in scope and methodology. Targeted systematic reviews, such as those emphasizing formal primary education or particular areas within physics, typically consolidate relatively limited evidence bases. For example, one review comprises merely 9 studies (García-Tudela & Marín-Marín, 2023), whereas another meta-analytic synthesis includes 16 studies (Lee, 2020a). Conversely, comprehensive STEM-focused systematic reviews typically encompass substantially larger datasets, frequently exceeding 100 studies (Kondaveeti et al., 2021). Bibliometric mappings that encompass extensive landscapes of science education publications can yield significantly higher counts, such as 1,115 publications (Prabowo & Irwanto, 2023). This variation highlights differences in scope, ranging from general education to STEM and physics education, as well as differences in methodology, including meta-analysis, systematic review, and bibliometric analysis. **Table 1** illustrates that prior studies have frequently recognized overarching benefits and drawbacks of microcontroller-based learning; however, comprehensive syntheses specifically addressing physics are limited and tend to focus on particular physics areas (e.g., mechanics) rather than integrating evidence across diverse physics domains and distinctly identifying unique learning mechanisms relevant to microcontroller-based physics instruction (Fauza et al., 2023; Lotriet & Gouws, 2025; Monteiro et al., 2022).

We can conclude that prior reviews differ substantially in scope, physics-domain coverage, and learner population. This variability helps explain why the review literature remains fragmented. Some reviews are tightly bounded and therefore offer stronger comparability within specific contexts. For example, Lee (2020a) synthesized Arduino-based intervention studies in Korea, whereas Fauza et al. (2023) focused on microcontroller-supported learning in mechanics. Neto et al. (2021) reviewed Arduino use in physics education in Brazil. In their review, the included studies were concentrated mainly in secondary and higher education, and topic coverage was strongest in waves and

Table 1. Prior reviews, bibliometric studies, or meta-analyses on microcontrollers in STEM/physics education

Authors	N[a]	Research focus
Lee (2020a)	16 (SE)	Meta-analysis of Arduino-based interventions: moderators (learner level, sample size, setting); pooled effects on cognitive/affective outcomes (d = 0.656); study designs and measurement instruments; reported benefits and challenges.
Kondaveeti et al. (2021)	100+ (SE)	Microcontroller/embedded platforms in STEM: application purposes and learning contexts; reported benefits (e.g., affordability/flexibility) and limitations; implementation barriers; common platform/technology features.
Neto et al. (2021)	85 (PH)	Arduino use in Brazilian physics education: physics topic distribution and educational levels; main classroom/lab applications; reported pedagogical benefits and constraints; trends in study designs within national literature.
Monteiro et al. (2022)	41 (PH)	Using sensors, mobile devices, and microcontrollers in physics education: how they are used in different areas of physics (like wave mechanics and optics); benefits and difficulties reported.
Fauza (2023)	44 (PH)	Microcontroller supported physics (mechanics) instruction includes the dominance of mechanics topics, learning outcomes and effectiveness trends, study methods, instructional approaches (e.g., prevalence of guided inquiry), and reported implementation issues.
García-Tudela and Marín-Marín (2023)	9 (GE)	Arduino in formal primary education: learning contexts (often STEM/PBL); common tools/components (Scratch/Blockly, LEDs/sensors); reported outcomes (motivation, CT, basic programming/circuits); limited evidence base in formal settings.
Prabowo and Irwanto (2023)	1,115 (SCE)	Mapping of microcontroller related science education research: publication growth over time; geographic distribution and collaboration; education level and research field categories; and commonly reported hardware/software ecosystems.
Marín-Marín et al. (2024)	37 (SE)	Arduino serves as a microcontroller for computational thinking in STE(A)M, covering learner level distribution, typical toolchains (Arduino and Scratch/LED/sensors), instructional strategies, outcomes that emphasize CT/programming skills, and commonly reported classroom problems.
Pabuçcu Akış (2024)	79 (SE)	Arduino-related education research: annual output trends; journal and country distribution; methodological patterns; frequently reported benefits and challenges; fragmentation in assessment and integration across disciplines.
Setya et al. (2024)	20 (SE)	Microcontrollers in PBL/STEM settings include intended uses and learning objectives, affordances and limitations in PBL contexts, reported effectiveness and engagement outcomes, and instructional design patterns along with classroom implementation constraints.
Lotriet and Gouws (2025)	29 (PH)	Microcontroller and robotics enabled learning for physics concept acquisition includes STEM and physics application areas, typical hardware and software platforms, learning activity design elements and visual features, and instructional methods linked to physics learning goals.
Ubaidillah et al. (2025)	32 (SCE)	Remote science experimentation using Arduino and block based tools includes trends in remote lab environments, technology configurations, access and diversity barriers, and assessment and rubric approaches for online experiments.
Vergara et al. (2025)	43 (SE)	K-12 physical computing interventions: microcontrollers with sensors/actuators; intervention structures (intro and hands-on teamwork); assessment approaches across studies; outcomes (CT/CS skills, learning/attitudes); equity gaps and need for longitudinal/comparative evidence.

Note. N[a]: Number of reviewed articles; PH: Physics; GE: General education; SE: STEM education; SCE: Science education

electromagnetism, while optics and modern physics were less represented. Other reviews are broader and more cross-disciplinary, combining physics with STEM, or with themes such as computational thinking, robotics, remote experimentation, or primary education (e.g., García-Tudela & Marín-Marín, 2023; Kondaveeti et al., 2021; Marín-Marín et al., 2024; Prabowo & Irwanto, 2023; Ubaidillah et al., 2025; Vergara et al., 2025). These broader reviews are valuable, but their wider remit means that they often emphasize publication trends, platforms, implementation contexts, or general educational benefits rather than empirical evidence on physics learning specifically.

Even reviews that are closer to physics education tend to focus on a single platform such as Arduino (e.g., Pabuçcu Akış, 2024), a particular national context (e.g., Lee, 2020a; Neto et al., 2021), a specific learner population (e.g., García-Tudela & Marín-Marín, 2023; Vergara et al., 2025), or a particular physics subdomain such as mechanics (e.g., Fauza et al., 2023), rather than examining how microcontrollers support learning across a broader range of physics topics. In addition, such reviews often emphasize publication patterns, implementation issues, general benefits, or technology adoption, rather than examining how microcontrollers support learning in specific physics topics (e.g., Lotriet & Gouws, 2025; Monteiro et al., 2022). Consequently, the field still lacks a review that systematically examines how microcontrollers support learning across different physics content areas and what learning affordances are reported in relation to particular physics topics. It also lacks an integrated empirical picture of how

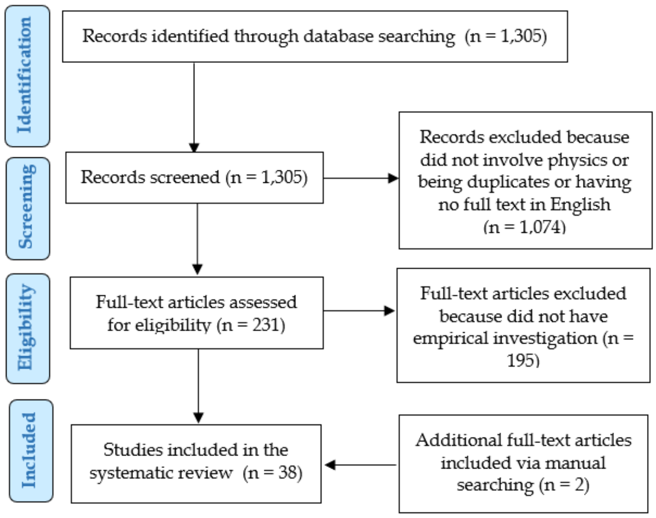

Figure 1. PRISMA flow diagram of the article selection process [Adapted from the PRISMA 2009 flow diagram (Moher et al., 2009), distributed under the Creative Commons Attribution License]

microcontrollers are used across physics content areas and what cognitive, affective, and practical outcomes and challenges are reported in relation to those areas. The present review addresses this gap by synthesizing peer-reviewed empirical studies on microcontroller-based physics learning across multiple physics domains and by examining the associated learning affordances, reported outcomes, challenges, and research designs.

Research Questions

We aimed to answer the following research questions:

RQ1. How do microcontrollers (e.g., Arduino, ESP32, and Micro:bit) facilitate learning physics?

Significance: Answering this research question could contribute to discovering the different ways in which microcontrollers are used in physics learning and in clarifying the mechanisms by which microcontrollers promote learning of concrete physics topics.

RQ2. What are the cognitive, affective and practical benefits and challenges of integrating microcontrollers into physics learning environments?

Significance: Answering this research question can provide evidence-based insights for educators, curriculum developers, and policymakers who are considering incorporating microcontrollers into physics education.

METHODS

We first had to identify a pool of high-quality articles related to microcontrollers-based learning and teaching physics. To ensure methodological transparency and reproducibility, our article selection procedures followed the guidelines provided by preferred reporting items for systematic reviews and meta-analyses

Table 2. Inclusion criteria

No	Inclusion criteria
1	Published between 1 January 2010 and 31 December 2025
2	Peer-reviewed journal articles indexed in ERIC or Scopus
3	Related to microcontrollers in learning physics and astronomy
4	Full text in English available
5	Original (non-review) publication

(PRISMA). The workflow of our article selection process is presented in **Figure 1**.

Initially, we conducted a search for pertinent articles in the Scopus and ERIC databases. If a paper meets the criteria outlined in **Table 2**, we consider it relevant for our review.

The second author of this paper searched Scopus and ERIC using the following query: (“microcontroller” OR “Arduino” OR “ESP32”) AND (“physics” OR “science” OR “STEM”). The search was limited to publications from 1 January 2010 to 31 December 2025, and to records for which an English full-text version was available.

The database searches identified 1,305 records. Next, the second author performed screening of the 1,305 article titles and abstracts, with the aim to identify duplicates and articles that are clearly not related to learning physics. For screening purposes, physics was defined as the conceptual and procedural frameworks used to study natural phenomena, aligned with standard textbook curricula. Thereby, 1,074 duplicates and articles which are not related to learning physics were found. The second author also identified six articles for which an English full-text was not available, although the English full-text filter had been applied which probably may be explained by the fact that these articles came from a journal that publishes articles in Portuguese and/or English. After the removal of above mentioned articles, 231 unique articles were retained for full-text assessment. To avoid excluding potentially relevant studies too early, both empirical studies and developmental papers were retained at this stage. For purposes of establishing transparency, as well as for providing physics educators with a comprehensive list of references related to microcontroller-based learning of physics, all these 231 papers along with their DOI numbers are listed in the **Electronic Supplement**. For articles for which no DOI exists, a direct link to the article is provided instead. In the next step, our aim was to remove developmental papers, as operationally defined in **Table 3**. The first and second author then independently assessed the 231 full-text articles for empirical eligibility. Initial agreement between these two raters on whether an article was empirical or developmental was 99.1% (229/231), with two discrepancies (0.9%) resolved through discussion. Consequently, 195 articles were excluded, leaving 36

Table 3. Exclusion criteria

No	Exclusion criteria
1	Theses, dissertations, conference papers, books, non-peer-reviewed reports, and other grey literature
2	Theoretical, conceptual, or opinion papers without a concrete microcontroller-based activity, apparatus, or educational relevance
3	Developmental articles, i.e. articles that did not include gathering empirical data related to the experience of learning or teaching physics with microcontrollers
4	Studies focused primarily on general programming/STEM/robotics, where physics content was only incidental or peripheral (i.e., no explicit physics learning goals, instructional focus, or physics-related outcomes/assessment)
5	Developmental articles without empirical evaluation

empirical studies for inclusion from the database search. No formal quality appraisal instrument was applied, but we believe that a basic quality filtering has been achieved through selecting only articles from relatively prestigious databases such as Scopus or ERIC.

