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Research Trends and Future Directions of Sensor-Based Physics Education: A Bibliometric Analysis Toward a Real-Time Smart Thermal Learning System

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Abstract

ABSTRACT
Sensor-based laboratories have long been promoted as a way to connect measurement with conceptual understanding in physics, yet it is unclear how far this literature addresses thermal physics and students' misconceptions. This study mapped the performance, intellectual base, and thematic development of sensor-based physics education research and examined its coverage of thermal concepts and misconceptions. A bibliometric analysis was conducted on 195 Scopus-indexed journal articles published between 1987 and 2026 using bibliometrix/Biblioshiny, complemented by a content screening of titles and abstracts. Output grew at an annual rate of 8.92%, with 131 articles (67.2%) published from 2020 onward. *Physics Education* formed the single core source (78 articles), authorship was highly dispersed (91.1% of 615 authors contributed one article), and international co-authorship was limited (11.28%). The intellectual base centred on smartphone and Arduino tools, led by Staacks et al. (2018) with 273 citations, and the most frequent keywords were physics education (41) and Arduino (28). Only 15 articles (7.7%) dealt with thermal physics: 11 reported apparatus or measurement methods, three reported learner data, and one reported expert validation. None diagnosed misconceptions, and no article in the dataset involved vocational students. The field has therefore matured technically faster than it has pedagogically. Building on these gaps, we outline a research agenda for a dashboard-assisted smart thermal learning system that couples real-time temperature sensing with diagnostic assessment of misconceptions in vocational education.

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INTRODUCTION

Physics is learned not only through equations but also through measuring phenomena and interpreting the resulting data. Since microcomputer-based laboratories were proposed as "tools for scientific thinking" (Thornton, 1987), sensor-based data acquisition has been promoted as a way to let students watch a physical quantity change as it happens and to connect that change with graphical and conceptual representations. Low-cost microcontrollers and smartphones have widened this possibility considerably. Arduino-based experiments now span mechanics, electricity, optics, and heat (Goncalves et al., 2023; Kortemeyer, 2022), and the sensors built into mobile devices have been organised into dedicated tools and resource collections for physics teaching (Monteiro & Martí, 2022; Staacks et al., 2018).

Thermal physics is a domain in which real-time visualisation may matter most. Physics education research has documented persistent inconsistencies in students' interpretations of

thermal phenomena at all age levels, where everyday and calorimetric ideas coexist with the thermodynamic view based on states and processes (De Angelis et al., 2025). Commonly reported difficulties include confusing heat with temperature and attributing temperature differences to the materials themselves rather than to thermal interaction. In Indonesia, misconceptions on temperature and heat have been the target of remediation through predict–observe–explain strategies (Firmanto et al., 2021). Because misconceptions are robust and are often held with confidence, identifying them requires instruments that distinguish a misconception from a simple lack of knowledge, such as multi-tier diagnostic tests including the four-tier test.

These issues are particularly relevant to vocational secondary education. Students in Indonesian vocational high schools (*Sekolah Menengah Kejuruan*, SMK) encounter thermal concepts in contexts that are close to technical practice , so an incorrect understanding of heat and temperature can carry over into their work. Real-time temperature sensing combined with a learning dashboard is one promising response, because it allows students to compare their predictions with live data during an experiment. Whether the research on sensor-based physics education has examined such uses, and for which learners, is the question that motivates this study.

The literature on sensor-based physics teaching has expanded rapidly and in several directions at once: device design, measurement validation, remote and Internet of Things (IoT) laboratories, STEM projects and, most recently, artificial-intelligence-assisted instrumentation (Castaño et al., 2024; Mortimer, 2026; Suñer et al., 2026). Reviews in neighbouring areas have synthesised specific topics, such as student difficulties with kinematics graphs, where real-time sensors appear as one of several instructional strategies (Afifah et al., 2026), or sensorimotor activities in physics education (Yoon, 2026). To our knowledge, however, no study has mapped this body of work as a whole to show how it is distributed, which works form its intellectual base, which themes dominate, and how much attention it gives to thermal concepts and misconceptions.

Bibliometric analysis suits this purpose because it combines performance analysis of productivity and impact with science mapping of the intellectual and conceptual structure of a field (Donthu et al., 2021). The bibliometrix package and its Biblioshiny interface provide a documented and reproducible workflow for both (Aria & Cuccurullo, 2017). Classical regularities such as Bradford's law of source scattering (Bradford, 1934) and Lotka's law of author productivity (Lotka, 1926) further allow the structure of a small and young field to be compared with established expectations.

This study is part of a research and development project that is building a dashboard-assisted smart thermal learning system based on real-time temperature sensors to reduce vocational students' misconceptions on thermal physics. Its contribution is twofold. First, it provides a bibliometric map of sensor-based physics education research published between 1987 and 2026. Second, it reads that map through a specific design problem, thermal misconceptions, so that the gaps it reveals can be translated into concrete directions for development rather than remaining general calls for further research. Accordingly, four research questions guided the study:

RQ1: How have the publication output and citation impact of sensor-based physics education research evolved, and which sources, authors, affiliations, and countries are the most productive and influential?

RQ2: Which documents and cited references form the intellectual base of the field?

RQ3: Which themes dominate the field, and how have they shifted over time?

RQ4: To what extent does the field address thermal physics concepts and students' misconceptions, and what directions follow for a real-time smart thermal learning system?

METHOD

Research Design

This study used a descriptive bibliometric design that followed the two main techniques described by Donthu et al. (2021): performance analysis, which describes the productivity and impact of sources, authors, institutions, and countries, and science mapping, which describes the relationships among documents, references, and keywords. Because bibliometric indicators alone cannot show what a study teaches or measures, RQ4 was answered with an additional structured content screening of titles and abstracts.

