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Low-Cost Instrumentation for Physical Measurements: Mapping Technologies, Measurement Principles, and Performance Evaluation

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Abstract

Low-cost instrumentation has expanded opportunities for physical measurements across scientific, industrial, environmental, and educational applications. However, differences in technological architectures, sensing principles, and performance evaluation approaches complicate comparisons across measurement systems. This study aimed to map low-cost instrumentation technologies, examine their underlying measurement principles, and synthesize approaches to evaluating measurement performance. A structured Scopus-based evidence mapping and qualitative thematic synthesis were conducted using bibliographic records and published abstracts. An initial search identified 133 records, of which 22 publications were retained for analysis following database filtering and screening. Among these publications, optical and photonic instrumentation accounted for the largest proportion (31.8%), followed by electrical and dielectric (27.3%), mechanical (22.7%), integrated and environmental (13.6%), and acoustic and ultrasonic systems (4.5%). The thematic synthesis identified five interconnected dimensions concerning accessible instrument design, physical transduction, performance validation, application-driven deployment, and metrological reporting. Performance indicators included measurement error, sensitivity, precision, repeatability, resolution, signal-to-noise ratio, and classification accuracy, reflecting different measurement characteristics that require context-specific interpretation. Low-cost instrumentation offers opportunities to reduce financial barriers, increase experimental accessibility, support adaptable instrument development, and extend physical measurements beyond conventional laboratory settings. Nevertheless, affordability and operational functionality do not independently establish measurement reliability. The scientific value of low-cost instrumentation therefore lies in combining technological accessibility with appropriate measurement principles, calibration, and performance validation to produce credible physical measurements across diverse applications.

Keywords: Low-cost instrumentation; Physical measurements; Measurement principles; Performance evaluation; Evidence mapping

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INTRODUCTION

Physical measurement underpins experimental inference because an instrument must transform an interaction with a physical system into a quantity that can be interpreted, compared, and reproduced. The expense and specialized infrastructure associated with conventional laboratory equipment can restrict the spatial coverage, frequency, and accessibility of measurements. Accessible instrumentation has consequently become a practical concern in experimental physics, engineering laboratories, and environmental research. Low-cost sensor development has enabled measurements beyond centralized facilities, but the credibility of an economical device still depends on its intended measurand and the procedures used to evaluate its performance (Chan et al., 2021; Payet et al., 2025; Eichstädt et al., 2023).

Developments in low-priced microcontrollers, embedded processing, commercially available sensor modules, and open-source software have expanded the range of architectures available for experimental measurement. Affordable instrumentation is no longer limited to replacing one expensive component: it may incorporate a complete chain of sensors, signal conditioning, data acquisition, processing, storage, and visualization. Modular implementations can be configured for different measurement requirements, as demonstrated by accessible vibration-acquisition systems, embedded motor-characterization platforms, and low-cost logging devices (Trujillo-Franco et al., 2024; Kurniawan et al., 2026; Pineda-Tobón et al., 2024). Yet the accessibility of individual components does not establish equivalence between different measurement chains or justify adopting a single performance threshold across applications.

The development of open scientific hardware has also introduced a distinct concern with reproducibility. Hardware that can be fabricated or modified locally is valuable only when the assembly, component specifications, software, and operating procedure can be understood and recreated. Instrument reproducibility therefore extends beyond publishing a schematic or naming a microcontroller; it also depends on accessible design files, documented configurations, and transparent conditions for repeating a measurement (Bowman, 2023; Diederich et al., 2022; Hohlbein et al., 2022). Reviews of open microscopes and electrochemical potentiostats illustrate how technical access and replicability can be studied within particular device families without resolving broader cross-domain questions about measurement validity (Salido et al., 2022; von Zuben et al., 2024).

The meaning of low cost is inherently dependent on the technology being replaced and the physical quantity being investigated. For example, an open-source scanning tunneling microscope addresses nanometer-scale imaging under very different hardware constraints from a portable optical microscope or an optical-fiber spectrometer. These configurations differ in the interactions being sensed, the resolution that may be required, and the conditions that may disturb their output (Ma, 2024; Salvadori et al., 2024; Tunens et al., 2024). A useful appraisal of technological accessibility must therefore identify whether cost refers to the sensing element, the complete apparatus, its supporting electronics, or the resources needed to maintain credible measurements.

Optical measurement offers an instructive example of the diversity hidden within a broad instrument label. Photodetection, microscopy, spectroscopy, and hyperspectral imaging use different measurement geometries and physical responses, even when affordable cameras or embedded processors are shared across platforms. Modular autofocus microscopy, an open spectroradiometer, and portable hyperspectral data acquisition systems address different observables and impose different requirements for calibration, dynamic range, timing, and signal interpretation (Lightley et al., 2023; Troscianko, 2023; Mao et al., 2023). Consequently, categorizing systems by hardware price or application domain alone risks obscuring the measurement principles by which observations acquire physical meaning.

Comparable distinctions apply to electrical and mechanical instrumentation. Electrical measurements may concern current or voltage directly, while capacitive or impedance signals may instead serve as indirect indicators of another physical

state. Similarly, an instrument designed for mechanical dynamics may combine transducers, conditioned signals, computational transformations, and reference measurements within a single acquisition architecture. The role of hardware and software co-design is especially visible when imaging spectrometers require reliable real-time storage, and when inexpensive motion-sensing devices require calibration of inertial channels before inferred quantities can be interpreted (Fernández-Conde, 2023; Harindranath & Arora, 2024). The transduction mechanism and the target measurand should thus be considered as related but analytically distinct dimensions.