After completion of the full-text screening process, the first author conducted a supplementary manual search, primarily through backward and forward citation tracking, and identified two additional eligible empirical articles that had not been retrieved by the original database search strategy. The final article pool for our systematic review therefore included 38 studies.

FINDINGS AND DISCUSSION

In this section, for each of our research questions, we present and discuss the corresponding findings.

How Are Microcontrollers Used for Facilitating Learning About Physics Topics?

Table 4 summarizes ideas about microcontroller-based learning and teaching physics across concrete physics domains. Additionally, it provides an overview of the implemented research designs.

From **Table 4** we can conclude that microcontrollers support physics learning through multiple distinct affordances. Below, these affordances are synthesized into seven categories and discussed sequentially.

Table 4. How microcontrollers are used for facilitating physics learning and what research designs were implemented in earlier research (all 38 empirical articles are included)

No	Author	Topics	Research design	Microcontrollers-based learning
1	Chaudry (2020)	Electric circuits (series/parallel, current & voltage)	A case study was implemented. The activity ran across multiple semesters and was evaluated using an anonymous post activity student survey (quantitative summaries and qualitative comments).	Students completed an optional extra credit Arduino activity in an algebra based undergraduate physics course, progressing from replicating known projects to building simple real-world applications, with the goal of increasing interest in physics; the activity ran over multiple semesters and concluded with an anonymous student feedback survey (with some comments reported).
2	Castro (2020)	Optics (Malus' law, inverse-square) and nanoscience	Didactic development/ instructional proposal with classroom implementation. Presents device demonstrations and activity examples but does not report a formal experimental or quasi-experimental learning outcomes evaluation. Students' feedback about the learning experience was assessed through a post-intervention survey.	Students built dye sensitized solar cells (Grätzel cells) from low-cost materials (TiO_2 nanoparticles, FTO glass, KI/I_2 electrolyte, graphite, grape juice dye) and interfaced them with an Arduino Uno as photosensors/photometers. Activities included reading light-dependent voltage (with signal averaging), LED/relay control, building a photometer for Malus' law and light intensity vs distance (inverse square law), and programming an Arduino based distance sensor using calibration/curve fitting. The project also connected nanoscale/material concepts via UV-Vis spectra of TiO_2 and dye to explain photo sensing mechanisms.
3	Hadiati et al. (2019)	Ohm's law/ electric circuits	Quasi-experimental comparative design with three intact classes using different lab work styles. Outcomes (e.g., scientific attitude, student activity) were measured quantitatively and compared across groups.	Students make Ohm's law observable by collecting real-time voltage/current readings via Arduino and sensors, then using the measurements to justify circuit reasoning across different lab work styles; the immediate feedback supports evidence based argumentation and is linked with improved scientific attitude/activity indicators.
4	Walkup et al. (2019)	Speed of light	Instructional laboratory implementation report with student feedback evidence. A structured 3 phase lab sequence was implemented and evaluated using survey style student responses (primarily descriptive).	Students used a microcontroller based timing setup to measure the travel time of light pulses over a known path length, using the recorded times to calculate the speed of light and discuss sources of experimental uncertainty in an introductory optics lab.

Table 4 (Continued).

No	Author	Topics	Research design	Microcontrollers-based learning
5	Coban and Erol (2025)	Mechanics	Pre-experimental one group pre-/post-test (N = 32 pre-service science teachers). Cognitive domain scale of mechanics (CDSM) and scientific creativity scale (SCS) administered pre/post; paired analyses plus gender-based subgroup analyses.	In a one group pre-/post-test implementation, teacher candidates used Arduino (UNO) with sensors to build/program measurement setups, collect real mechanics data, and analyze it with physics/maths; pre/post CDSM and SCS scores (plus gender subgroup checks) were then compared within the same group.
6	Yasin et al. (2018)	Electricity	Pre-experimental one group pre-/post-test. STEM-literacy test administered before/after; analyzed with paired comparison and normalized gain (overall and strand level).	STEM learning implemented via an Arduino Uno, Android game and breadboard/circuit kits sequence: students use an Arduino Uno (microcontroller) and Arduino software for a traffic light circuit project (build and modify), plus an Android game (MGames science) for circuit reasoning and calculations; also uses a circuit kit (YWRobot) and multimeter-based measurements to support hands-on circuit construction and testing.
7	Kuan et al. (2016)	Physics lab instrumentation	Mixed methods curriculum evaluation (case study). Implementation was evaluated with surveys (quantitative/statistical analysis) and interviews (qualitative analysis).	First year physics students followed an integrated instrumentation curriculum in which they used Scratch, LabVIEW, and LabVIEW for Arduino to program data-acquisition and control routines for simple physics experiments, learning how to design algorithms and graphical interfaces that interact with real measurement setups in the lab.
8	Bouquet et al. (2017)	General physics–Project-based labs	Descriptive evaluation of a project-based laboratory. Questionnaire data from students/teachers were analyzed to report perceptions of autonomy and project based learning outcomes (no control group).	Students were given complete autonomy to design and build their own experimental setup and investigate a self-chosen physics phenomenon using Arduino and low cost sensors, collecting and analyzing real data to experience the full cycle of experimental physics.
9	Bulus and Basaran (2019)	Electric circuits	Mixed-methods classroom intervention study. Quantitative instruments (attitude/engagement/ICT related scales) were combined with qualitative evidence (open-ended responses/observations/interviews).	In an Arduino-based electrical laboratory, students constructed basic circuits and employed microcontroller assisted measurement devices to record voltage and current in real time. The data was recorded and visualized, fundamental circuit principles were applied (such as Ohm's law and series/parallel rules), and the impact of component variations on the measurements was analyzed.
10	Sousa et al. (2020)	UV radiation and sustainability	Qualitative action-research/case study. Small group implementation over several sessions; data from observations, artifacts, interviews, and recordings were analyzed qualitatively (with supporting descriptive survey elements).	Uses an Arduino board along with a UV sensors to (1) measure UV intensity and (2) compute/display UVI in real time. Students assemble and program two sensor setups, take outdoor measurements, and test effectiveness of sunscreens, sunglasses, parasols, linking measured UVI to recommended protection (WHO guidance). Emphasizes hands-on instrumentation, basic programming and data handling to "materialize" an abstract concept.
11	Koumara et al. (2024)	Terminal velocity and air resistance	Qualitative case study in an informal learning setting. Pre/post quiz results were used descriptively, supported by analysis of student diaries and recorded discussions.	Students use BBC micro:bit sensors and 3D printed parts to design and test parachutes, collecting accelerometer data (with a button trigger) to compare canopy designs and analyze forces, descent time, and terminal velocity.
12	Bezerra et al. (2024)	Solar UV radiation	Classroom intervention (pilot) using inquiry based small group investigations. Learning evidence is reported from implementation outcomes (no random assignment; no clear control group reported).	ESP32 along with a ML8511 UV sensor prototype (Arduino programmed) used for real-world data collection of UVI; students test materials/contexts (shade, sunglasses, clothing, sunscreen, reflections) by placing them between sun and sensor and recording UVI results (LCD/serial output).

Table 4 (Continued).

No	Author	Topics	Research design	Microcontrollers-based learning
13	Doucette et al. (2020)	Physics lab skills	Research based implementation/case study of laboratory transformation. Evidence derived from classroom use, student observation, and feedback (descriptive evaluation; no control group).	In a transformed second year honors physics lab, students used Arduino Due based data acquisition and control in several experimental modules, taking responsibility for designing parts of the measurement setup, troubleshooting their electronics and code, and analyzing their own data instead of working with pre-configured "black-box" apparatus.
14	Ghai et al. (2022)	Physics lab skills	Design based development with pilot usability evaluation. Includes technical validation/performance testing and user feedback (not experimental/quasi-experimental learning comparison).	Arduino UNO (ATmega328) powers "talking" lab modules (thermometer, contrast/light detector, water level beeper, timer, color detector). Students could collect readings independently via audio cues, distinguish light/contrast changes, and time observations at fixed intervals while doing standard lab activities.
15	Organtini and Tufino (2022)	Physics lab skills	Quasi-experimental pre-post evaluation of a redesigned lab course. Uses standardized survey instruments (e.g., E-CLASS) and end of course questionnaires; no randomization/ control group reported.	Arduino UNO and smartphone sensors (Phyphox app) used for data collection (e.g., ultrasonic distance along with a temp sensor; accelerometer/gyroscope). Students developed experimental design agency, practiced instrument limits/uncertainty, and improved confidence using digital data along with a Python/Colab analysis.
16	Herendi and Jenei (2025)	Fluids (air pressure, flow rate/Bernoulli)	Quasi-experimental pre-/post-test classroom intervention (intact groups implied). Learning outcomes and perception data were collected and analyzed quantitatively.	Students explore fluid dynamics through the utilization of Arduino and a pressure sensor to quantify variations in air pressure. They utilize these measurements to ascertain altitude and compute airflow velocity in a Venturi tube. This interactive approach markedly enhances comprehension of pressure concepts and elevates motivation relative to conventional classroom instruction.
17	Karakotsou and Zafiriadis (2023)	Uniform linear motion	Classroom teaching intervention with survey style evaluation. Outcomes were collected from student work/feedback (descriptive; no control group reported).	Students connected real motion to x-t graphs, identified uniform motion as a straight line x-t graph, used slope/$\Delta x \div \Delta t$ to calculate constant velocity, and improved graph interpretation and teamwork
18	Farcas et al. (2024)	Physics lab skills	Non formal STEM intervention with pre/post questionnaires plus observation over an extended program. No control group; treated as a one group pre-post evaluation with qualitative observation support.	Students: built and programmed low-cost Arduino sensor/robotics devices (e.g., pressure, conductivity, electromagnetic/coil, seismograph, electromagnet/telegraph), then measured physical signals (force/pressure, water conductivity, EM/induction effects), logged/visualized data (serial monitor/data streamer), and designed a final self-chosen sensor.
19	Růžička et al. (2018)	Fluid dynamics	Quasi-experimental comparative evaluation (details limited in your notes). Compares outcomes/ implementation of a project based hydromechanics activity (group comparison implied).	Students built a computer-controlled fluid/pipe experiment, integrated flow/pressure/deformation sensing, programmed Arduino to run/collect data, and modeled the system in Agros2D to compare simulation with measured data.
20	Rivera-Ortega et al. (2023)	Projectile motion	Quasi-experimental pre-/post-test evaluation (intact group(s); random assignment not reported). Uses questionnaires before/after the intervention.	Students used an Arduino controlled Scratch (S4A) simulation (joystick/accelerometer) to adjust launch angle, initial speed, and plane inclination, completed pre/post questionnaires, and then applied the same ideas in a follow-up hands-on projectile activity using a PASCO launcher.
21	Schiavon et al. (2023)	Electrical and thermal energy (energy transformations)	Pre-experimental one-group pre-/post-test (questionnaire based). Small group classroom intervention; analyzed using quantitative comparison of pre/post responses (no control group).	Students worked in small groups to carry out three hands on experiments on converting electrical energy into thermal energy (Joule heating, a Peltier module setup, and induction heating using a ZVS module coupled to Arduino for monitoring current).
22	Schnider and Hömöstrei (2023a)	Electrical conductance	Observational implementation/ classroom project evaluation. Student perceptions were collected via post activity questionnaire (cross-sectional; no control group).	Students used an Arduino based conductance probe (series resistor and electrodes in water/salt solutions, with an H-bridge to generate AC) to measure voltage repeatedly, calculate conductance, and graph/analyze how conductance changes with salt content in Excel.