Data Source and Search Strategy

Bibliographic records were retrieved from Scopus, accessed through Universitas Gadjah Mada, on 11 October 2026. The search covered titles, abstracts, and keywords with the following query: TITLE-ABS-KEY ((sensor* OR "data logger" OR arduino OR microcontroller OR "internet of things" OR "microcomputer-based lab*" OR "real-time data") AND ("physics education" OR "physics learning" OR "physics teaching" OR "physics laboratory")). The query returned 697 documents. Limiting the results to the subject area Physics and Astronomy left 422 documents, limiting them to the document type Article left 254, and limiting them to English left 230. Records indexed under keywords unrelated to the scope of the study were then excluded with the Scopus keyword filter, which removed 35 records and left 195 articles (Figure 1). No restriction on publication year was applied, so the dataset spans 1987 to 2026 and covers 39 sources; all 195 records are final-stage journal articles (Table 1). Because the search was run on 11 October 2026, the figures for 2026 cover only part of that year. The records were exported from Scopus as a CSV file and analysed with Biblioshiny, the web interface of the bibliometrix package version 5.5.0, running in R version 4.6.1.

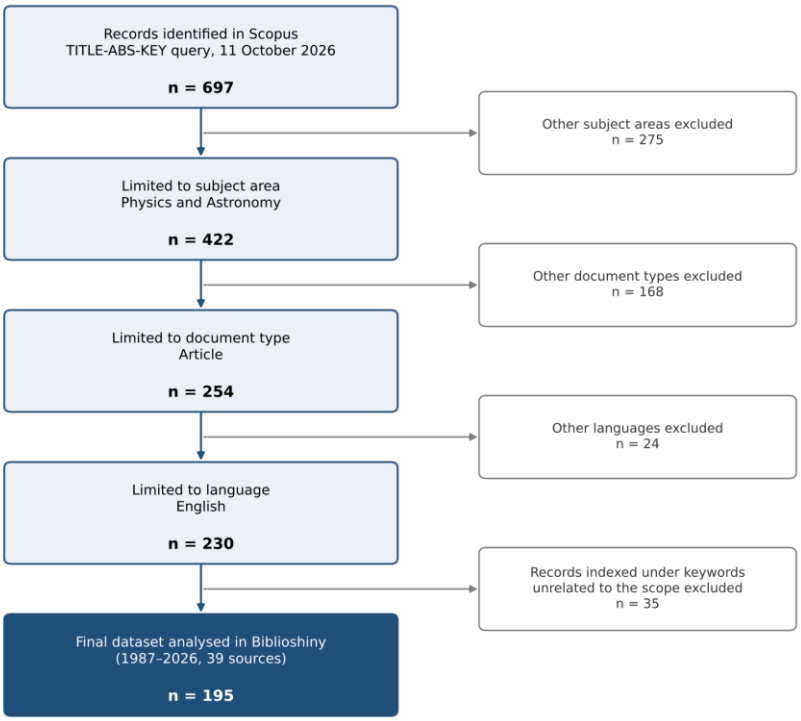


Figure 1. Selection of records from Scopus

Data Quality

Biblioshiny's completeness check showed that abstracts, authors, document types, sources, languages, publication years, titles, and citation counts were complete for all 195 records. Affiliations and cited references were missing for nine records each (4.62%), DOIs for 20 records (10.26%), corresponding-author information for 48 records (24.62%), author keywords for 77 records (39.49%), and Keywords Plus for 148 records (75.90%). Web of Science categories were absent from all records because the data came from Scopus. These gaps affect specific analyses: the corresponding-author country analysis covers only records with that field, and keyword-based results rely on the merged author keywords and Keywords Plus available for each record.

Data Analysis

For RQ1, we analysed annual scientific production, the annual growth rate, average citations per year, the most relevant sources, authors, affiliations, and countries, and the local impact of sources and authors measured by the h-index (Hirsch, 2005) together with the g- and m-indices reported by Biblioshiny. Source dispersion was examined with Bradford's law (Bradford, 1934), author productivity with Lotka's law (Lotka, 1926), and international collaboration with the split between single-country publications (SCP) and multiple-country publications (MCP) by corresponding-author country. For RQ2, we compared global citations (citations from the whole Scopus database) with local citations (citations from within the dataset), identified the most locally cited references, and used a three-field plot linking cited references, authors, and keywords. For RQ3, we analysed keyword frequency, a treemap of keyword shares, cumulative keyword occurrence over time, and trend topics. All keyword analyses used the author keywords and Keywords Plus of each record combined; trend topics included terms with at least five occurrences and up to three terms per year.

For RQ4, two procedures were applied to all 195 records. First, titles and abstracts were searched for the terms *misconception*, *alternative conception*, *preconception*, *four-tier*, *two-tier*, *diagnostic test*, *conceptual change*, *pre-test/post-test*, *vocational*, and *dashboard*. Second, articles were classified as thermal physics studies when their main learning content was temperature, heat, heat transfer, calorimetry, thermal expansion, thermal radiation, or thermodynamics. Articles in which temperature appeared only as a secondary variable, for example the temperature dependence of electronic components or the thermal management of research instruments, were not included. Each thermal physics article was then coded for its thermal topic, its sensor platform, its primary contribution (apparatus or measurement method, learner data, or expert validation), and the learner evidence it reported. A preliminary code was prepared for each of the 195 records following these rules. Two authors then checked every preliminary code independently against the title and abstract of each record. Both authors accepted all codes, so agreement between them was complete (Cohen's $\kappa = 1.00$ for each of the three variables; Landis & Koch, 1977). Because the authors verified preliminary codes rather than coding the records from scratch, this value indicates agreement on the verified codes and not two fully independent codings.

RESULTS AND DISCUSSION

Results:

RQ1: Publication Performance, Sources, Authors, and Countries

Table 1 summarises the dataset. The 195 articles were written by 615 authors, with an average of 3.6 co-authors per document; 31 articles were single-authored, and 11.28% involved international co-authorship. The articles had an average age of 7.19 years and received an average of 9.68 citations each.