The proliferation of integrated sensing platforms further complicates performance assessment because system behavior is affected by more than the nominal specifications of a transducer. Physiological computing toolkits, multi-sensor environmental platforms, and portable measurement systems may combine several sensing channels, acquisition rates, and computational transformations (Joshi et al., 2023; Silva et al., 2024; Zimmermann & Herbig, 2025). Operational reliability can be affected by sampling configuration, calibration transfer, sensor aging, and the relation between laboratory test conditions and actual deployment. These considerations require attention to the complete measurement chain rather than a favorable feature of an isolated component.

An important methodological challenge lies in the interpretation of instrument-performance indicators. Measurement error, precision, repeatability, sensitivity, resolution, and uncertainty describe different properties; neither improved signal amplitude nor successful classification necessarily establishes the accuracy of a physical measurand. Measurement practice is particularly complex in distributed networks, where cross-sensor dependence and changing environments introduce additional uncertainty and calibration requirements (Eichstädt et al., 2023; Vedurmudi et al., 2025). Calibration research on affordable environmental sensors and consumer-grade inertial units similarly highlights the need to specify reference conditions, correction models, and the applicability of a calibration beyond the original test environment (Nalakurthi et al., 2024; Harindranath & Arora, 2024).

Application-specific reviews have examined important aspects of affordable measurement technology, but their analytical boundaries remain relatively narrow. Reviews focusing on low-cost microscopes and open potentiostats emphasize device development within particular technological traditions, while a recent scoping review of optical sensors for freshwater monitoring focuses on analytical validation within a defined environmental application (Salido et al., 2022; von Zuben et al., 2024; Cirrone et al., 2026). These contributions are valuable and do not imply a general absence of scholarship on affordable instruments. Rather, they highlight a need to clarify how technological architectures, physical transduction, measurable quantities, and evaluation metrics may be compared across otherwise heterogeneous research settings.

The conceptual gap addressed in the present investigation concerns the integration of these distinct dimensions in a common literature-mapping framework. Device-centered accounts can illuminate fabrication and affordability without systematically distinguishing the raw physical signal from the inferred measurand; application-centered studies can describe successful deployment

without placing their indicators of performance on a comparable conceptual footing. Prior work on real-time acquisition, portable microscopy, and monitoring sensors offers different perspectives on these issues (Fernández-Conde, 2023; Salvadori et al., 2024; Chan et al., 2021). A structured mapping that explicitly separates instrumentation families, sensing principles, measurement targets, and performance-evaluation approaches is therefore warranted, while avoiding any assumption that fundamentally different instruments can be ranked on a single numerical scale.

Study Objectives and Research Questions

This study aims to map research on low-cost instrumentation for physical measurements, focusing on technological architectures, the physical principles by which sensor outputs are related to measurable quantities, and the approaches used to evaluate instrument performance. The investigation further seeks to clarify how application settings shape measurement requirements and to identify methodological and reporting questions that warrant closer study. In keeping with the defined scope, the objective is an integrative mapping of published evidence rather than a pooled estimate of accuracy or cost effectiveness. Four research questions guide the investigation:

- RQ1: What technological architectures and instrumentation families are addressed in research on low-cost physical measurement systems?
- RQ2: How are sensing and transduction principles related to different physical measurands and application contexts?
- RQ3: What approaches and indicators are used to evaluate measurement performance, including accuracy, precision, calibration, and uncertainty? (RQ4) What cross-cutting research themes, evidence-reporting issues, and priorities for subsequent investigation can be identified in the literature?

Study Novelty

The proposed contribution lies in the joint examination of three dimensions that are frequently considered within separate technical literatures: instrumentation architecture, the physical principles connecting sensor response to the measurand, and the evidentiary basis for evaluating measurement performance. Existing methodological discussions of open hardware emphasize documentation and reproducibility, while device-specific reviews emphasize their respective designs or application needs (Bowman, 2023; Diederich et al., 2022; Salido et al., 2022). The present mapping is designed to connect these concerns without assuming that openness, affordability, and metrological credibility are equivalent properties.

A further contribution is the explicit separation of instrument-performance evidence from more general claims of functionality or successful application. Approaches to network metrology, calibration, and analytical validation suggest that reported performance must be interpreted in relation to specific measurands, reference conditions, and the purpose of a measuring system (Eichstädt et al., 2023; Nalakurthi et al., 2024; Cirrone et al., 2026). By examining these distinctions across technologies and applications, this study seeks to provide a coherent basis for comparing research emphases and identifying questions requiring more detailed empirical or full-text examination. Its scope is a structured mapping and thematic

synthesis of indexed publication information, not a definitive certification of the quality of individual instruments.

METHODS

This study employed a structured, Scopus-based evidence-mapping approach and qualitative thematic synthesis of bibliographic abstracts concerning low-cost instrumentation for physical measurements. Identification, selection, and reporting were informed by PRISMA 2020 (Page et al., 2021), while documentation of the search strategy drew on PRISMA-S (Rethlefsen et al., 2021). The scope of inference was explicitly restricted to the information available in indexed records and abstracts.

Research Design and Reporting Approach

A systematic search and structured thematic synthesis were undertaken to characterize cost-oriented instrument design, physical transduction principles, measured quantities, performance evaluation, and application contexts. The analytical unit was the Scopus-indexed record. This design provided a reproducible mapping of abstract-reported evidence rather than a comprehensive appraisal of full-text studies.