Table 4 (Continued).

No	Author	Topics	Research design	Microcontrollers-based learning
23	Schnider and Hömöstrei (2023b)	Exoplanets	Observational implementation/project-based lesson evaluation. Post-activity student questionnaire was used (cross sectional; no pre/post achievement test; no control group).	Students designed an Arduino measurement setup with a photoresistor (plus lens and lamp) to model the exoplanet transit method, logged light intensity data, and graphed/analyzed the resulting "light curves" using Excel/data streamer.
24	Schnider and Hömöstrei (2024)	Motion	Quasi-experimental non-randomized control-group pre-/post-test with delayed follow-up (design based research). Quantitative comparison between test vs control and within group retention analysis.	Students used Arduino-supported measurements (HC-SR04 ultrasonic sensor and photoresistor) to collect, stream, and graph distance-time data in Excel (data streamer), then analyzed and interpreted motion (velocity/acceleration/oscillation/circular-motion tasks) through a guided workbook.
25	Ntourou et al. (2021)	Electricity	Quasi-experimental pre-/post-test with comparison group (non-randomized implied). Multiple outcome measures (self-efficacy, motivation, computational thinking, concept understanding) analyzed quantitatively.	Fifth-grade students used Scratch for Arduino to visually program and control simple Arduino-based electric circuits, combining block-based coding with hands-on circuit building to support computational thinking and understanding of basic electricity concepts.
26	Vitkóczi et al. (2025)	Thermodynamic measurement (thermometers)	Design based educational implementation with classroom trials. Provides build instructions and classroom applications; learning evidence from student feedback/pre-post knowledge checks described descriptively.	Students built and used an Arduino-controlled pair of NTC thermometers (voltage divider sensing) to log two temperatures in parallel and stream/plot real-time temperature-time data in Excel (data streamer) during thermodynamics experiments (e.g., thermal equilibrium, Newton's cooling).
27	Sukmak and Musik (2022)	Simple harmonic motion	Pre-experimental one-group pre-/post-test plus satisfaction evaluation. Purposive sample; quantitative comparison of pre vs post achievement plus descriptive satisfaction results.	Students used a microcontroller based setup to record the vertical position of a mass on a spring as a function of time, allowing them to analyze simple harmonic motion and compare the measured oscillation with theoretical predictions.
28	Ayub et al. (2023)	Hooke's law	Observational cross sectional needs analysis. Data collected through interviews/observations and a student questionnaire; analyzed descriptively (no intervention).	Students provided feedback on the need for an Arduino microcontroller based on Hooke's law teaching aid guidebook to support hands-on elasticity experiments (i.e., a planned microcontroller assisted practicum resource rather than an implemented device).
29	Zárate-Navarro et al. (2024)	Heat transfer (conduction)	Design-based research / multi-cohort implementation of STEM workshops across multiple course terms. Evaluation uses cohort grade distributions and statistical comparison (ANOVA) plus satisfaction survey evidence.	Students recorded temperature profiles along a copper rod over time and compare/validate the measured data against MATLAB (PDEtool/analytical) and COMSOL
30	Hachmi et al. (2022)	Light diffraction	Pre-experimental one-group activity with post activity feedback questionnaire. Device tested in a classroom practical activity; quantitative measurement validation and descriptive satisfaction results.	Students captured real-time light-intensity readings across a diffraction pattern using an Arduino controlled moving sensor, then plotted and compared the measured distribution with theoretical predictions to strengthen conceptual understanding of wave optics.
31	Lucenko et al. (2020)	Temperature	Quasi-experimental non-randomized comparison (experimental vs control). Virtual/remote lab implementation; post implementation survey data compared between groups.	In the virtual/remote lab condition, students accessed a LabVIEW web published front panel to remotely view (and request limited control of) an experiment that streams real thermocouple temperature data via a microcontroller and ADC. Survey results were then compared between the experimental (virtual/remote) group and the control group using the traditional laboratory format.
32	Prahani et al. (2025)	Free-fall motion	R&D using ADDIE with expert validation and small group trial. Data from validator ratings and student response questionnaires analyzed descriptively (development & practicality/effectiveness evidence).	Students used an Arduino Uno (ATmega328) along with infrared obstacle sensors and LCD setup to capture timing/position events during free fall, display measurement outputs, and support motivation/problem-solving through hands-on lab activities.

Table 4 (Continued).

No	Author	Topics	Research design	Microcontrollers-based learning
33	Vidal et al. (2022)	Self-guided PBL physics lab practices (mechanics/EM/ thermo) with Arduino science kit	Descriptive pilot of self-guided PBL lab guides (n ≈ 20). Evidence from guide-based before/after concept questions plus a post activity survey on teamwork, problem solving and self-learning; no control group.	Students used the Arduino science kit physics lab (MKR WiFi 1010 and sensors) with Google Science Journal to complete self-guided laboratory practices (plus an alternative-procedure phase), record measurements, and analyze data in the guides/reports to link results to the relevant physical laws.
34	Wibowo et al. (2023)	Refraction of light	R&D using ADDIE with expert validation and field testing. Implementation tested with students; evidence includes validation ratings and student response data.	Students measured and logged light-refraction angles using an Arduino Uno (ATmega328) Simple Kit, where a green laser and a photodiode sensor (moved by a stepper motor/potentiometer) detected the refracted beam and displayed incident and refraction angles on an LCD to visualize the concept.
35	Huda et al. (2023)	Collisions	R&D development study with expert validation & staged trials (limited and wider field testing). Data collected via questionnaires; analyzed descriptively.	Students recorded distance at fixed intervals and derive object speed, making collision experiments quicker, more accurate, and easier to vary.
36	Koyimah et al. (2020)	Impulse & momentum	Pre-experimental one-group pre-/-post-test. Students completed pre/post achievement measures after inquiry-based intervention.	Students used an Arduino-based speed sensor to record/display collision speeds (and related quantities) during inquiry based impulse momentum activities.
37	Dökme and Hancıoğlu (2025)	Electricity	Comparative quasi-experimental design with pre-/post-test experimental and control groups (7th grade; experimental group built and ran circuits with coding, control group ran without coding versions)	Pupils connect electricity concepts to functioning artifacts by assembling circuits and implementing coded robotic STEM activities, then iterating when the circuit behavior does not match expectations; compared with non-coding circuit work, the coding integrated pathway is associated with stronger gains in science attitudes and STEM career interest.
38	Omari et al. (2023)	Temperature	Quasi-experimental, two group pre-/post-test (control vs experimental) intervention. One group learned the temperature lesson with educational robotics, while the control group followed conventional instruction; outcomes compared with independent samples t-tests.	Students in the experimental group learned temperature concepts using an Arduino-based educational robot equipped with a temperature sensor and smartphone interface, which enabled real-time measurement and visualization of temperature during a guided classroom activity.

1. Facilitating learning through real-time feedback and visualization of physical quantities and their relationships (e.g., position vs. time, current vs. voltage, and pressure vs. height), including opportunities for embodied learning when live graphs respond directly to students' actions (Bulus & Basaran, 2019; Hadiati et al., 2019; Herendi & Jenei, 2025; Karakotsou & Zafiriadis, 2023; Schnider & Hömöstrei, 2024; Vitkóczi et al., 2025).
2. Facilitating learning through multiple synchronized representations of the same phenomenon (e.g., numerical readouts, real-time graphs, sensor streams, and underlying code), supporting connections between measurements, models, and interpretation (Castro, 2020; Kuan et al., 2016; Organtini & Tufino, 2022; Schnider & Hömöstrei, 2024; Vitkóczi et al., 2025).
3. Facilitating learning through automated and high-frequency data acquisition that captures fast-evolving dynamics and subtle temporal patterns that are difficult to observe with manual measurements (e.g., rapid oscillations, short-lived transients, and small gradients) (Hachmi et al., 2022; Lucenko et al., 2020; Sukmak & Musik, 2022; Vitkóczi et al., 2025; Walkup et al., 2019;).
4. Facilitating learning by influencing improved measurement accuracy and procedural consistency, reducing timing and recording errors, and enabling repeatable data collection so that students can focus on reasoning, uncertainty, and model testing (Castro, 2020; Ghai et al., 2022; Huda et al., 2023; Lucenko et al., 2020; Walkup et al., 2019).
5. Facilitating learning by creating broader access to laboratory experiences through low-cost and portable setups, enabling experimentation in resource-limited settings and outside formal laboratories (e.g., at home, remotely, or in the wonderful outdoors) (Bezerra et al., 2024; Castro, 2020; Ghai et al., 2022; Lucenko et al., 2020; Sousa et al., 2020; Vidal et al., 2022).

6. Facilitating learning by enabling learner agency via building and configuring experimental setups, where students assemble circuits, select sensors, tune parameters, and iteratively refine designs based on measured data, fostering inquiry and creativity (Bouquet et al., 2017; Castro, 2020; Coban & Erol, 2025; Doucette et al., 2020; Dökme & Hancıoğlu, 2025; Farcas et al., 2024).
7. Facilitating learning through the integration of IT skills with laboratory practice, requiring students to implement acquisition logic in code, manage variables and sample selections, calibrate sensors, troubleshoot hardware/software, and interpret data within a single coherent experimental workflow (Castro, 2020; Coban & Erol, 2025; Doucette et al., 2020; Kuan et al., 2016; Lucenko et al., 2020; Organtini & Tufino, 2022; Sousa et al., 2020).