Table 1. Main information about the dataset

Indicator	Value
Timespan	1987–2026
Sources (journals)	39
Documents (all journal articles)	195
Annual growth rate	8.92%
Average document age (years)	7.19
Average citations per document	9.68
Cited references	3,225
Keywords Plus (ID)	662
Author keywords (DE)	410
Authors	615
Single-authored documents	31
Co-authors per document	3.6
International co-authorship	11.28%

Annual output stayed between zero and four articles per year until 2014, a period that produced 34 articles in total. Output then rose to five to eight articles per year between 2015 and 2019 (30 articles) and increased sharply from 2020, when it reached 15 articles, to 28 articles in the partial year 2026 (Figure 2). The period from 2020 onward accounts for 131 articles, or 67.2% of the dataset; the only interruption was a drop to 12 articles in 2024. Average citations per article per year peaked in 2013 (7.64) and 2018 (5.17), the publication years of the two most cited documents. The logistic life-cycle model in Biblioshiny estimated a saturation level of about 1,188 articles with an inflection point around 2036, which places the field in its growth phase.

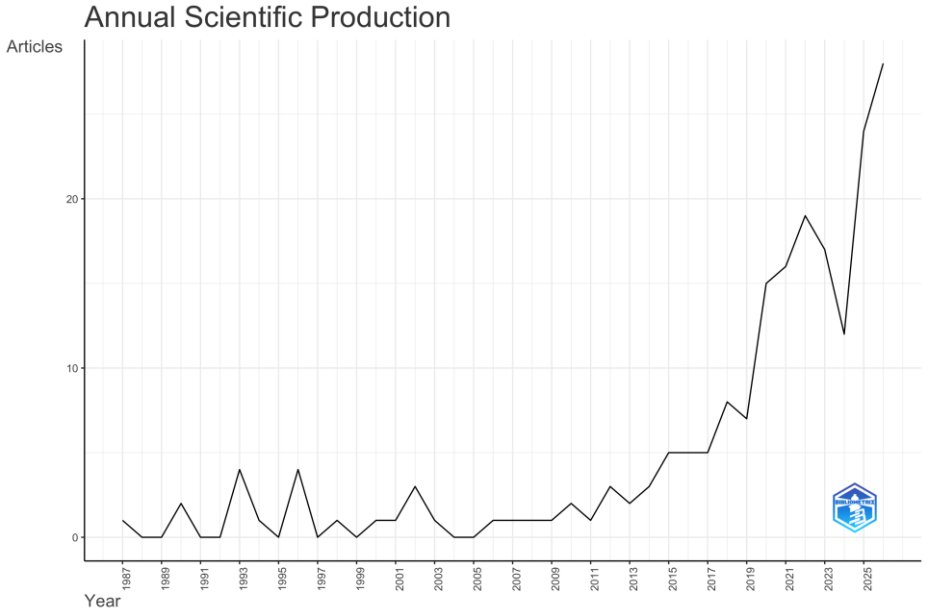


Figure 2. Annual scientific production, 1987–2026 (2026 is a partial year)

The 195 articles were scattered across 39 sources. Under Bradford's law, the core zone consisted of a single journal, *Physics Education*, with 78 articles (40.0%). Zone 2 contained three sources, *Physics Teacher* (26), *European Journal of Physics* (16), and *Johns Hopkins APL Technical Digest* (12), which together published 54 articles, and Zone 3 contained the remaining 35 sources with 63 articles (Figure 3). The Bradford model fitted the data well (R^2 = 0.9789; Bradford multiplier k = 7.33). *Physics Education* also had the highest local impact (h = 11; 707 citations), followed by *Physics Teacher* (h = 9; 327 citations) (Table 2). The cumulative production curves show that *Physics Education* overtook the other sources after 2019 and accounted for most of the recent growth, whereas the *Johns Hopkins APL Technical Digest* contributed mainly in the 1990s.

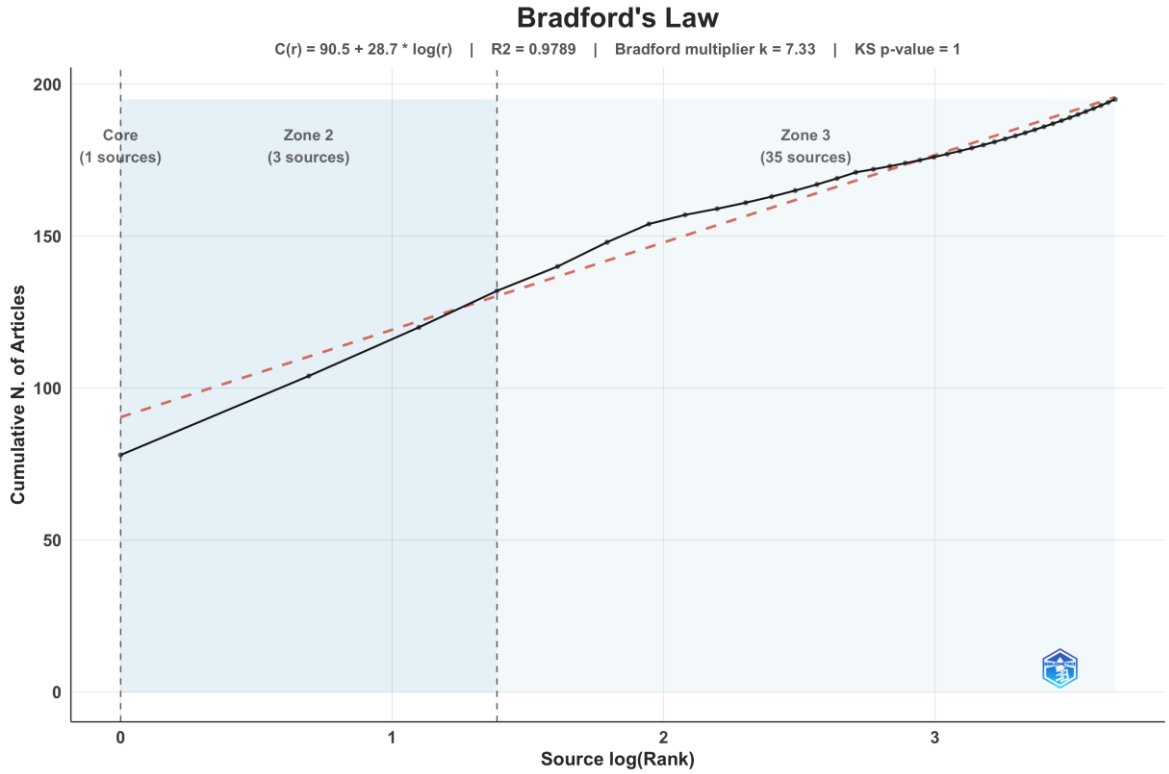


Figure 3. Source dispersion according to Bradford's law

Table 2. Most relevant sources and their local impact

Source	NP	h	g	TC	Since	Zone
Physics Education	78	11	24	707	1987	1
Physics Teacher	26	9	17	327	2007	2
European Journal of Physics	16	4	15	245	2012	2
Johns Hopkins APL Technical Digest	12	6	12	149	1990	2
Revista Brasileira de Ensino de Física	8	3	7	53	2015	3
Romanian Reports in Physics	8	3	7	50	2016	3
American Journal of Physics	6	4	6	100	2002	3

Note. NP = number of articles; h and g = local h- and g-index; TC = total citations; Since = year of the first article in the dataset.