For synthesis, descriptive bibliographic variables were distinguished from interpretive codes assigned to abstract content. A statement not contained in an abstract was treated as not reported at the abstract level, without assuming its absence from the complete article. Such distinctions were applied particularly to instrument cost, calibration procedures, metrological traceability, uncertainty estimation, and reproducibility.

Information Source and Search Strategy

Scopus was searched using the TITLE-ABS-KEY field. The initial expression, TITLE-ABS-KEY: (Low-Cost Instrumentation for Physical Measurements), was entered as an unquoted series of terms, which the Scopus interface displayed as a conjunction of search terms rather than an exact-phrase search. The database was subsequently restricted to articles published in English between 2016 and 2026 and indexed under Engineering (ENGI) or Physics and Astronomy (PHYS). The search was limited to Scopus; no additional databases were searched.

The restricted query was [TITLE-ABS-KEY (Low-Cost Instrumentation for Physical Measurements) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "PHYS")) AND (LIMIT-TO (DOCTYPE, "ar")) AND PUBYEAR > 2015 AND PUBYEAR < 2027]. Search outputs were exported in CSV format, preserving the available author names, titles, publication years, digital object identifiers (DOIs), Scopus EIDs, and abstracts. Search sensitivity was constrained by the selected terminology, subject classification, and single-database coverage.

Eligibility Criteria

Eligibility criteria were operationalized for title-and-abstract screening rather than full-text study assessment. Primary technical or experimental investigations were considered relevant when they concerned the design, configuration, or evaluation of low-cost instrumentation and described a physical measurand, measurement architecture, or instrument-performance evidence. An abstract that

omitted cost figures or calibration information was not automatically excluded when the central instrumentation focus remained plausible.

Table 1 presents the five content-based eligibility dimensions used to distinguish potentially relevant instrument studies from records identified only through lexical overlap. Bibliographic restrictions applied through Scopus were treated separately from these substantive criteria.

Table 1. Operational eligibility criteria used for record-level screening

Code	Criterion	Record-level decision rule
E1	Primary study	Original technical or experimental research rather than a review or methodological survey.
E2	Low-cost instrumentation	Development, configuration or evaluation of an instrument described as low-cost, affordable or economically accessible.
E3	Physical measurand	A measurable physical quantity or physical signal is identifiable.
E4	Instrument architecture	Instrument, sensing principle, components or acquisition approach described.
E5	Performance evidence	Evidence of testing, comparison, operation or performance evaluation is reported.

As specified in Table 1, each dimension was judged on positive evidence within the title or abstract. Explicitly incompatible studies were excluded, whereas insufficient detail was coded as uncertain. This procedure avoided interpreting incomplete abstracts as evidence that a measurement, validation procedure, or technical specification had not been performed.

The designation low-cost was accepted as a provisional description only when supported by the authors' abstract-level characterization of an instrument or measurement system. The use of a microcontroller, open-source software, or an embedded platform alone was not treated as sufficient evidence of affordability. Records were not removed simply because the abstract did not provide a component-level cost breakdown.

Record Screening and Selection

The filtered Scopus export was checked for repeated identifiers using DOI, title, and EID; no duplicates were detected among these exported records. Title and abstract content were then screened against criteria E1–E5 as supported, unclear, or not supported. Records with clear evidence of non-eligibility were excluded. Ambiguous records were retained for abstract-based mapping and separately flagged, so that uncertainty in their final eligibility remained visible. Screening and coding were conducted as a structured, AI-assisted single-reviewer analysis; independent duplicate screening was not undertaken.

Only database records and abstracts were assessed. Full-text reports were neither retrieved nor evaluated for eligibility. Consequently, records retained for mapping were not interpreted as fully eligible studies in the conventional systematic-review sense. Similarly, because detailed experimental reports were not examined, a formal risk-of-bias assessment of the underlying studies was not performed.

The identification, filtering, and screening sequence is shown in Figure 1. It distinguishes database restrictions from substantive title-and-abstract exclusion and

indicates the separate status of records clearly supported by their abstracts and records retained despite unresolved details.