Using microcontroller platforms makes it easier for teachers to create opportunities for interactive learning. Primarily, microcontroller-based activities facilitate real-time feedback and visualization of critical variable relationships (e.g., distance vs. time, voltage vs. current, temperature vs. time, and pressure vs. altitude), helping students connect changing quantities to underlying concepts as phenomena unfold in authentic measurements (Bulus & Basaran, 2019; Hadiati et al., 2019; Herendi & Jenei, 2025; Schnider & Hömöstrei, 2024; Vitkóczi et al., 2025). In addition, it is common for these tasks to incorporate various synchronized representations, such as sensor streams, numerical readouts/tables, dynamic graphs (e.g., through data streamer/Excel), and adjustable code/parameters. This approach is in line with learning from multiple external representations, as suggested by Ainsworth (2006), and has been used in numerous microcontroller-supported laboratory designs, as shown by Kuan et al. (2016), Castro (2020), Organtini and Tufino (2022), Schnider and Hömöstrei (2024), and Vitkóczi et al. (2025).

Microcontroller-based activities can enhance learner autonomy and engagement while supporting manageable cognitive demands when instructional tasks are appropriately structured (Bouquet et al., 2017; Doucette et al., 2020; Ntourou et al., 2021). In addition, they support design-focused inquiry as learners construct or modify experimental setups, select sensors, adjust parameters, and troubleshoot hardware and software issues. In this way, practical work shifts from following rigid protocols toward making design decisions based on empirical data (Coban & Erol, 2025; Farcas et al., 2024). Furthermore, automated and/or high-frequency data acquisition can capture temporal nuances that are challenging to discern through manual measurement, including oscillation traces, ephemeral transients, or dense spatial and temporal sampling. This broadens the spectrum of phenomena that students can simulate and comprehend in educational environments (Hachmi et al., 2022; Lucenko et al., 2020; Sukmak & Musik, 2022; Vitkóczi et al., 2025; Walkup et al., 2019).

Finally, students acquire practical experience in an IT-supported laboratory setting by analyzing streaming datasets, calibrating and debugging systems, implementing acquisition logic, and assembling microcontrollers with modular sensors. Numerous studies indicate that this integration facilitates computational thinking, experimental reasoning, and data interpretation (Bulus & Basaran, 2019; Kuan et al., 2016; Ntourou et al., 2021; Organtini & Tufino, 2022).

What Are the Potential Advantages and Disadvantages of Using Microcontrollers in Learning About Physics Topics?

Next, we will analyze possible advantages and disadvantages of microcontroller-based physics learning activities. Our analysis is based on findings from the 38 empirical research articles that we included in our systematic review. A meta-analysis of the microcontroller effects has not been performed because the article pool includes very heterogenous research contexts and designs.

Positive effects on the affective domain of learning

A substantial number of empirical studies highlight that learning physics with microcontrollers is associated with positive influences on students' affective domain through enhanced motivation, interest, engagement, attitudes, and confidence/self-efficacy related to experimental and programming tasks (Bouquet et al., 2017; Bulus & Basaran, 2019; Doucette et al., 2020; Kuan et al., 2016; Ntourou et al., 2021). These affective dimensions are fundamental to learning because they shape not only students' willingness to participate in learning activities but also their longer-term identification with physics practices and experimentation (Doucette et al., 2020). Unlike cookbook-style experiments, microcontroller-based activities allow students to modify experimental setups and procedures, which can increase learner autonomy, engagement, and ownership of the activity (Bouquet et al., 2017; Doucette et al., 2020; Vidal et al., 2022). Several studies, including Bouquet et al. (2017), Doucette et al. (2020), and Ntourou et al. (2021), indicate that microcontroller-based activities can enhance learner autonomy and engagement while supporting manageable cognitive demands when instructional tasks are appropriately structured. This is especially meaningful because students directly manipulate equipment while observing the consequences of their actions in real time, which strengthens involvement through prompt feedback and visible outcomes (Hachmi et al., 2022; Schnider & Hömöstrei, 2024; Sukmak & Musik, 2022; Vitkóczi et al., 2025). In introductory and laboratory-based contexts, students have also reported positive feedback, stronger emotional engagement with physics, and greater confidence in programming and experimental tasks when they move from passive observation to active design, measurement, troubleshooting, and analysis (Bulus & Basaran, 2019; Chaudry, 2020; Kuan et al., 2016; Ntourou et al., 2021; Walkup et al., 2019). In particular, overcoming practical challenges such as debugging code, calibrating sensors, and refining measurement setups can strengthen students' sense of competence and support persistence during experimental work (Bouquet et al., 2017; Doucette et al., 2020; Kuan et al., 2016; Ntourou et al., 2021). Overall, the reviewed evidence suggests that microcontroller-based instruction can strengthen students' interest, engagement, confidence, and willingness to confront experimental challenges independently, particularly when activities emphasize autonomy, real-time feedback, and hands-on problem-solving.

Positive effects on the cognitive domain of learning

Research studies indicate that microcontroller-based instruction in physics can improve cognitive learning outcomes, including stronger conceptual understanding, better application of physics concepts to real-world contexts, and improved problem-solving in laboratory tasks. These outcomes are commonly attributed to instructional mechanisms such as real-time measurement and immediate visualization of variables, multiple coordinated representations of the same phenomenon (e.g., sensor stream, graph, table, and code), and collaborative inquiry-based work that supports interpretation, troubleshooting, and model testing. In this way, microcontroller-supported activities can reduce avoidable procedural demands (e.g., manual timing/recording) and redirect students' effort toward reasoning, explanation, and evidence based decision making (Doucette et al., 2020; Hadiati et al., 2019; Schnider & Hömöstrei, 2024; Vitkóczi et al., 2025).

Authentic inquiry and self-regulated learning: Microcontroller-based environments can support authentic inquiry and self-regulated learning by enabling learners to conduct hands-on investigations, make decisions about procedures, and develop teamwork, problem-solving, and self-learning skills through project-based laboratory practices (Bouquet et al., 2017; Doucette et al., 2020; Vidal et al., 2022).

Mechanics: Vidal et al. (2022) assert that high school students who participate in tasks involving microcontrollers linked to diverse modular sensors actively investigate physics concepts and cultivate engineering skills, while simultaneously enhancing teamwork abilities through collaborative activities (Coban & Erol, 2025; Vidal et al., 2022). Research indicates that Arduino-based instruction in physics enhances students' conceptual comprehension (Chaudry, 2020). Schnider and Hömöstrei (2024) conducted a quasi-experimental pretest-posttest study with a control group and discovered that students' kinematics learning outcomes enhanced when utilizing Arduino sensors to relay real-time distance-time data into Excel for visualization and analysis. The microcontroller-based method allowed students to gather real-time kinematic data, juxtapose experimental measurements with theoretical predictions, and cultivate hypothesis-testing and experimental design competencies. Further evidence from secondary school applications indicates learning advancements in mechanics-related scenarios: students employing Arduino pressure-sensor data to ascertain altitude variations and airflow (venturi) exhibited measurable knowledge improvements (Herendi & Jenei, 2025).

Electricity and electronics: Engaging students in microcontroller-based laboratories such as Arduino activities enabled them to build circuits, measure voltage and current, and analyze capacitor behavior in real time. These activities also supported collaborative problem-solving and evidence-based reasoning in electricity-related tasks (Bulus & Basaran, 2019; Hadiati et al., 2019; Ntourou et al., 2021). Similar evidence from electricity-focused implementations shows that real-time acquisition of voltage and current data can make circuit relationships observable and support evidence-based reasoning (Hadiati et al., 2019), and microcontroller-supported measurement has also been used in classroom activities focused on electricity-related concepts (Schiavon et al., 2023). Experimenting Arduino (S4A) microcontrollers and the Scratch programming language helped fifth-grade students to improve their understanding of electricity and computational thinking (Ntourou et al., 2021).

Optics: In optics, curriculum-oriented instrumentation tasks show that microcontroller-based measurement design supports authentic inquiry: when learners build automated measurement systems (e.g., light sensors and optical gates), they move from passive observation to active construction, troubleshooting, and data interpretation (Kuan et al., 2016). Project-based implementations further show that low-cost microcontroller-supported optical instruments can turn abstract wave-optics theory into tangible experimental challenges that foster self-regulation and conceptual understanding (Bouquet et al., 2017; Hachmi et al., 2022). Similar optics-oriented activities also report the use of microcontroller-based timing or automated measurements to support data interpretation and reasoning about uncertainty and measurement outcomes (Walkup et al., 2019; Wibowo et al., 2023).

Thermodynamics: In order to support better data interpretation and model-based reasoning, learners built and utilized Arduino-controlled thermometer pairs (NTC thermistors in a voltage-divider circuit) to log two temperatures in parallel and stream real-time temperature data over time into Excel for plotting and interpretation across core thermodynamics activities (e.g., thermal interaction and Newton's law of cooling) (Vitkóczi et al., 2025). Students who used an Arduino-based educational robot with a temperature sensor to record and display real-time temperature data in a quasi-experimental study showed better post-test learning outcomes and motivation than students who received instruction using conventional methods (Omari et al., 2023). The use of sensor-driven feedback allows for a more flexible learning environment and makes temperature more easily measurable (Omari et al., 2023). Students conducted experimental tests of the theory of heat conduction, a basic thermodynamic transport mechanism, using an Arduino-based lab kit that consisted of thermocouples strung along a copper rod. Then, to validate the models and understand the concepts better, they compared the experimental results to analytical and simulation-based models (COMSOL and MATLAB PDEtool/analytical solutions) (Zárate-Navarro et al., 2024).

Facilitating visual learning: Visual learning significantly improves conceptual understanding for most individuals. Since physics concepts are often related to space and time, visualization is very important. So, when students are presented with graphs, various tables, or animations, and all this in real time, they can learn physics through multiple representations (Schnider & Hömöstrei, 2024; Vitkóczi et al., 2025).

Mechanics: With the use of microcontroller-based sensors and real-time visualization, students can convert abstract motion variables into comprehensible graphs and patterns. Streaming sensor data into spreadsheets allows students to see how distance changes over time instantly. They can then infer acceleration and velocity using slope analysis (Organtini & Tufino, 2022; Schnider & Hömöstrei, 2024). Students utilized an Arduino-controlled ultrasonic sensor to present distance-time data in real-time within Excel (data streamer). They subsequently employed the graph to analyze uniform motion and calculate velocity through linear fitting (Schnider & Hömöstrei, 2024). Students compared recorded displacement with theoretical motion and extended the study to velocity and acceleration curves by utilizing an Arduino-based setup to graph the vertical oscillation of a mass-spring system in real time (Sukmak & Musik, 2022). Connecting formulas to observable experimental behavior, these instantaneous multi-representation presentations (tables and graphs) facilitate conceptual understanding (Organtini & Tufino, 2022).

Electricity and electronics: Visual feedback from microcontroller-based circuits, featuring real-time displays of current, voltage, and capacitor charging and discharging patterns, can improve students' comprehension of fundamental electrical concepts as they endeavor to connect theoretical principles to practical applications (Bulus & Basaran, 2019; Hadiati et al., 2019; Ntourou et al., 2021). Ntourou et al. (2021) documented that visual programming combined with real-time Arduino experiments improved fifth-grade students' conceptual understanding of electrical concepts through interactive graphical feedback.