Authorship was highly dispersed. Of the 615 authors, 560 (91.1%) contributed one article, 35 contributed two, 12 contributed three, five contributed four, two contributed five, and one contributed six. The fitted Lotka coefficient was β = 3.44 (C = 0.8125; R^2 = 0.9954). The Kolmogorov–Smirnov test did not reject the classical form with β = 2 (p = 0.441), although the fitted curve declines more steeply than the classical one. The most productive author was Erol M. (six articles, 2021–2024), followed by Miron C. and Çoban A. (five each) (Table 3). The highest local h-index (4) was shared by El Hadi M., El Moussaouy A., and Ouariach A., who published

as one Moroccan team from 2020, and by Goncalves A. M. B. Galeriu C. had the highest number of citations among the most productive authors (93) and, together with Staacks S., Hütz S., Heinke H., and Stampfer C., was the most locally cited author (eight local citations each).

Table 3. Most productive authors and their local impact

Author	NP	NP (frac.)	h	TC	Since
Erol, M.	6	3.00	3	19	2021
Miron, C.	5	1.35	3	42	2016
Çoban, A.	5	2.33	3	14	2021
El Hadi, M.	4	0.63	4	43	2020
El Moussaouy, A.	4	0.63	4	43	2020
Galeriu, C.	4	2.83	3	93	2014
Goncalves, A. M. B.	4	0.93	4	34	2018
Ouariach, A.	4	0.63	4	43	2020

Note. NP (frac.) = fractionalised count of articles; h = local h-index; TC = total citations.

At the institutional level, Dokuz Eylül University (8 articles), the University of Bucharest (7), and Yeditepe University (6) were the most productive, followed by Universidad de la República, Universidade Federal de Mato Grosso do Sul, and Universitat Politècnica de València (5 each). By author affiliations, the United States appeared most often (41), followed by Brazil (29) and China, Germany, and Turkey (23 each); Indonesia appeared 14 times. By corresponding author, Brazil led with 17 articles, all of them single-country publications, followed by the United States (13) and Turkey (12) (Figure 4, Table 4). Indonesia had seven corresponding-author articles, two of them with international co-authors (MCP = 28.6%), the highest MCP share among the eight leading countries. Citation impact was led by the United States (142 citations), while Switzerland (39.0 citations per article) and Uruguay (30.0) had the highest average impact per article.

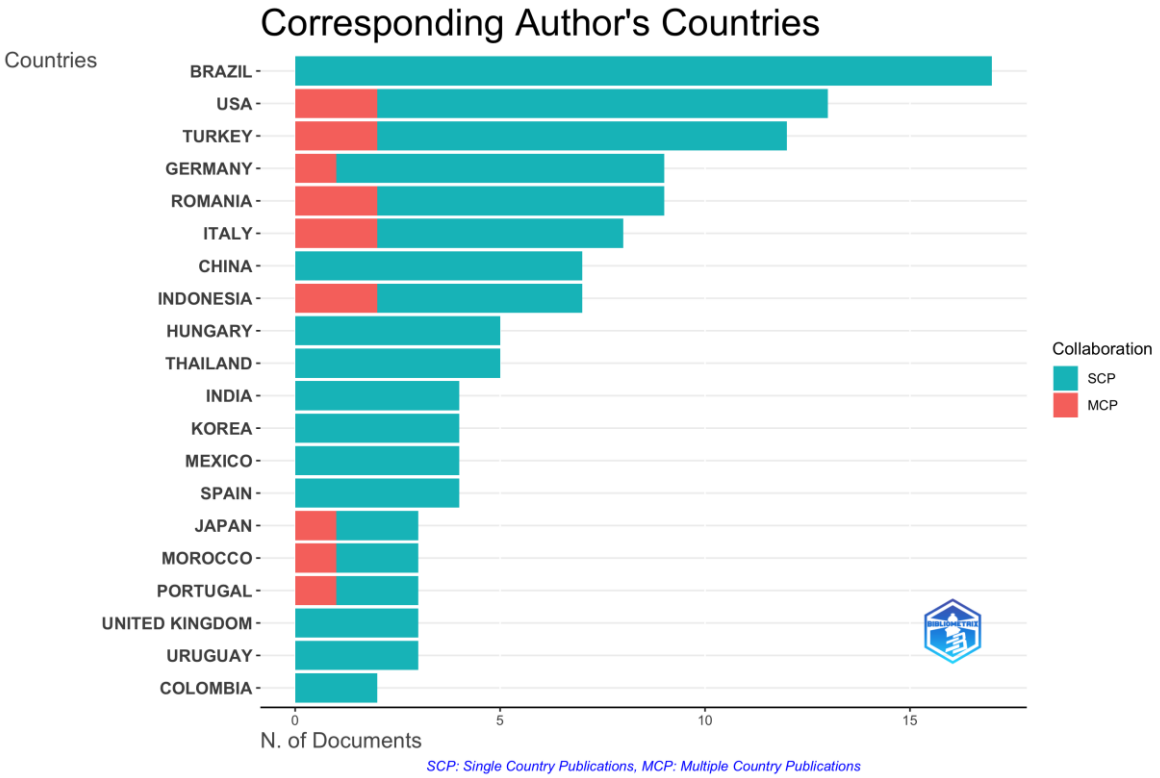


Figure 4. Corresponding authors' countries and collaboration type (SCP = single-country publications; MCP = multiple-country publications)

Table 4. Leading countries by corresponding author, collaboration, and citations

Country	Articles	SCP	MCP	MCP %	TC	TC/article
Brazil	17	17	0	0.0	39	2.3
United States	13	11	2	15.4	142	10.9
Turkey	12	10	2	16.7	39	3.2
Germany	9	8	1	11.1	49	5.4
Romania	9	7	2	22.2	73	8.1
Italy	8	6	2	25.0	59	7.4
China	7	7	0	0.0	15	2.1
Indonesia	7	5	2	28.6	31	4.4

Note. SCP = single-country publications; MCP = multiple-country publications; TC = total citations attributed to the country by Biblioshiny.