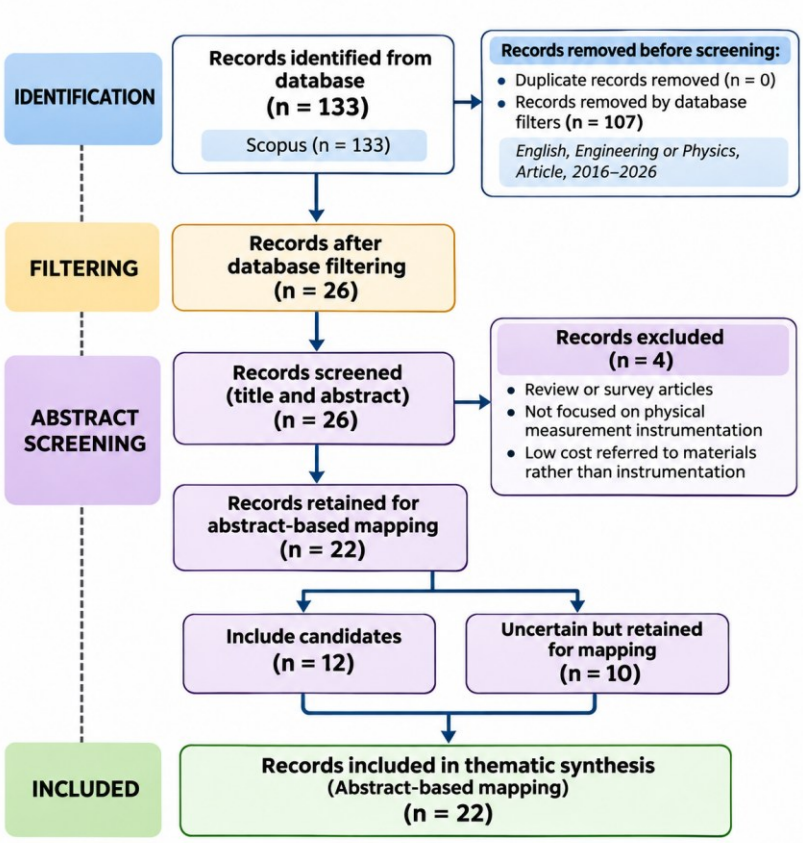

Figure 1. PRISMA-informed identification and abstract-screening flow for Scopus-indexed records.

Figure 1 documents the transition from the initial Scopus search output to the filtered export and the abstract-mapping corpus. The removal attributed to database filters reflects their combined effect; the contribution of each filter was not isolated. The absence of duplicate DOI, title, and EID entries was established for the 26 exported records, not independently for all 133 initial search results. The final mapping corpus includes both stronger abstract-level candidates and records retained with unresolved information; it does not represent full-text-confirmed inclusion.

Data Extraction and Coding Framework

Bibliographic metadata and abstract statements were transferred into a structured extraction matrix and linked using stable identifiers. Author–year labels were used in the manuscript, while record IDs remained available for auditing. Instrument design, sensing mechanism, measurand, application setting, cost evidence, and reported performance indicators were coded from explicit abstract content. Unavailable details were marked not reported (NR); analytical interpretations were distinguished from factual extraction.

Table 2 summarizes the extraction domains and coding conventions applied consistently across the abstract-mapping corpus. Separating measurement principles from measured quantities was necessary because a single sensing mechanism may serve multiple physical measurands.

Table 2. Abstract-based extraction domains and coding conventions

Domain	Operational content	Coding convention
Bibliography	Author, year, title, DOI/EID	Verbatim metadata; study ID retained in audit matrix.
Instrument design	Device type, component/platform, cost-oriented strategy	Extract stated details only; NR if absent.
Transduction/measurand	Sensing principle and measured physical quantity	Independent codes; multiple codes permitted.
Application	Laboratory, field, environmental, industrial or biomedical context	Abstract-defined setting; no inferred validation.
Performance	Error, precision, resolution, sensitivity, uncertainty, SNR or classification accuracy	Original metric and unit retained; no cross-metric pooling.
Calibration/limitations	Reference instruments, reported limitations, operating constraints	Reported evidence separated from missing abstract information.
Theme membership	Design, transduction, validation, applications, reporting gaps	Nonexclusive qualitative assignment supported by text.

The conventions in Table 2 allowed more than one sensing principle or thematic code to be assigned when supported by the abstract. A single primary instrumentation-family label was retained solely for descriptive grouping. Reported measurement accuracy, classification accuracy, precision, resolution, and signal-to-noise changes were preserved as distinct outcomes rather than combined into a common numerical scale.

Thematic Analysis and Evidence Synthesis

Thematic synthesis combined deductive and inductive coding. The review questions provided initial sensitizing categories concerning accessible design strategies, transduction architecture, validation, applications, and technical constraints. Abstracts were then examined for recurrent explicit concepts, which were assigned codes and compared across studies. Codes were grouped into broader themes, with category boundaries reviewed against the abstract statements that supported them. Theme membership was nonexclusive.

Descriptive frequencies summarized the distribution of publication characteristics and primary instrumentation families. Cross-study narrative synthesis compared design approaches, physical measurands, validation claims, and reported applications, while retaining the original definition and units of each performance metric. No meta-analysis or cross-instrument pooling was attempted because the measures, evaluation contexts, and available abstract-level data were heterogeneous.

The synthesis was confined to reported evidence and reporting patterns identifiable from abstracts. Unspecified calibration methods, traceability, cost data, or measurement uncertainty were classified as absent from the abstract, not absent from the full study. The analysis therefore provides a structured overview of research directions and reported technical evidence, but cannot establish comprehensive

methodological quality, reproducibility, or comparative effectiveness of the underlying measurement systems.

RESULTS AND DISCUSSION

The results present the initial Scopus search profile, the screening pathway, and an evidence map derived from 22 candidate records. Bibliographic distributions for the initial 133 records are distinguished throughout from the 22-record abstract-based synthesis corpus.

Initial Scopus Identification, Publication Profile, and Abstract-Based Selection

The initial Scopus search yielded 133 records published between 1967 and 2026. Figure 2 displays the complete annual distribution, while Figure 3 summarizes document types and Scopus subject-area assignments within the same initial search population. All 133 records are included in the temporal reconstruction, including years with no identified publications.