Optics: Microcontroller-supported activities allow learners to translate wave-based signals into real-time visual outputs, making abstract wave behavior easier to interpret through graphs and data streams (Hachmi et al., 2022; Schnider & Hömöstrei, 2023b).

Learners working with Arduino-based optical measurement systems can transform light intensity changes into tangible visual representations and link wave theory to empirical practice (Kuan et al., 2016). Project-based lab formats enhance these objectives by providing learners with the autonomy to construct and assess low-cost optical setups, thereby fostering deeper engagement with measurement, calibration, and interpretation (Bouquet et al., 2017).

Thermodynamics: By transforming temperature fluctuations into an observable, time-resolved dataset, measurements enabled by Arduino can make thermodynamic processes more tangible (Vitkóczi et al., 2025). Instead of focusing on manual documentation, students can use an Arduino-controlled thermometer system to record two temperatures at the same time and create real-time temperature-time graphs in Excel. This allows them to analyze thermal interactions and cooling behavior more effectively (Vitkóczi et al., 2025). Students can enhance their abilities to compare and validate models with data by recording temperature profiles along a heated rod with various sensors as part of a larger thermodynamics learning sequence (Zárate-Navarro et al., 2024). Across these thermodynamics' activities, the common mechanism is automated data acquisition along with immediate visualization, which shifts learners' effort from recording values to interpreting graphs, checking consistency with theory, and refining experimental conditions key features of inquiry-oriented lab work (Doucette et al., 2020). In the same direction, sensor-based educational robotics can make "temperature" observable in real time, because learners directly see changes displayed on a screen and can link the observed trend to the underlying concept, which is associated with higher motivation and better post-test outcomes than conventional instruction (Omari et al., 2023).

Development of core cognitive competencies: When students engage in Arduino-based tasks, they enhance their critical thinking skills in physics by interpreting sensor outputs, justifying measurement choices, and connecting observed patterns to underlying concepts (Kuan et al., 2016; Ntourou et al., 2021). Additionally, students develop the ability to reason hypothetically when designing experimental projects and solving problems (Bouquet et al., 2017; Ntourou et al., 2021). The way students build different circuits, write codes, or figure out what's wrong with something makes them come up with testable predictions. They are already used to making conclusions based on what they see by looking at data in numbers (Bouquet et al., 2017; Doucette et al., 2020; Kuan et al., 2016). Ntourou et al. (2021) and Bouquet et al. (2017) reported that the routine of repeating experimental practices increases students' awareness of experimental uncertainty, variable control, and the iterative nature of inquiry (i.e., planning, testing, revising, and re-testing). Thus, students strengthen metacognitive skills that are fundamental to scientific research. Also, IT skills are developed students' concurrent development of programming, debugging, and data-handling competencies are part of the experimental workflow (Bouquet et al., 2017; Kuan et al., 2016). The systematic incorporation of microcontrollers into physics education is associated with cognitive benefits, including improved conceptual retention, increased problem-solving abilities, and the development of independent learning habits. Enhancements in students' knowledge and changes in constructs related to higher-order thinking, including computational thinking and self-efficacy were observed in pre-post and quasi-experimental implementations of Arduino-supported instruction (Herendi & Jenei, 2025; Ntourou et al., 2021). Additionally, findings from mixed-method classroom research reveal that students have more positive perceptions of technology and information and communication technology (ICT), supporting claims of improved technological literacy (Bulus & Basaran, 2019). These activities promote higher-order reasoning by necessitating that students plan, test, revise, and justify measurement decisions within a unified experimental framework. Consequently, microcontroller-based tasks foster the development of scientific reasoning and problem-solving abilities, surpassing the procedural approaches typical of traditional "cookbook" laboratories.

Optimization of cognitive load: Microcontroller-based experimentation can improve cognitive efficiency by automating repetitive procedural tasks and transforming sensor output into immediate, intelligible feedback (Doucette et al., 2020; Vidal et al., 2022). Real-time data streaming and visualization can redirect students' focus on sense-making, model-data comparison, and error analysis instead of mere rote recording. Nonetheless, these advantages rely on suitable scaffolding, as wiring and debugging may otherwise impose extra cognitive burdens that disrupt conceptual processing (Doucette et al., 2020). Block-based visual programming, such as Scratch for Arduino/S4A, has been utilized to reduce the entry barrier for novices in coding and circuit control (Ntourou et al., 2021; Rivera Ortega et al., 2023).

Temporal efficiency and enhanced learning productivity: The integration of microcontrollers significantly decreases the time required to complete experimental tasks by automating sensor calibration and enabling immediate data acquisition and visualization, thereby allowing for swift iteration between repeated measurement trials and systematic adjustments of experimental parameters (Doucette et al., 2020; Vidal et al., 2022). This temporal efficiency reallocates student cognitive resources to more valuable tasks, such as quantitative analysis of experimental outcomes, investigation of parameter variations, and contemplation/discussion about fundamental physical principles. Potential educational advantages include reduced instructional demands for educators, enhanced formative assessment practices, and the maintenance or enhancement of learning outcomes relative to traditional laboratory methodologies (Doucette et al., 2020; Vidal et al., 2022).

High accessibility and usability

Over the years, advancements in microcontroller technologies like Arduino and ESP32 have significantly increased their presence in physics classrooms. These tools have been well-received and are being progressively integrated into educational settings for physics. Their cost-effectiveness helps alleviate financial barriers and supports the extensive implementation of practical, project-based initiatives (Bezerra et al., 2024; Bouquet et al., 2017; Vidal et al., 2022). Moreover, these platforms enable differentiated instruction, as the identical core hardware can be employed in tasks that vary from structured, guided activities to more open-ended inquiries customized to students' prior knowledge and available time (Bulus & Basaran, 2019).

Ease of use and practicality: Microcontrollers enhance the practicality of physics labs by digitizing measurements and automating data logging. This technology can alleviate the procedural burden for both instructors and students (Doucette et al., 2020; Vidal et al., 2022). Once sensors are connected and a working program is uploaded, data collection can run with minimal manual recording, allowing students to spend more time interpreting results rather than copying values by hand (Doucette et al., 2020; Vidal et al., 2022). Students in a project-based learning setting employ an Arduino kit to execute autonomous laboratory procedures and collect sensor data following established protocols, as evidenced by Vidal et al. (2022). Furthermore, instrumentation focused education illustrates the enhancement of measurement and analysis processes through the integration of Arduino with interface-driven data acquisition systems (Kuan et al., 2016). Kuan et al. (2016) describe a physics instrumentation curriculum in which students utilize visual interfaces in LabVIEW and LabVIEW for Arduino to control experiments and manage data acquisition.

This facilitates the execution and evaluation of measurement protocols. For beginners and non-majors, this practicality matters because it lowers the entry barrier: Arduino activities can be run with simple wiring, reusable components, and immediate data display, while still supporting meaningful experimental work (Chaudry, 2020). Across implementations from introductory lab transformations to guided project work microcontroller-based setups often show an advantage: they are robust enough to generate real measurement data, yet simple enough to scale across different classroom levels when the activities are well-structured (Doucette et al., 2020; Vidal et al., 2022).

Low cost: One important advantage of microcontroller-based laboratories is the reduction in equipment costs compared to traditional equipment. This economic efficiency enables institutions with limited budgets such as vocational and resource-constrained settings, to provide experimental experiences (Bouquet et al., 2017; Organtini & Tufino, 2022). Bouquet et al. (2017) provides a foundational argument for "low-cost open-source hardware," demonstrating that standard physics experiments can be performed with "everyday objects" and cheap sensors for a fraction of the cost of commercial proprietary equipment. To save even more money, Organtini and Tufino (2022) show that Arduino-based labs can work with students' own smartphones (for example, through Phyphox) to collect data using built-in sensors instead of buying separate instruments. Such approaches leverage powerful sensors that are already present in students' pockets (accelerometers and gyroscopes), thus eliminating the need for investment in expensive independent detectors and promoting a scalable laboratory model. In vocational settings, "self-designed experimental tools" reduce budgetary requirements while still improving learning outcomes in topics like circular motion (Çoban & Erol, 2025). Ghai et al. (2022) conducted a showcase demonstrating how affordable components can support accessible physics measurement activities. In school contexts where resources are limited, low-cost Arduino activities can still support measurable learning gains, making them practical for vocational or resource-constrained environments (Dökme & Hancıoğlu, 2025).

Health and environment: A valuable approach to connecting abstract concepts in physics to real-world issues is to incorporate microcontrollers into health and environmental monitoring contexts (Bezerra et al., 2024; Sousa et al., 2020). These interdisciplinary applications can transform the physics lab from a detached environment into a platform for learners to engage in real-world measurement and decision-making. Students used an ESP32/Arduino-programmed ultraviolet (UV) sensor to record real-world UV index (UVI) values and evaluate how materials and contexts (shade, clothing, reflections) reduce exposure, linking sensor data to environmental health protection (Bezerra et al., 2024). Similarly, outdoor UV monitoring activities have been used to connect measurements with practical protection recommendations and everyday contexts (Sousa et al., 2020).

Adaptability to various students' needs: Microcontroller-based learning can be tailored to meet the needs of various student groups. For instance, research shows that technology can be adapted for younger learners, such as those in 5th grade, by integrating Arduino with "visual programming" tools like Scratch. This visual approach enhances self-efficacy and computational thinking among elementary students by reducing the barriers to coding and circuit control (Ntourou et al., 2021). Students can be motivated by interactive and gamified learning methods. For example, they can use the microcontroller to make a "learning game" (Yasin et al., 2018). Earlier research highlights a "STEM-Kit" approach that provides an interdisciplinary pathway, particularly appealing to students interested in physics and computer science (Vidal et al., 2022). The text examines how restructured laboratory settings leverage the open architecture of microcontrollers, facilitating more sophisticated experimentation and diagnostics (Doucette et al., 2020). Students who are unable to physically attend a laboratory session can still participate in the learning process thanks to the adaptability of these technological tools (Lucenko et al., 2020).

Potential negative effects on affective domain of learning

Without deliberate, progressive instructional support, microcontroller-based physics activities can generate affective challenges (e.g., frustration, reduced motivation, and anxiety) for learners (Ntourou et al., 2021). It is acknowledged that physical computing activities, although potentially engaging, can also be quite demanding and may result in an unpleasant learning experience when tasks increase cognitive load (Ntourou et al., 2021). Findings of this type support the important idea that technological tools do not necessarily increase students' motivation. Concretely, in the study by Ntourou et al. (2021), Arduino-based learning failed to prove a positive effect on motivation (Ntourou et al., 2021, p. 1), suggesting that affective benefits are not automatic. As noted by Bouquet et al. (2017, p. 216), project-based learning using Arduino "can be somewhat destabilizing" for instructors who are used to traditional verification labs with predetermined outcomes. This approach requires instructors to embrace uncertainty and adapt their implementation and assessment practices, which may pose challenges for both teachers and students.