RQ2: Intellectual Base

Table 5 lists the most globally cited documents in the dataset. Staacks et al. (2018), which introduced the phyphox application for smartphone-based experiments, received 273 citations (30.3 per year) and was also the most locally cited document (eight local citations). Ibarra-Castanedo et al. (2013), an overview of thermography as a nondestructive testing technique that can also be used as a teaching tool, ranked second with 175 citations. Three of the ten most globally cited documents, by Affolderbach et al. (2002), Axness et al. (1996), and Carkhuff and Cain (2003), are instrumentation or engineering papers rather than teaching studies. None of them is among the ten most locally cited documents, which indicates that the field's own citation network does not draw on them.

Table 5. Most cited documents: global and local citations

Document	Focus	GC	GC/year	LC
Staacks et al. (2018)	Smartphone experiments (phyphox)	273	30.3	8
Ibarra-Castanedo et al. (2013)	Thermography (nondestructive testing)	175	12.5	–
Affolderbach et al. (2002)	Optical magnetic gradiometer	76	3.0	–
Thornton (1987)	Microcomputer-based laboratories	71	1.8	–
Axness et al. (1996)	Shared aperture technology	65	2.1	–
Galeriu et al. (2014)	Arduino, simple harmonic motion	64	4.9	6
Monteiro and Martí (2022)	Mobile devices and sensors (resource letter)	51	10.2	5
Pili et al. (2018)	Smartphone magnetometer, g measurement	47	5.2	3
Carkhuff and Cain (2003)	Corrosion sensors for bridges	45	1.9	–
Shakur and Sinatra (2013)	Angular momentum	39	2.8	–

Note. GC = global citations; LC = local citations; – = not among the ten most locally cited documents. Other locally cited documents: El Hadi et al. (2020), Espindola et al. (2018), and Moya (2019) with three local citations each; Galeriu (2018), Schnider and Hömöstrei (2023), Pendrill and Rohlén (2011), and Goncalves et al. (2023) with two each.

The most locally cited documents were all teaching-oriented: smartphone tools (Staacks et al., 2018; Monteiro & Martí, 2022; Pili et al., 2018; Pendrill & Rohlén, 2011) and Arduino experiments (Galeriu et al., 2014; El Hadi et al., 2020; Espindola et al., 2018; Moya, 2019; Galeriu, 2018). Galeriu (2018), on Newton's law of cooling, was the only thermal physics article among them. The reference base was fragmented: the most locally cited references were cited only three times each. They were a study of project-based physics laboratories using low-cost open-source hardware published in the *American Journal of Physics* in 2017, two smartphone studies by Castro-Palacio and colleagues from 2013, an Arduino measurement of the speed of sound by Çoban and Çoban from 2020, a general physics textbook, and the phyphox article. Some of these references were split across differently spelled entries, so their counts are slightly understated. The three-

field plot (Figure 5) shows the same pattern. Arduino and smartphone references (Galeriu's photogate, RC-circuit, and simple-harmonic-motion experiments; project-based laboratories with open-source hardware; smartphone studies) flow to the most active authors (Erol, Çoban, Miron, and the Moroccan team of El Hadi, El Moussaouy, and Ouariach), and from them to the keywords physics education, Arduino, smartphone, and STEM education.

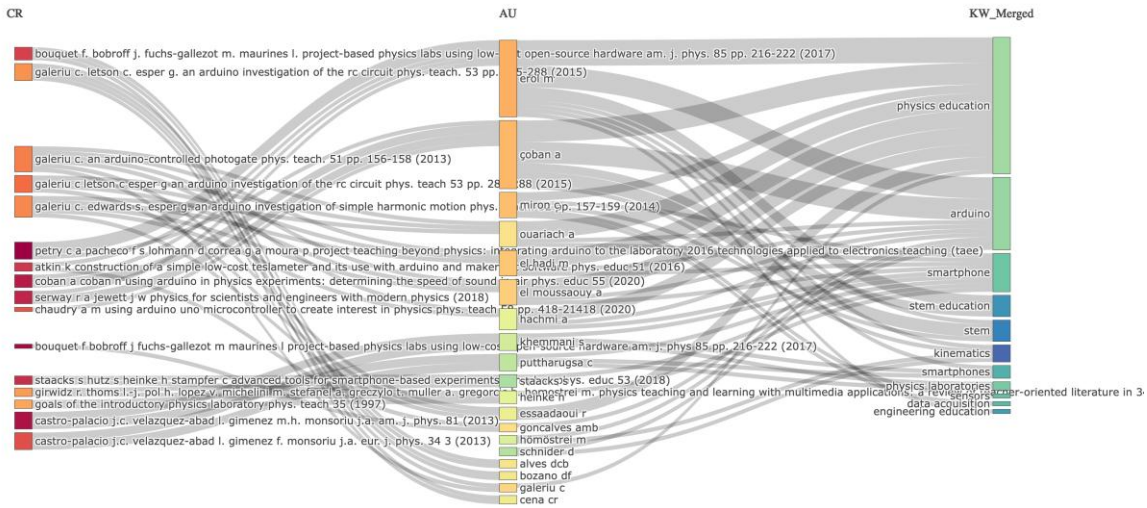


Figure 5. Three-field plot linking cited references (left), authors (middle), and keywords (right)

RQ3: Dominant Themes and Their Development

The most frequent keywords were physics education (41 occurrences; 17% of the treemap), Arduino (28; 12%), physics teaching (10), physics laboratories (9), smartphone (9), sensors (8), data acquisition (7), smartphones (7), students (7), and engineering education, STEM education, and teaching (6 each). The singular and plural forms smartphone and smartphones, together with smart phones (3), were counted separately; combined, they would occur 19 times and rank third. Keywords on thermal physics were rare. Newton's law of cooling occurred three times, and heat capacity, specific heat, thermal expansion, thermodynamics, thermodynamics education, temperature measurement, thermometer, and thermistor occurred once each. The term misconception did not occur as a keyword at all.