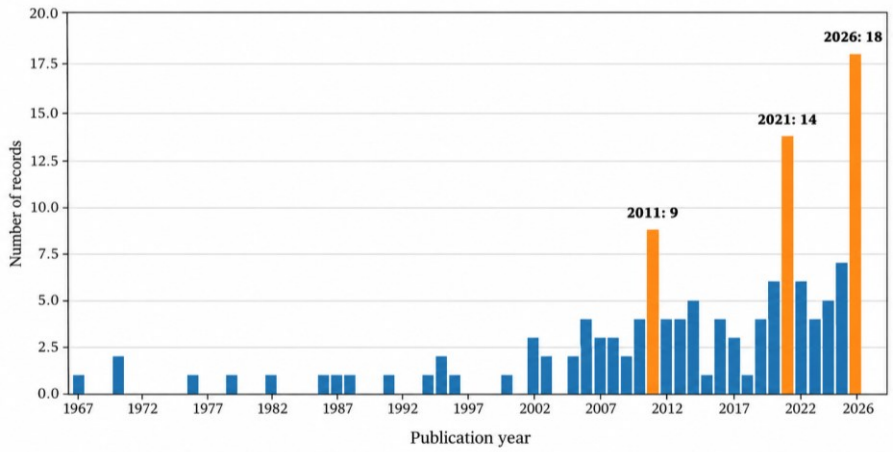

Figure 2. Annual distribution of records identified in the initial Scopus search (n = 133, 1967–2026).

The complete annual series sums to 133 records and shows fluctuating rather than continuous annual growth. The most prominent annual counts were 9 in 2011, 14 in 2021, and 18 in 2026. The initial search was concentrated in the more recent years: 60 records (45.1%) appeared during 2020–2026, compared with 39 (29.3%) in 2010–2019, 20 (15.0%) in 2000–2009, and 14 (10.5%) in 1967–1999. Although these figures indicate a larger share of search results in the most recent period, the annual trajectory remains uneven, and 2026 is a partial publication year. The temporal profile describes the unfiltered search output rather than the publications later retained for thematic mapping.

Publication Distribution Across Periods

Table 3. Distribution of the initial 133 Scopus records across publication periods

Period	Records (n)	Share (%)
1967–1999	14	10.5
2000–2009	20	15.0
2010–2019	39	29.3
2020–2026	60	45.1
Total	133	100.0

Table 3 provides an aggregate view of the complete year-by-year series shown in Figure 2. The 2020–2026 interval contributes the largest share of the initial search results. These descriptive frequencies should not be interpreted as an annualized growth rate because the intervals differ in duration and 2026 has not concluded.

Document Types and Subject Areas at Initial Identification

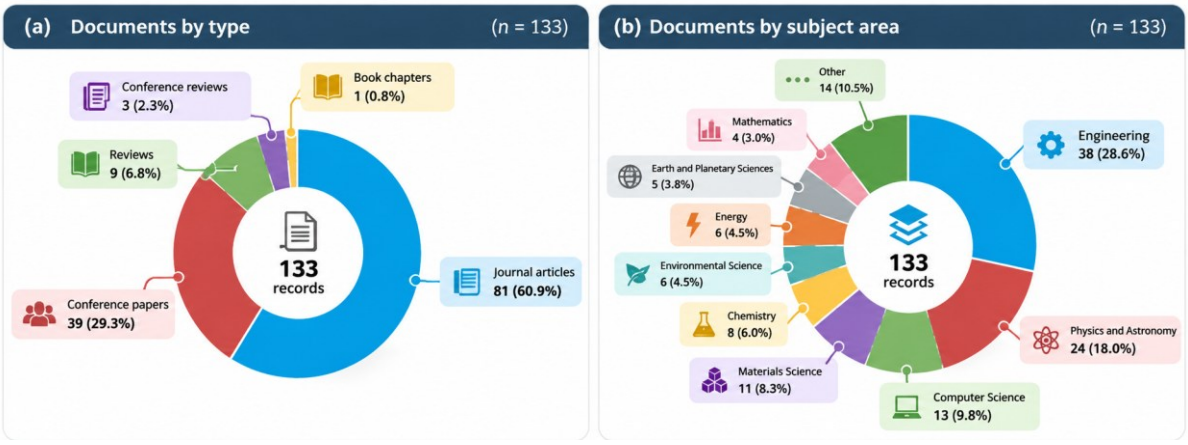

Figure 3. Document-type and subject-area shares reported for the 133 initial Scopus records.

Journal articles represented 60.9% of the initial search results, followed by conference papers (29.3%), reviews (6.8%), conference reviews (2.3%), and book chapters (0.8%). The prominence of conference papers is relevant when interpreting the later article-only filter: that filter excludes a substantial portion of the original publication landscape. Percentages are taken from the Scopus dashboard, and approximate counts in Table 4 are rounded from them.

Table 4. Document-type composition of the initial 133 Scopus records

Document type	Share (%)	Approx. n	Interpretation
Article	60.9	81	Dominant source of evidence and the basis for the later Scopus filtering strategy.
Conference Paper	29.3	39	Strong secondary publication channel, reflecting the engineering-oriented nature of the field.
Review	6.8	9	Useful for contextualizing research development but not treated as primary studies in the abstract-based mapping.
Conference Review	2.3	3	Minor component of the overall corpus.
Book Chapter	0.8	1	Very limited presence in the initial search results.

Subject-area assignments were led by Engineering (28.6%), Physics and Astronomy (14.7%), and Computer Science (9.3%), followed by smaller shares across additional disciplines. These dashboard categories describe the indexing profile and should not be interpreted as direct evidence of each record's eligibility for a physics-focused review. The later filtering retained Engineering and Physics and Astronomy as eligible indexing categories.