Potential negative effects on cognitive domain of learning

While some empirical studies suggest that Arduino-based laboratories may be stimulating, they do not guarantee cognitive enhancements in physics for all students (Ntourou et al., 2021; Zárate-Navarro et al., 2024). Their benefits are most evident when activities provide immediate and clear sensory feedback, permit repeated trials, and enable reasoning about calibration, uncertainty, and model-data comparison (Çoban & Erol, 2025; Doucette et al., 2020; Schnider & Hömöstrei, 2024; Sukmak & Musik, 2022; Walkup et al., 2019). Numerous studies indicate that students frequently allocate excessive effort to wiring, debugging, programming, and equipment management, rather than engaging in conceptual reasoning in physics (Doucette et al., 2020; Bouquet et al., 2017; Bulus & Basaran, 2019; Kuan et al., 2016). In such cases, practical activity does not necessarily lead to cognitive engagement, especially when students have limited prior knowledge or insufficient instructional support (Bulus & Basaran, 2019; Ntourou et al., 2021). Without explicit scaffolding, directed prompts, and troubleshooting support, tasks involving microcontrollers may increase unnecessary cognitive load and reduce students' ability to analyze data, evaluate assumptions, and apply conceptual knowledge across various contexts.

Low accessibility and usability

Complexity of use and practicality: Empirical studies suggest that accessibility may be limited by the practical complexities of performing microcontroller-based tasks, particularly for beginners. Effective classroom implementation, notwithstanding the cost-effectiveness of hardware, often depends on the accessibility of appropriate materials, reliable computing access, reusable components, and adequate instructor support (Doucette et al., 2020; Kuan et al., 2016; Vidal et al., 2022). Remote implementations may pose further difficulties when students do not have immediate support for setup and troubleshooting (Lucenko et al., 2020). The effective implementation of microcontroller-based instruction depends on technological resources and the availability of organizational and instructional support.

Health and safety: The empirical literature identifies practical handling risks, even though Arduino platforms generally function at low-voltage logic levels. In open-ended, project-based environments, equipment damage may arise when learners are permitted to experiment freely, as indicated by Bouquet et al. (2017), who assert that instructors may "encourage students to experiment on whatever they think is interesting, even risking damaging the equipment" (Bouquet et al., 2017, p. 217). This study suggests that autonomy-oriented implementations benefit from appropriate guidance and oversight during hands-on work (Bouquet et al., 2017; Doucette et al., 2020).

High cost: The characterization of Arduino as "low-cost" requires careful examination when applied to classroom settings. Despite microcontroller boards and numerous sensors being characterized as cost-effective, classroom implementation may necessitate several kits, compatible sensors, and components for various experiments, computers for programming and data acquisition, as well as replacement parts due to wear or damage incurred during practical activities (Bouquet et al., 2017; Vidal et al., 2022). In project-based formats, authors also note that effective implementation may require a versatile set of equipment and materials, and such requirements can reduce the appeal of project-based approaches in university curricula (Bouquet et al., 2017). Moreover, hardware damage during open-ended experimentation is reported as a realistic cost consideration: Bouquet et al. (2017) note that "one or two Arduino boards were damaged during the projects," which they frame as an acceptable trade-off for autonomy but which may still pose a practical constraint in resource-limited settings. Finally, several implementations emphasize that additional instructional time and teacher preparation/support may be needed to make Arduino-based activities run smoothly, adding indirect costs beyond the equipment itself (Doucette et al., 2020; Vidal et al., 2022).

Suggestions for Teaching and Research Practice

In our paper, we have discussed the ways in which microcontroller technologies may facilitate learning physics, their potential advantages and disadvantages. We also briefly reflected on the research designs in earlier microcontroller-based learning research. Next, we propose a few suggestions that may help to improve the existing teaching and research practices.

When it comes to the teaching practice:

1. Teachers should take as much time as necessary to carefully select microcontroller boards and sensors that meet their specific needs, technical capabilities, and learning objectives (e.g., choosing between block-based coding for novices vs. C++/Python for advanced students, or selecting sensors with appropriate precision/sampling rates).
2. Teachers and educational hardware developers are advised to pay more attention to the quality of the experimental setup design (e.g., clarity of wiring diagrams, code readability, circuit stability, and ease of sensor calibration).
3. When planning the implementation of microcontroller-based lectures, physics teachers are advised to carefully consider how to avoid technical difficulties reported in earlier research, such as driver installation issues, library conflicts,

loose breadboard connections, baud rate mismatches, and sensor noise.

4. It is recommended to secure enough microcontroller kits and spare components in the classroom, so that all students can actively participate in the wiring and coding process rather than passively watching.
5. Teachers are recommended to incorporate checkpoints or debugging sessions into lectures to avoid students' frustration when circuits fail to work. Furthermore, they are advised to avoid using poorly documented sensors or incompatible hardware modules that distract from the physics concepts.

Next, we provide suggestions for physics education researchers. In future microcontroller research, it would be interesting to:

1. Explicitly compare different types of microcontroller platforms, implemented for teaching about a single topic (e.g., Arduino Uno vs. ESP32/Wi-Fi modules when teaching about remote data acquisition, or physical hardware vs. simulation tools like Tinkercad circuits).
2. Investigate whether the effectiveness of microcontroller-based learning depends on certain students' characteristics, such as prior programming experience, manual dexterity (breadboarding skills), and attitudes toward technology.
3. Conduct long-term studies lasting for several months to investigate the impact of the novelty effect, for different population groups.
4. Thoroughly investigate ways for optimizing the cognitive load in microcontroller-based learning (balancing the load of coding/wiring vs. physics concept learning), which should also include measurements of cognitive load.
5. Conduct more in-depth, qualitative studies about the students' experience with troubleshooting and "making" in the context of learning physics.

Finally, following the example of the PhET repository, it would be useful to create a centralized repository of standardized microcontroller physics scripts (codes) and wiring schematics along with guidelines for their implementation in physics teaching practice.

Limitations of the Study

This systematic literature review includes only empirical studies on microcontroller-based physics learning. The review was limited to English-language publications indexed in ERIC or Scopus and published between 1 January 2010 and 31 December 2025. We did not systematically search Web of Science (WoS) or Google Scholar. Google Scholar was not included because it indexes a very broad range of materials of uneven scholarly quality, which would have increased the screening burden for this topic. WoS was not searched because its coverage for this area overlaps substantially with Scopus. Nevertheless, the use of only two databases may have led to the omission of some relevant studies.

A further limitation concerns the search strategy itself. The search was restricted to the terms "microcontroller," "Arduino," and "ESP32," combined with "physics," "science," and "STEM." Although these terms captured a substantial portion of the relevant literature, some eligible studies may still have been missed because they used alternative terminology, as suggested by the manually identified studies (e.g., "robotic"). In addition, the restriction to English-language full-text publications may have excluded relevant work from other linguistic and cultural contexts. The exclusion of conference proceedings, theses, dissertations, and technical reports may also have contributed to publication bias, particularly in a field where innovative educational applications are sometimes first reported outside journal articles.

Another limitation is that no formal quality appraisal or risk-of-bias instrument was applied to the 38 included empirical studies. As a result, studies with differing levels of methodological rigor were synthesized descriptively without being weighted according to quality. This means that the review is better interpreted as a systematic descriptive synthesis of the available empirical literature than as a basis for strong effectiveness claims. At the same time, restricting inclusion to peer-reviewed journal articles indexed in ERIC and Scopus likely provided at least a basic level of quality control.

Finally, although the empirical eligibility assessment of the 231 full-text articles was conducted independently by two authors, the earlier screening steps and the supplementary manual search were conducted by a single author. While these procedures were guided by explicit inclusion and exclusion criteria (**Table 2** and **Table 3**), this partial reliance on single-author screening may still have introduced a limited risk of selection bias.

CONCLUSION

This paper presents findings from a systematic review that synthesized 38 peer-reviewed empirical studies published between 1 January 2010 and 31 December 2025 regarding microcontroller-based physics education. Our findings show that platforms such as Arduino, ESP32, and Micro:bit potentially help students learn physics by enabling them to collect and visualize data from sensors in real time (Bezerra et al., 2024; Koumara et al., 2024; Schnider & Hömöstrei, 2024; Vitkóczi et al., 2025).

By merging the seven previously identified and partly overlapping categories of educational affordances into broader interpretative themes, we conclude that microcontrollers may support physics learning through:

1. **Providing real-time representational support for learning**, by making physical quantities and their relationships immediately visible and, in some cases, directly responsive to students' actions (Bulus & Basaran, 2019; Hadiati et al., 2019; Herendi & Jenei, 2025; Karakotsou & Zafiriadis, 2023; Schnider & Hömöstrei, 2024; Vitkóczi et al., 2025).
2. **Supporting learning through multiple synchronized representations** of the same phenomenon, such as sensor streams, numerical readouts, live graphs, and code, thereby helping students connect measurements, models, and interpretation (Castro, 2020; Kuan et al., 2016; Organtini & Tufino, 2022; Schnider & Hömöstrei, 2024; Vitkóczi et al., 2025).
3. **Enhancing experimental work through automated and high-frequency data acquisition**, which enables more consistent, repeatable, and fine-grained measurements while reducing routine recording errors and shifting attention toward interpretation, uncertainty, and model testing (Castro, 2020; Ghai et al., 2022; Hachmi et al., 2022; Huda et al., 2023; Lucenko et al., 2020; Sukmak & Musik, 2022; Vitkóczi et al., 2025; Walkup et al., 2019).
4. **Expanding access to laboratory experiences** through low-cost, portable, and flexible setups, making experimentation feasible in resource-limited contexts and beyond traditional laboratory environments (Bezerra et al., 2024; Castro, 2020; Ghai et al., 2022; Lucenko et al., 2020; Sousa et al., 2020; Vidal et al., 2022).
5. **Supporting learner agency through inquiry-oriented experimental and computational work**, as students build and refine setups, calibrate sensors, adjust parameters, work with code, troubleshoot systems, and interpret data within a coherent experimental workflow (Bouquet et al., 2017; Castro, 2020; Coban & Erol, 2025; Doucette et al., 2020; Dökme & Hancıoğlu, 2025; Farcas et al., 2024; Kuan et al., 2016; Lucenko et al., 2020; Organtini & Tufino, 2022; Sousa et al., 2020).

Our review of empirical studies (n = 38) reveals that microcontroller-based interventions often produce favorable effects on students' affective outcomes, such as increased engagement and self-efficacy, and, in some instances, enhanced conceptual understanding or improved laboratory problem-solving abilities (Bulus & Basaran, 2019; Doucette et al., 2020; Herendi & Jenei, 2025; Ntourou et al., 2021; Schnider & Hömöstrei, 2024). Numerous studies, including those by Bouquet et al. (2017), Doucette et al. (2020), and Ntourou et al. (2021), consistently demonstrate that microcontroller-based activities can enhance learner autonomy and engagement, while promoting problem-solving and sustaining manageable cognitive demands when instructional tasks are appropriately structured. These advantages are intricately linked to the experiential aspect of learning and to students' agency in designing, evaluating, and enhancing experimental configurations.