The cumulative keyword curves show a clear shift in vocabulary. Sensors was the main keyword until the 2010s and reached its total of eight occurrences by 2016, whereas physics education rose from four occurrences in 2019 to 41 in 2026 and Arduino rose from zero in 2019 to 28 in 2026 (Figure 6). The trend-topic analysis confirms this sequence (Figure 7). Sensors had a median year of 2002, smartphone 2022, STEM education 2022, Arduino and physics education 2023, physics teaching 2024, and physics laboratories 2025, while students, teaching, and engineering education emerged as the newest topics with a median year of 2026.

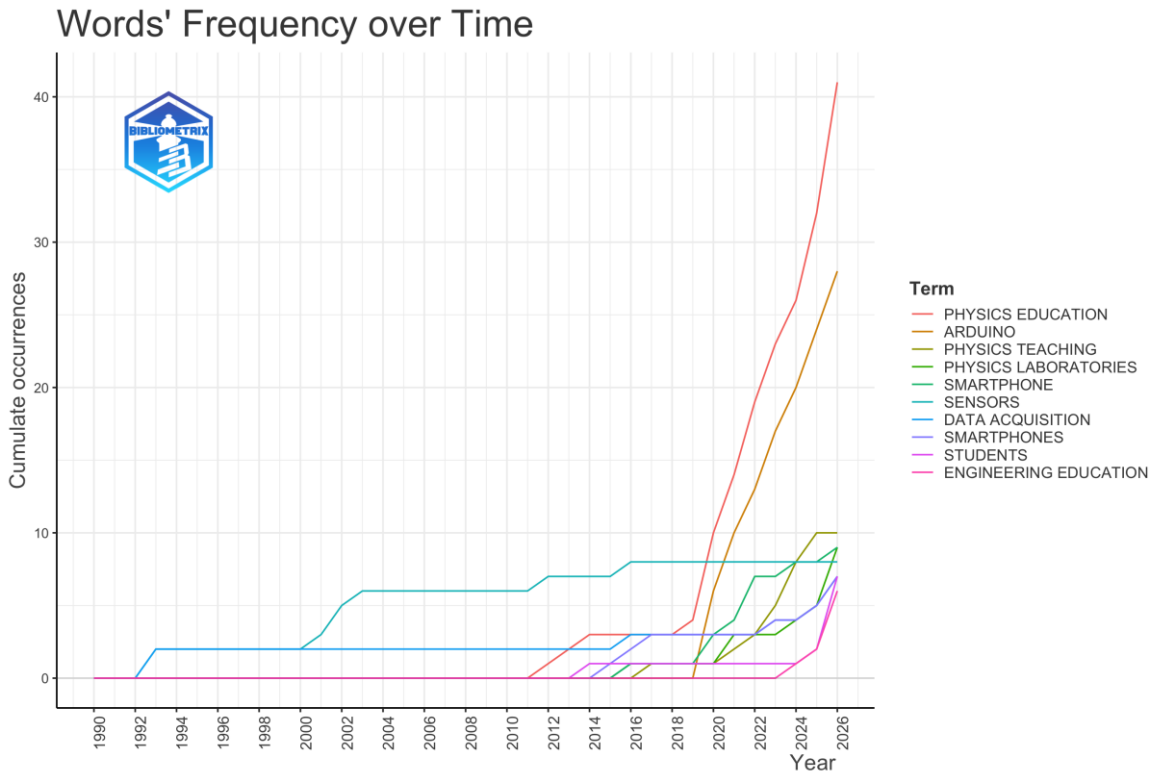


Figure 6. Cumulative occurrences of the ten most frequent keywords over time

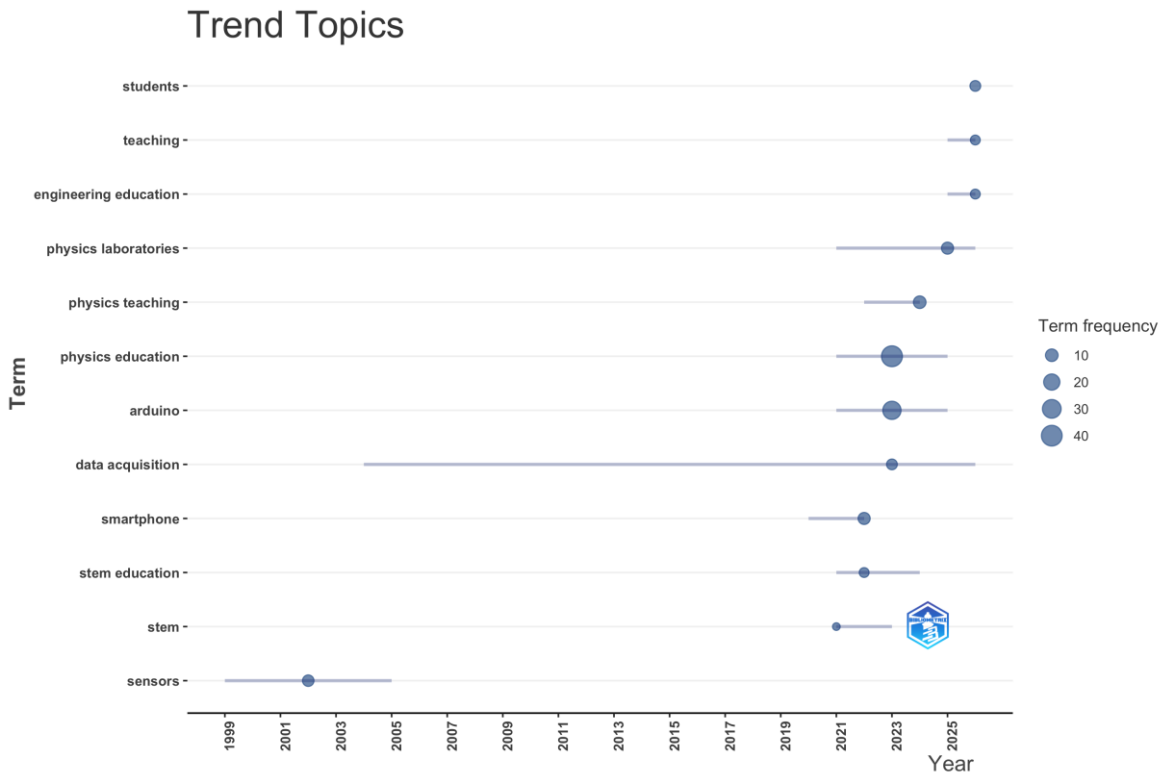


Figure 7. Trend topics (points = median year; lines = interquartile range of occurrence years)

RQ4: Coverage of Thermal Physics and Misconceptions

Fifteen of the 195 articles (7.7%) were classified as thermal physics studies (Table 6). Five were published between 2013 and 2023 and ten between 2024 and 2026, so attention to thermal topics has grown recently. Eight appeared in *Physics Education*. Newton's law of cooling was the most frequent topic (five articles), followed by calorimetry and specific heat, heat conduction,

thermal radiation, and thermodynamics. Arduino or ESP32 boards with digital temperature sensors or thermistors were the most common platform.

Eleven of the 15 thermal articles reported an apparatus or a measurement method and validated it against reference values or theory, without reporting data from learners. Three reported learner data: students' talk about real-time graphs and their perceptions of computer-assisted experiments (Stoica et al., 2016), student calculations and ratings of a Stirling engine laboratory (Stevens et al., 2023), and a qualitative analysis of the interpretations of 64 upper-secondary students who explored thermal phenomena with real-time sensors (De Angelis et al., 2025). One article developed an IoT-based learning ecosystem with a digital dashboard for teaching heat transfer and thermodynamics and reported its expert validity (Santiani & Annovasho, 2026). Only De Angelis et al. (2025) explicitly addressed conceptual change. No thermal article used the term misconception or applied a diagnostic test.

The term search across all 195 records gave the same picture. Misconception appeared in a single abstract, a systematic review of kinematics graphs (Afifah et al., 2026). Conceptual change appeared once (De Angelis et al., 2025), and a pre-test/post-test design was reported once, in an Arduino air-pressure study with secondary school students (Herendi & Jenei, 2025). Dashboard also appeared once (Santiani & Annovasho, 2026). The terms alternative conception, preconception, four-tier, two-tier, diagnostic test, and vocational did not appear in any record.

Table 6. Thermal physics articles in the dataset

Study	Thermal topic	Sensor / platform	Primary contribution	Learner evidence
Ibarra-Castanedo et al. (2013)	Thermography	Infrared thermal camera	Technique overview	None
Stoica et al. (2016)	Specific heat; melting point	Microcomputer-based laboratory	Learner data	Students' talk about real-time graphs; perceptions
Galeriu (2018)	Newton's law of cooling	Arduino Uno, DS18B20	Apparatus	None