Table 5. Subject-area distribution of the initial Scopus search

Subject area	Share (%)	Interpretation
Engineering	28.6	Most prominent disciplinary context, consistent with the design and implementation focus of low-cost instrumentation.
Physics and Astronomy	14.7	Core disciplinary anchor for the present review theme.
Computer Science	9.3	Reflects data acquisition, embedded systems, signal processing, and AI-enabled measurement applications.
Environmental Science	6.2	Indicates frequent deployment of low-cost instrumentation in monitoring contexts.
Medicine	5.8	Shows that low-cost physical measurement systems are often adapted to biomedical applications.
Chemistry	5.4	Associated with analytical and sensing applications using physical detection principles.
Biochemistry, Genetics and Molecular Biology	5.0	Represents cross-disciplinary sensing applications rather than core physics-only studies.
Earth and Planetary Sciences	3.9	Suggests application in geophysical and field-based measurement contexts.
Materials Science	3.9	Relevant to device fabrication and material characterization studies.
Social Sciences	3.5	Minor but notable presence, likely linked to technology implementation contexts.
Other	13.9	Residual share shown by Scopus for additional smaller subject categories.

Following the initial profile, the search was filtered to English-language journal articles from 2016–2026 indexed under Engineering or Physics and Astronomy. This retained 26 records (19.5%) and excluded 107 records (80.5%) through the combined database filters. The contribution of each individual filter cannot be reconstructed from the available CSV. The 26 retained records contained abstracts and unique DOI, title, and EID identifiers; no duplicates were detected.

The abstract-level assessment classified 12 records as strong candidates, 10 as uncertain candidates, and four as provisionally excluded. The resulting corpus of 22 candidate records was carried forward to descriptive extraction (84.6% of the 26 filtered records). The 10 uncertain records were deliberately retained because missing cost, design, or validation details in an abstract do not demonstrate their absence from a study. The following tables and figures are therefore based on 22 abstract records, not on 22 studies that passed full-text eligibility.

Table 6. Database filtering and abstract-based selection accounting

Processing step	Number	Interpretation
Initial Scopus identification	133	Broad initial search, 1967–2026
Filtered Scopus export	26	English; ENGI/PHYS; Article; 2016–2026
Duplicate records	0	Checked by DOI, title, and Scopus EID
Strong abstract candidates	12	Criteria sufficiently supported by abstract

Processing step	Number	Interpretation
Uncertain abstract candidates	10	Insufficient detail; retained for mapping
Provisionally excluded	4	Abstract-based subject/type mismatch
Mapped candidate records	22	Abstract-only synthesis population

These screening categories represent title-and-abstract decisions rather than full-text eligibility outcomes. The mapped corpus therefore comprises 22 records retained for abstract-based synthesis.

Characteristics of the Abstract-Mapped Corpus

The temporal distribution of the 22 mapped records is presented in Figure 4, providing a comparison between the narrower abstract corpus and the broader identification-stage search profile.

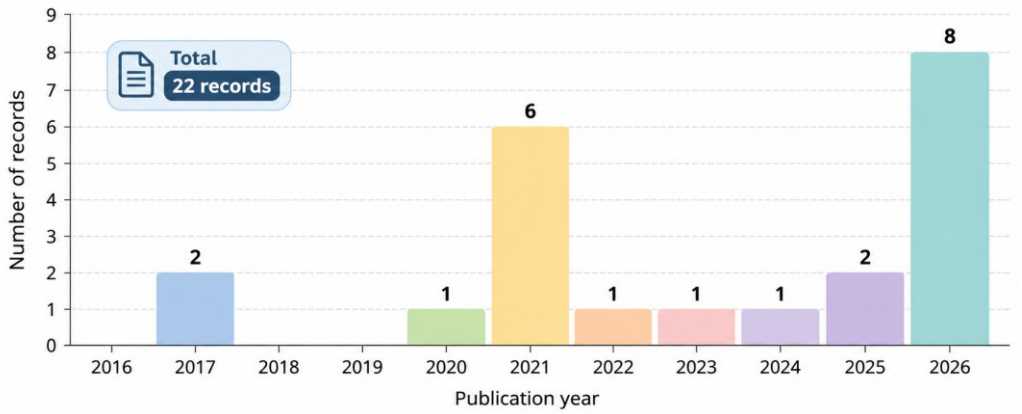

Figure 4. Annual distribution of the 22 candidate records mapped from abstracts.

The mapped corpus extended from 2017 to 2026. Eight studies (36.4%) appeared in 2026 and six (27.3%) in 2021; together these two years accounted for 14 of 22 candidate records (63.6%). The distribution also contained individual contributions in 2020, 2022, 2023, and 2024, while the remaining records were distributed across 2017 and 2025. The concentration of abstracts in 2026 should not be interpreted as a complete annual publication total or a statistically established growth trajectory.

The range of applications was broad, including polymer curing, soil-water monitoring, integrated-circuit inspection, underwater geometry, environmental logging, photon detection, tactile sensing, laboratory permittivity testing, and circuit emulation. Because application setting and measurement mechanism are different dimensions, a subject-oriented classification alone would obscure the physical principles underpinning the instruments. The analysis therefore assigned each record one primary transduction or instrumentation category, accompanied by an explicit description of its measured quantity or observable.

Instrumentation Families and Technical Architectures

Figure 5 summarizes the primary instrumentation families derived from the 22 mapped abstracts. Each record was assigned once according to its principal sensing or acquisition architecture.