When it comes to the development of conceptual understanding, it could be primarily explained by the fact that automated data collection and real-time visualization can free time for data interpretation and classroom discussion (Schnider & Hömöstrei, 2024; Vitkóczi et al., 2025; Walkup et al., 2019). The analyzed studies indicate the cultivation of extensive competencies, such as critical thinking, creativity, and digital skills, especially when students participate in debugging, measurement decisions, and sensor-based experimental design (Bouquet et al., 2017; Coban & Erol, 2025; Doucette et al., 2020; Farcas et al., 2024; Kuan et al., 2016; Ntourou et al., 2021). Eventually, the effectiveness of microcontroller-based learning of physics is determined by a combination of the didactic potential of microcontroller-based activities combined with teacher guidance and students' characteristics (Bouquet et al., 2017; Doucette et al., 2020). Concretely, students need direction to avoid getting bogged down in wiring, coding, calibration, and debugging rather than focusing on the core concepts of physics (Doucette et al., 2020; Kuan et al., 2016).

The review also highlights several ongoing challenges that can prevent microcontroller-based learning from being more widely used in classrooms, including the practical demands of implementation (e.g., calibration and debugging), limited classroom time, and the need to maintain adequate kits and computing infrastructure (Bouquet et al., 2017; Bulus & Basaran, 2019; Doucette et al., 2020; Vidal et al., 2022). In addition, the 38 included empirical studies show substantial heterogeneity in research design, participant groups, instructional contexts, intervention duration, and the types of evidence used to support learning claims. This diversity broadens the empirical picture of microcontroller-based physics learning, but it also limits direct comparability across studies and calls for caution when interpreting the overall strength and generalizability of the findings. To progress, it is essential for the field to shift from short-term implementations to research that assesses the long-term effects of microcontroller-based laboratories on student learning (Doucette et al., 2020; Schnider & Hömöstrei, 2024). Future initiatives must prioritize equity and access, especially in resource-constrained environments, as numerous studies highlight low cost and portability as critical factors for implementation (Bezerra et al., 2024; Bouquet et al., 2017; Castro, 2020; Sousa et al., 2020).

Finally, for microcontrollers to become a standard component of physics education, studies repeatedly indicate the value of clear scaffolding and reusable instructional materials (e.g., wiring diagrams, working code, and calibration guidance) to support teachers and students in practice (Doucette et al., 2020; Kuan et al., 2016; Vidal et al., 2022).

Author contributions: BS: conceptualization, formal analysis, methodology, data curation, investigation, writing – original draft, writing – review & editing; **AV:** methodology, writing – review & editing; **VM:** conceptualization, formal analysis, methodology, supervision, writing – review & editing. All authors agreed with the results and conclusions.

Funding: No funding source is reported for this study.

Acknowledgments: The authors would like to thank the first author's family for providing financial support for materials and related research expenses.

Ethical statement: This study is a systematic literature review based exclusively on previously published peer-reviewed articles. No human participants were recruited, no intervention was conducted, and no personal, sensitive, or confidential data were collected or processed by the authors. Therefore, ethics committee approval and informed consent were not applicable to this study.

AI statement: During the preparation and revision of this manuscript, the authors used QuillBot to rephrase selected sentences and improve clarity and readability. The tool was used only for language refinement and not for generating research questions, selecting studies, extracting data, analyzing results, interpreting findings, or preparing references. All AI-assisted text was carefully reviewed, edited, and approved by the authors, who take full responsibility for the accuracy, originality, integrity, and final content of the manuscript.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

REFERENCES

Ainsworth, S. (2006). DeFT: A conceptual framework for considering learning with multiple representations. *Learning and Instruction, 16*, 183-198. https://doi.org/10.1016/j.learninstruc.2006.03.001

Ayub, Y. N. L., Setiawan, I., & Wardana, R. W. (2023). Needs analysis for the development of Arduino microcontroller-based Hooke's law teaching tool guidebook. *Jurnal Ilmiah Ilmu Terapan Universitas Jambi, 7*(1), 27-32. https://doi.org/10.22437/jiituj.v7i1.26693

Bezerra, I., Schivani, M., & Fontoura, G. (2024). Solar ultraviolet radiation: Didactic prototype and investigations in northeastern Brazil. *Physics Education*, *59*(6), Article 065010. https://doi.org/10.1088/1361-6552/ad72c4

Bouquet, F., Bobroff, J., Fuchs-Gallezot, M., & Maurines, L. (2017). Project-based physics labs using low-cost open-source hardware. *American Journal of Physics, 85*(3), 216-222. https://doi.org/10.1119/1.4972043

Bulus, E., & Basaran, B. (2019). Investigation of the effect of the integration of Arduino to electrical experiments on students' attitudes towards technology and ICT by the mixed method. *European Journal of Educational Research, 8*(1), 31-48. https://doi.org/10.12973/eu-jer.8.1.31

Castro, T. J. (2020). Using Grätzel cells as Arduino-controlled photosensors: Proposals for the insertion of nanoscience and nanotechnology in classroom. *Revista Brasileira de Ensino de Física, 42*. https://doi.org/10.1590/1806-9126-rbef-2020-0072

Chaudry, A. M. (2020). Using Arduino Uno microcontroller to create interest in physics. *The Physics Teacher, 58*(6), 418-421. https://doi.org/10.1119/10.0001841

Çoban, A. (2020a). Determination of kinetic friction coefficient using an Arduino. *Physics Education, 55*(6), Article 063009. https://doi.org/10.1088/1361-6552/abb88a

Çoban, A. (2020b). Using Arduino in physics experiments: Determining the speed of sound in air. *Physics Education, 55*(5), Article 055004. https://doi.org/10.1088/1361-6552/ab94d6

Coban, A., & Erol, M. (2025). Impact of Arduino based stem education on cognitive domain level of mechanics and scientific creativity. *LUMAT: International Journal on Math, Science and Technology Education, 12*(4), Article 16. https://doi.org/10.31129/lumat.12.4.2231

Dökme, İ., & Hancıoğlu, Z. Ş. (2025). Three-stage robotic STEM program ignites secondary school students' interest in STEM career and attitudes toward science. *Education and Information Technologies, 30*(9), 12079-12100. https://doi.org/10.1007/s10639-025-13318-w

Doucette, D., D'Urso, B., & Singh, C. (2020). Lessons from transforming second-year honors physics lab. *American Journal of Physics, 88*(10), 838-844. https://doi.org/10.1119/10.0001641

Farcas, L., Enachescu, C., & Neculau, B. (2024). Boosting the study of physics for high-school students through non-formal activities with small robotics devices. *Romanian Reports in Physics, 76*(2), 904-904. https://doi.org/10.59277/romrepphys.2024.76.904

Fauza, N. (2023). Microcontroller-based mechanics experiments in physics learning: Systematic literature review using PRISMA. *Jurnal Penelitian Pendidikan IPA, 9*(9), 558-568. https://doi.org/10.29303/jppipa.v9i9.5258

Galeriu, C. (2018). An Arduino investigation of Newton's law of cooling. *The Physics Teacher, 56*(9), 618-620. https://doi.org/10.1119/1.5080580

García-Tudela, P. A., & Marín-Marín, J.-A. (2023). Use of Arduino in primary education: A systematic review. *Education Sciences, 13*(2), Article 134. https://doi.org/10.3390/educsci13020134

Ghai, G., Raj, R., & Kaur, R. (2022). An inclusive science laboratory for visually impaired students. *Journal of Engineering Education Transformations, 36*(2), 87-100. https://doi.org/10.16920/jeet/2022/v36i2/22157

Gkiolmas, A., Dimakos, C., Chalkidis, A., & Stoumpa, A. (2020). An environmental education project that measures particulate matter via an Arduino interface. *Sustainable Futures, 2*, Article 100027. https://doi.org/10.1016/j.sftr.2020.100027

Hachmi, A., El Hadi, M., Essaadaoui, R., Mommadi, O., Ouariach, A., & El Moussaouy, A. (2022). Development of an educational device, based on Arduino, to facilitate the understanding of light diffraction. *Physics Education, 57*(4), Article 045032. https://doi.org/10.1088/1361-6552/ac65d0

Hadiati, S., Kuswanto, H., Rosana, D., & Pramuda, A. (2019). The effect of laboratory work style and reasoning with Arduino to improve scientific attitude. *International Journal of Instruction, 12*(2), 321-336. https://doi.org/10.29333/iji.2019.12221a

Herendi, B., & Jenei, P. (2025). Interactive physics education with Arduino: Determining altitude and flow rate by measuring air pressure. *Physics Education, 60*(5), Article 055032. https://doi.org/10.1088/1361-6552/adf933

Huda, I., Girei, M. M., & Keizi, F. (2023). Development of a practical tool for linear momentum collisions using a microcontroller. *Journal of Educational Technology and Learning Creativity, 1*(2), 42-49. https://doi.org/10.37251/jetlc.v1i2.788

Hutchins, E. (1995). *Cognition in the wild*. MIT Press. https://doi.org/10.7551/mitpress/1881.001.0001

Karakotsou, C., & Zafiriadis, I. (2023). Teaching uniform linear motion using an Arduino sensor and a smartphone device. *Physics Education, 58*(2), Article 025013. https://doi.org/10.1088/1361-6552/acace2

Kircher, E., Girwidz, R., & Fischer, H. E. (Eds.). (2015). *Physikdidaktik* [Physics education]. Springer. https://doi.org/10.1007/978-3-642-41745-0

Kolb, D. A. (1984). *Experiential learning: Experience as the source of learning and development*. Prentice Hall.