Casaburo (2022)	Newton's law of cooling	Arduino	Measurement method	None
Stevens et al. (2023)	Work and power of a Stirling engine	Gas pressure sensor	Learner data	Student calculations; ratings
de Almeida et al. (2024)	Heat conduction; thermal diffusivity	Arduino, thermistors	Measurement method	None
Erol and Kuzucu (2024)	Specific heat	Arduino Uno	Measurement method	None
Leitão (2024)	Calorimetry	Arduino, internet-enabled (remote)	Apparatus	None
Baotong et al. (2025)	Thermal expansion; cooling	ESP32, DS18B20, IoT platform (real-time)	Apparatus	None
De Angelis et al. (2025)	Temperature, thermal equilibrium and processes	Sensors in real-time mode	Learner data	Qualitative; 64 upper-secondary students
Moreira et al. (2025)	Newton's law of cooling	Temperature sensors	Measurement method	None
Pickup and Roch (2025)	Thermal radiation (Leslie cube)	Arduino Nano, infrared sensor	Apparatus	None
Vitkóczi et al. (2025)	Temperature measurement	Arduino thermometers	Apparatus (STEM project)	Benefit claimed; no data in abstract
Pal et al. (2026)	Temperature measurement; cooling	NTC thermistor, multimeter	Apparatus (activity)	None
Santiani and Annovasho (2026)	Heat transfer; thermodynamics	IoT monitoring, digital dashboard	Learning ecosystem	Expert validation

Note. Coding based on titles and abstracts.

Discussion:

Publication performance (RQ1). The present study found a field that grew slowly for three decades and then expanded quickly after 2019, with two-thirds of all articles published from 2020 onward. The timing matches the spread of low-cost Arduino boards and smartphone sensor applications, which the most cited works in the dataset document (Monteiro & Martí, 2022; Staacks et al., 2018), and by the growth of remote laboratories, from teaching during the COVID-19 pandemic (Casaburo, 2021) to IoT platforms for remote regions (Castaño et al., 2024). The dominance of one core journal and the high share of one-time authors indicate that the field is still young: most articles report a single experiment written by a small team, and few research groups publish repeatedly. The modest level of international co-authorship, particularly the absence of MCP articles from Brazil and China, suggests that the expertise needed to build sensor-based materials is spreading through local communities rather than through international networks. For Indonesia, the comparatively high MCP share is a starting point for collaboration but rests on a small number of articles.

Intellectual base (RQ2). The intellectual base is built on tools rather than on learning theory. The most locally cited works describe how to measure something with a smartphone or an Arduino, and the most cited references within the dataset are cited only three times. This is consistent with the view that microcomputer-based laboratories were proposed first as instruments for scientific thinking (Thornton, 1987) and that their later versions have been documented mainly as resources for teachers (Goncalves et al., 2023; Monteiro & Martí, 2022). The presence of highly cited engineering papers that are never cited locally also shows that a keyword-based Scopus search captures a technical periphery that does not belong to the educational conversation. The implication for the field is that claims about learning still rest on a thin evidential base.