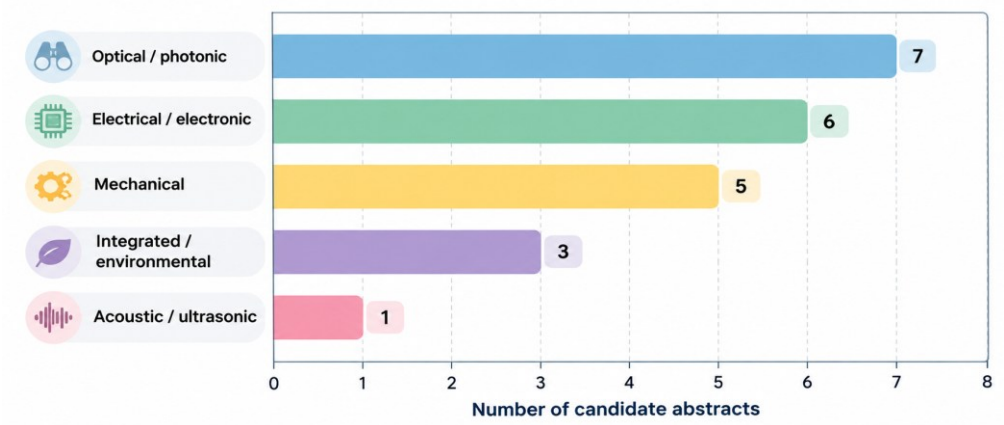

Figure 5. Primary instrumentation families identified among the 22 candidate abstracts.

Optical and photonic devices formed the largest umbrella group (7/22; 31.8%), followed by electrical and dielectric systems (6/22; 27.3%), mechanical techniques (5/22; 22.7%), integrated or environmental data-acquisition platforms (3/22; 13.6%), and acoustic or ultrasonic techniques (1/22; 4.5%). These five groups were constructed by combining nine more specific abstract-based categories. Each record contributed once to the figure; the categorization does not indicate a mutually exclusive set of physical principles.

Table 7. Instrumentation families, study identifiers, and measured observables

Family	n	Supporting studies	Examples of observables
Optical / photonics	7	Gugliandolo et al. (2024), Runyan et al. (2025), Jakob et al. (2021), Zhao et al. (2026), Grossi et al. (2020), Rousseau et al. (2026), Kuo et al. (2026)	Transmitted light; Underwater 3D dimensions; Photon counts; Slice thickness (30–1000 nm); Solid fat content; Luminescence lifetime; Multi-band optical response
Electrical / dielectric	6	Yang et al. (2021), Placidi et al. (2023), Mazini et al. (2026), Merla et al. (2017), do Couto and da Silva (2021), Guerrero-rodríguez et al. (2021)	Temperature; Soil volumetric water content; Level; Complex permittivity; Electric potential difference; Electronic circuit responses (emulated)
Mechanical	5	Vaquero-Martínez et al. (2026), Miranda-Martínez et al. (2022), Pan et al. (2026), Laferrière and Payeur (2017), Scariot et al. (2025)	Mass changes; Viscosity and viscoelastic properties; Clamping force; Surface proximity; Weight variation
Integrated / environmental	3	Lujan et al. (2026), Izett and Tortell (2021), Chilcott and Kjærgaard (2021)	Ambient temperature; Dissolved gas ratios ΔO2/N2; Multiple physical operating parameters
Acoustic / ultrasonic	1	Chen et al. (2026)	Ultrasound echo amplitude

Electrical and dielectric studies used impedance, capacitance, electric potential, current, and related responses to quantify either electrical properties themselves or indirect physical states. Placidi et al. (2023) described an impedance meter based on a modified capacitive probe and an AD5933 chip for soil-water

measurements, whereas Merla et al. (2017) examined portable complex-permittivity measurement. Mazini et al. (2026) used capacitive responses to infer level, angular position, and pressure. In other instances, dielectric monitoring tracked changes during polymer curing (Yang et al., 2021), electrical uncertainty was estimated for a photovoltaic prototype (do Couto and da Silva, 2021), or electrical responses were emulated in a teaching-oriented platform (Guerrero-rodríguez et al., 2021). These examples show substantial variation between direct metrology and the use of electrical signals as proxies for non-electrical quantities.

The optical and photonic group combined transmitted-light detection (Gugliandolo et al., 2024), stereo imaging for underwater dimensional assessment (Runyan et al., 2025), single-photon lock-in detection (Jakob et al., 2021), microscopy-based thickness determination (Zhao et al., 2026), near-infrared evaluation of solid-fat content (Grossi et al., 2020), CMOS luminescence imaging of temperature, oxygen, and pH (Rousseau et al., 2026), and NIR classification of plastic materials (Kuo et al., 2026). Imaging geometry, photon-count statistics, absorption or scattering, and lifetime-dependent luminescence represent different physical mechanisms, despite a shared reliance on light. Consequently, their numerical performance indicators cannot be combined without defining common targets and reference procedures.

Mechanical methods encompassed gravimetric lysimetry (Vaquero-Martínez et al., 2026), a quartz-crystal or rheological approach to synovial-fluid properties (Miranda-Martínez et al., 2022), tactile force and slip sensing (Pan et al., 2026), robotic contact and proximity detection (Laferrière and Payeur, 2017), and balance-based monitoring of animal activity (Scariot et al., 2025). The integrated/environmental group connected multiple physical channels within logging or monitoring platforms (Lujan et al. (2026), Izett and Tortell (2021), Chilcott and Kjærgaard (2021)), while the single ultrasonic record (Chen et al., 2026) primarily improved acoustic imaging via a transmission-line anti-reflection coating. This distinction matters: in Chen et al. (2026), low-cost terminology refers to a device enhancement rather than necessarily demonstrating a low-cost standalone instrument.

Cross-Study Thematic Synthesis

Beyond the assignment of one primary instrumentation family, the abstracts revealed recurring design, measurement, validation, and deployment concerns that cut across physical domains. Table 8 presents five interpretive themes and identifies the studies supporting each theme. Unlike the mutually exclusive family classification in Figure 5, thematic memberships were allowed to overlap because individual studies could report several relevant characteristics.