Kondaveeti, H. K., Kumaravelu, N. K., Vanambathina, S. D., Mathe, S. E., & Vappangi, S. (2021). A systematic literature review on prototyping with Arduino: Applications, challenges, advantages, and limitations. *Computer Science Review, 40*, Article 100364. https://doi.org/10.1016/j.cosrev.2021.100364

Koumara, A., Bakaloglou, M., & Polatoglou, H. M. (2024). Applying design thinking to teach physics and mathematics: A case study on building a parachute and analyzing its properties. *World Journal of Education*, 14(4), 22–47. https://doi.org/10.5430/wje.v14n4p22

Koyimah, K., Widodo, W., Suprapto, N., & Prahani, B. K. (2020). Effectiveness of interactive microcontroller based speed sensors to improve students' analytic thinking skills. *International Journal of Online and Biomedical Engineering, 16*(09), 173-182. https://doi.org/10.3991/ijoe.v16i09.15185

Kress, G., & Van Leeuwen, T. (2006). *Reading images: The grammar of visual design* (2nd ed.). Routledge. https://doi.org/10.4324/9780203619728

Kuan, W.-H., Tseng, C.-H., Chen, S., & Wong, C.-C. (2016). Development of a computer-assisted instrumentation curriculum for physics students: Using LabVIEW and Arduino platform. *Journal of Science Education and Technology, 25*(3), 427-438. https://doi.org/10.1007/s10956-016-9603-y

Kubínová, Š., & Šlégr, J. (2015). Physics demonstrations with the Arduino board. *Physics Education, 50*(4), 472-474. https://doi.org/10.1088/0031-9120/50/4/472

Lee, E. (2020a). A meta-analysis of the effects of Arduino-based education in Korean primary and secondary schools in engineering education. *European Journal of Educational Research, 9*(4), 1503-1512. https://doi.org/10.12973/eu-jer.9.4.1503

Lee, E. (2020b). Developing a low-cost microcontroller-based model for teaching and learning. *European Journal of Educational Research, 9*(3), 921-934. https://doi.org/10.12973/eu-jer.9.3.921

Lotriet, H. H., & Gouws, P. M. (2025). Educational robotics in physics education: A systematic review. *Studies in Science Education, 62*(1), 107-136. https://doi.org/10.1080/03057267.2025.2455334

Lucenko, G., Kuzminskyi, A., & Burchak, S. (2020). Organising the process of physics students' cognitive activity. *Universal Journal of Educational Research, 8*(8), 3449-3458. https://doi.org/10.13189/ujer.2020.080819

Marín-Marín, J.-A., García-Tudela, P. A., & Duo-Terrón, P. (2024). Computational thinking and programming with Arduino in education: A systematic review for secondary education. *Heliyon*, *10*(8), Article e29177. https://doi.org/10.1016/j.heliyon.2024.e29177

Mayer, R. E. (2014). *The Cambridge handbook of multimedia learning* (2nd ed.). Cambridge University Press. https://doi.org/10.1017/CBO9781139547369

Mendes, G. A., da Costa e Silva, J., & de O. G. Rebouças, G. (2023). Instantaneous measurement of the speed of sound in air and water using Arduino. *The Physics Teacher, 61*(5), 394-395. https://doi.org/10.1119/5.0118245

Moghimi-Araghi, S. (2025). Teaching an acoustics lab remotely during the pandemic and beyond. *The Physics Teacher, 63*(7), 591-594. https://doi.org/10.1119/5.0204272

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & The PRISMA Group. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLOS Medicine*, *6*(7), Article e1000097. https://doi.org/10.1371/journal.pmed.1000097

Monteiro, J. A., Vilhena, M. de F., Silva, F. H. S. da, Lucena, I. C. R. de, & Coutinho Júnior, A. de L. (2022). Arduino no ensino de física: Uma revisão sistemática de literatura de 2011 a 2021 [Arduino in physics education: A systematic literature review from 2011 to 2021]. *Amazônia: Revista de Educação em Ciências e Matemáticas, 18*(40), 177-190. https://doi.org/10.18542/amazrecm.v18i40.12175

Moya, A. A. (2018). An Arduino experiment to study free fall at schools. *Physics Education, 53*(5), Article 055020. https://doi.org/10.1088/1361-6552/aad4c6

Neto, S. C. M., Silva, V. M. L., Silva, J. W. C., & Sousa, R. R. (2021). Plataforma de prototipagem arduino no ensino da física: Uma revisão sistemática da literatura [Arduino prototype platform in physics teaching: A systematic literature review]. *Brazilian Journal of Development, 7*(7), 65714-65737. https://doi.org/10.34117/bjdv7n7-039

Ntourou, V., Kalogiannakis, M., & Psycharis, S. (2021). A study of the impact of Arduino and visual programming in self-efficacy, motivation, computational thinking and 5th grade students' perceptions on electricity. *Eurasia Journal of Mathematics, Science and Technology Education, 17*(5), Article em1960. https://doi.org/10.29333/ejmste/10842

Omari, S., Mamane, A., Daoui, A., Ouahi, M. B., & Benjelloun, N. (2023). Investigating the effect of a proposed educational robot on students' motivation and learning of thermodynamic concepts. *International Journal of Information and Education Technology, 13*(7), 1085-1093. https://doi.org/10.18178/ijiet.2023.13.7.1908

Organtini, G., & Tufino, E. (2022). Effectiveness of a laboratory course with Arduino and smartphones. Education *Sciences, 12*(12), Article 898. https://doi.org/10.3390/educsci12120898

Pabuçcu Akış, A. (2024). Using Arduino in science, technology, engineering, and mathematics (STEM) education: Bibliometric analysis. *Science Education International, 35*(2), 73-84. https://doi.org/10.33828/sei.v35.i2.1

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. Basic Books.

Piaget, J. (1970). *Science of education and the psychology of the child* (D. Coltman, Trans.). Orion Press.

Prabowo, N. K., & Irwanto, I. (2023). The implementation of Arduino microcontroller boards in science: A bibliometric analysis from 2008 to 2022. *Journal of Engineering Education Transformations, 37*(2), 106-123. https://doi.org/10.16920/jeet/2023/v37i2/23154

Prahani, B. K., Hariyono, E., Saphira, H. V., Zakhiyah, I., Eliezanatalie, S., & Ismail 4, M. H. (2025). Digitalization of physics laboratory tools: Increase undergraduate students learning motivation and problem-solving skills. *TEM Journal, 14*(3), 2371-2380. https://doi.org/10.18421/tem143-42

Pusch, A., Ubben, M. S., Laumann, D., Heinicke, S., & Heusler, S. (2021). Real-time data acquisition using Arduino and Phyphox: Measuring the electrical power of solar panels in contexts of exposure to light in physics classroom. *Physics Education, 56*(4), Article 045001. https://doi.org/10.1088/1361-6552/abe993

Redish, E. F. (2004). Teaching physics with the physics suite. *American Journal of Physics, 72*(3), 414-414. https://doi.org/10.1119/1.1691552

Rivera-Ortega, U., Hernández-Montero, P., & Hugo-Teutli. (2023). Interactive STEM educational resource regarding to the projectile motion phenomenon on inclined plane. *Physics Education, 58*(3), Article 035017. https://doi.org/10.1088/1361-6552/acbf1c

Růžička, M., Rejthárek, M., & Major, Š. (2018). Project-based learning in basic course of technical physics: Computer-controlled experiments and Agros2D modeling. *WSEAS Transactions on Applied and Theoretical Mechanics, 13*, 46-52.

Schiavon, G. J., Pittner, V. D., Santos, O. R., Batista, M. C., & Braga, W. S. (2023). Experimental activities for the study of transformation of electrical energy into thermal. *Physics Education, 58*(5), Article 055020. https://doi.org/10.1088/1361-6552/acea51

Schnider, D., & Hömöstrei, M. (2023a). Electrical conductance lab: A low-cost, simple and useful project with Arduino. *Physics Education, 58*(6), Article 065023. https://doi.org/10.1088/1361-6552/acf817

Schnider, D., & Hömöstrei, M. (2023b). Exoplanets: An easy, practice-oriented and fun project with Arduino. *Physics Education, 58*(5), Article 055004. https://doi.org/10.1088/1361-6552/ace1c9

Schnider, D., & Hömöstrei, M. (2024). Arduino-supported kinematics measurements. *Physics Education, 59*(5), Article 055015. https://doi.org/10.1088/1361-6552/ad672a

Setya, S. C., Krismadinata, Ganefri, & Weriza, J. (2024). Systematic literature review and meta-analysis of microcontroller learning development in the Industry 4.0. *Nanotechnology Perceptions, 20*(S7), 873-896. https://doi.org/10.62441/nano-ntp.v20is7.73

Sousa, A., Rodrigues, P., Maia-Lima, C., Pinto, A., & Barbot, A. (2020). Learning about UV radiation and sustainability with Arduino and sensors. *International Journal of Curriculum and Instruction, 12*(Special Issue), 422-434.

Sukmak, W., & Musik, P. (2022). Real-time graphing of simple harmonic motion of mass on springs with an Arduino based on an experiment set for teaching and learning physics. *Turkish Online Journal of Educational Technology, 21*(1), 114-130.

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science, 12*(2), 257-285. https://doi.org/10.1207/s15516709cog1202_4

Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive load theory*. Springer. https://doi.org/10.1007/978-1-4419-8126-4

Ubaidillah, M., Marwoto, P., Wiyanto, W., Subali, B., Widiyatmoko, A., & Cahyono, A. N. (2025). A systematic literature review on trends in the use of science experiments in online learning environments. *The International Review of Research in Open and Distributed Learning, 26*(3), 149-169. https://doi.org/10.19173/irrodl.v26i3.8221

Uzal, G. (2022) The use of Arduino in physics laboratories. *The Turkish Online Journal of Educational Technology, 21*(3), 88-100.

Vergara, K., Rossel, P. O., & Herskovic, V. (2025). Understanding the use of physical computing in K-12 education: A systematic literature review. *Educational Research Review, 48*, Article 100705. https://doi.org/10.1016/j.edurev.2025.100705

Vidal, J., Bravo, D. A., & Rengifo, C. F. (2022). Teaching physical sciences using Arduino physics lab at the Universidad del Cauca. *IEEE Revista Iberoamericana de Tecnologías del Aprendizaje, 17*(3), 223-229. https://doi.org/10.1109/RITA.2022.3191266

Vitkóczi, F., Jenei, P., Piláth, K., & Kopasz, K. (2025). Practical STEM project with Arduino: Classroom applications and constructing thermodynamic measurement tool. *Physics Education, 60*(4), Article 045015. https://doi.org/10.1088/1361-6552/add980

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. Harvard University Press.

Walkup, J. R., Key, R. A., & Talbot, P. R. M. (2019). Timing a light pulse in the introductory physics lab. *Physics Education, 54*(4), Article 045007. https://doi.org/10.1088/1361-6552/ab15b4

Wibowo, F. C., Maemunah, A. N., Nasbey, H., Costu, B., Prahani, B. K., Permana, N. D., Darman, D. R., & Samsudin, A. (2023). Development of simple kits (SK) refraction of light using photodiode sensors for student understanding. *EUREKA: Physics and Engineering*, (2), 3-16. https://doi.org/10.21303/2461-4262.2023.002728

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review, 9*(4), 625-636. https://doi.org/10.3758/bf03196322

Yasin, A. I., Prima, E. C., & Sholihin, H. (2018). Learning electricity using Arduino-Android based game to improve STEM literacy. *Journal of Science Learning, 1*(3), Article 77. https://doi.org/10.17509/jsl.v1i3.11789

Zárate-Navarro, M. A., Schiavone-Valdez, S. D., Cuevas, J. E., Warren-Vega, W. M., Campos-Rodríguez, A., & Romero-Cano, L. A. (2024). STEM activities for heat transfer learning: Integrating simulation, mathematical modeling, and experimental validation in transport phenomena education. *Education for Chemical Engineers, 49*, 81-90. https://doi.org/10.1016/j.ece.2024.06.004