Themes and their development (RQ3). The vocabulary shifted from generic sensors and data acquisition towards Arduino, smartphones, and STEM, and only very recently towards students and teaching. The most frequent keywords name the platform or the discipline, not the concept being learned or the learning outcome. The emergence of students, teaching, and engineering education as the newest trend topics, together with recent articles on remote and IoT laboratories (Castaño et al., 2024; Trebbi et al., 2025) and AI-assisted instrumentation (Mortimer, 2026; Suñer et al., 2026), suggests that the field is beginning to turn from building devices to studying how they are used in class. This turn is still at an early stage, and the evidence it will need, namely controlled comparisons of learning outcomes, is not yet visible in the dataset.

Thermal physics and misconceptions (RQ4). The present study found that thermal physics is a small but growing topic in which technical development clearly outweighs pedagogical evaluation. Thermal experiments are well suited to low-cost sensors because temperature changes slowly enough to be followed live, which explains why Newton's law of cooling and calorimetry recur (Erol & Kuzucu, 2024; Galeriu, 2018; Leitão, 2024). However, only De Angelis et al. (2025) examined how real-time sensing changes students' interpretations, and their finding that real-time exploration supports the idea of temperature as a state property points directly to the kind of conceptual target that a thermal learning system could pursue. Earlier work with microcomputer-based laboratories reported that real-time graphs help students connect thermal phenomena with abstract representations (Stoica et al., 2016), and the Peatland-Smart project showed that IoT data and a dashboard can be organised into a coherent learning ecosystem (Santiani & Annovasho, 2026). None of these studies diagnosed misconceptions with a validated multi-tier instrument, measured change with a pre-test and a post-test, or involved vocational students. Misconception research on heat and temperature has relied on such diagnostic designs and Indonesian remediation studies have used conceptual strategies without real-time sensors (Firmanto et al., 2021). These two lines of research have therefore developed in parallel rather than together.

Table 7 translates these gaps into directions for the dashboard-assisted smart thermal learning system that this project is developing. The directions are a research agenda derived from the bibliometric evidence; they are not results of the system itself.

Table 7. Gaps identified and corresponding directions for a smart thermal learning system

Gap identified in the dataset	Direction for the smart thermal learning system
Thermal studies mostly validate apparatus; only three report learner data	Treat the system as a learning intervention and report learning outcomes, not only measurement accuracy
No study diagnoses misconceptions or uses multi-tier tests	Use a four-tier diagnostic test before and after learning to separate misconceptions from lack of knowledge
Conceptual targets are rarely stated; temperature as a state property is supported by real-time exploration (De Angelis et al., 2025)	Design activities around specific conceptual targets, such as the difference between heat and temperature and thermal equilibrium
Real-time and IoT features appear mainly as technical add-ons; one dashboard study reports only expert validation	Use the dashboard to display live temperature data alongside students' predictions (predict–observe–explain), and evaluate its use with learners
No study involves vocational students	Situate tasks in contexts relevant to vocational programmes and test the system with SMK students

Implications. Theoretically, the findings indicate that sensor-based physics education has developed largely without an explicit model of conceptual change, so studies that link real-time data to a diagnostic account of students' ideas can contribute a missing layer to the field. Practically, the many validated low-cost thermal set-ups in the dataset mean that developers do not need to start from zero: the effort can shift to the design of learning activities and assessment. For policy, the absence of vocational contexts suggests that curriculum developers and teacher education programmes for vocational schools should not assume that the existing evidence applies directly to their students.

Contribution and limitations. This study is, to our knowledge, the first to map sensor-based physics education research over four decades with explicit attention to thermal concepts and misconceptions. Several limitations apply. The data come from a single database (Scopus), so journals indexed elsewhere, including many Indonesian journals, are not represented. The search returned a technical periphery, including engineering and instrumentation papers, and 2026 is a partial year, so the most recent counts and citations are underestimated. Author keywords and Keywords Plus were missing for 39.49% and 75.90% of records, which weakens keyword-based analyses, and variant spellings split some keyword and reference counts. The thermal coding relied on titles and abstracts and may miss studies whose full texts report learner data. In addition, the preliminary codes were produced with AI assistance and verified by the authors rather than coded independently from scratch, which may have anchored their judgements. Future studies could repeat the analysis with Web of Science and national databases, clean the dataset of non-educational records, merge keyword variants with a thesaurus file, and add co-word, thematic-map, and thematic-evolution analyses. Empirical work should test whether real-time thermal sensing combined with diagnostic assessment reduces misconceptions in vocational classrooms.

CONCLUSION

Sensor-based physics education research has moved from a niche of computer-based laboratories to a fast-growing field centred on Arduino and smartphone tools, concentrated in one core journal and produced mostly by small, locally organised teams. Its intellectual base consists of practical measurement resources rather than learning theory, and its themes have only recently begun to turn towards students and teaching. Thermal physics remains a minor strand

within this field, dominated by apparatus development, and the intersection of real-time thermal sensing, diagnosed misconceptions, and vocational learners has not yet been studied.

The study contributes a field-level map that makes this intersection visible and translates it into concrete design directions: treating sensor-based systems as learning interventions, embedding multi-tier diagnostic assessment, defining conceptual targets, using dashboards to confront predictions with live data, and testing these designs with vocational students. These directions will guide the development and evaluation of the dashboard-assisted smart thermal learning system in the next stage of this project, and they offer other researchers a basis for studies that measure conceptual change rather than measurement accuracy alone.

AUTHOR CONTRIBUTION STATEMENT

RH: conceptualisation, data collection, bibliometric analysis, writing – original draft. BHI: supervision, methodology, writing – review and editing. IS: supervision, validation, writing – review and editing.

AI DISCLOSURE STATEMENT

The authors used Claude (Anthropic) to assist in drafting and editing the English text and to generate the preliminary title and abstract codes for the thermal physics and term analysis (RQ4), which were subsequently verified by the authors. All figures and indicators were produced by the authors using Biblioshiny, and all text, coding decisions, and references were reviewed and edited by the authors, who take full responsibility for the content of this publication.

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