Table 8. Thematic synthesis of design, measurement, validation, and reporting patterns across the 22 abstract-mapped records. The studies shown are illustrative, and themes are not mutually exclusive.

Theme	Empirical pattern in abstracts	Illustrative supporting studies
Cost-aware and accessible design	Simplified electronics, integrated probes, open architectures, and portable acquisition mechanisms are	Yang et al. (2021); Placidi et al. (2023); Lujan et al. (2026); Mazini et al. (2026);

Theme	Empirical pattern in abstracts	Illustrative supporting studies
	used to reduce deployment complexity.	Merla et al. (2017); Kuo et al. (2026)
Transduction across measured domains	Electrical, optical, mechanical, and acoustic effects are used either to measure a physical quantity directly or infer a material or application-specific observable.	Placidi et al. (2023); Runyan et al. (2025); Miranda-Martínez et al. (2022); Mazini et al. (2026); Pan et al. (2026); Rousseau et al. (2026)
Diverse performance validation	Studies report relative or absolute error, sensor sensitivity, signal improvement, uncertainty, resolution, and classification success using non-interchangeable metrics.	Chen et al. (2026); Placidi et al. (2023); Jakob et al. (2021); Merla et al. (2017); Pan et al. (2026); Zhao et al. (2026); Rousseau et al. (2026); Kuo et al. (2026)
Application-driven deployment	Architectures are tailored to field monitoring, composite manufacturing, underwater imaging, laboratory measurements, and multiparameter observation.	Yang et al. (2021); Vaquero-Martínez et al. (2026); Runyan et al. (2025); Lujan et al. (2026); Izett and Tortell (2021); Chilcott and Kjærgaard (2021); Rousseau et al. (2026)
Incomplete abstract-level cost and traceability information	Not every abstract states a bill of materials, traceable calibration chain, reference conditions, or full uncertainty budget.	Yang et al. (2021); Vaquero-Martínez et al. (2026); Lujan et al. (2026); Mazini et al. (2026); Grossi et al. (2020); do Couto and da Silva (2021); Guerrero-rodríguez et al. (2021)

The first two themes describe how accessibility-oriented instrument architectures depend on transduction principles that are not confined to any single application. For example, electrical impedance and capacitance are used for both material characterization and indirect monitoring, whereas optical techniques serve geometric reconstruction, spectroscopy, and multiparameter imaging. This cross-domain recurrence is visible in studies such as Placidi et al. (2023), Merla et al. (2017), Runyan et al. (2025), and Rousseau et al. (2026).

The third and fourth themes show that measurement validation is strongly shaped by the operating context. Placidi et al. (2023) and Merla et al. (2017) reported error- or uncertainty-based evaluation, whereas Jakob et al. (2021) emphasized photon-count and signal-to-noise improvement and Kuo et al. (2026) reported classification performance under laboratory and field conditions. These findings represent distinct evidentiary dimensions rather than a common scale of measurement quality.

The fifth theme concerns reporting visibility rather than demonstrated methodological deficiency. Abstracts that do not specify instrument cost or a traceable uncertainty budget cannot be taken as evidence that the corresponding

full reports omit those elements. The available records therefore permit identification of reporting patterns at abstract level but not a definitive appraisal of instrument affordability or metrological traceability.

Physical Quantities, Measurement Principles, and Application Contexts

Across the corpus, measured variables were not limited to textbook categories such as temperature, force, voltage, and light intensity. Several reports addressed derived or application-specific observables, including composite cure degree, volumetric soil water, plastic identity, biological tissue thickness, or inferred activity. The relationship between the raw sensor output and final reported quantity therefore forms a key analytical dimension of the evidence map. A capacitive or optical system may be classified by transduction physics even when the output is a mechanical displacement, material property, or categorical class.

Table 9. Examples of measurement principles and physical quantities

ID	Measurement principle	Measured / inferred output	Analytical distinction
Placidi et al. (2023)	Electrical impedance	Capacitance/conductance; soil water content	Instrument-to-reference comparison
Runyan et al. (2025)	Optical stereo vision	Underwater geometric dimensions	Imaging geometry and scale estimation
Mazini et al. (2026)	Capacitive sensing	Level, angle, pressure	Indirect mechanical measurements
Merla et al. (2017)	Dielectric response	Complex permittivity	Laboratory electrical material characterization
Pan et al. (2026)	Piezoresistive sensing	Force, slip, torsion	Tactile/mechanical observables
Zhao et al. (2026)	Image-based analysis	Slice thickness	Dimensional measurement
Rousseau et al. (2026)	Luminescence lifetime imaging	Temperature, oxygen, pH	Multiparameter spatial maps
Kuo et al. (2026)	Near-infrared spectroscopy	Spectral response; plastic class	Classification not equivalent to physical accuracy

Several devices used low-cost or open-source strategies in different ways. Some abstracts described custom sensing electronics or portable meters, others emphasized embedded processing, modified probes, imaging hardware, or downloadable logging architectures. Not all studies provided numerical component costs, total bill of materials, calibration expenditures, or comparisons against commercial equipment. The extracted low-cost attribute thus varies from an explicit but unquantified claim to an architectural or implementation rationale. On the available evidence, the mapped documents do not support a pooled estimate of instrument affordability.

Applications also crossed disciplinary boundaries. Agricultural or environmental instruments measured physical changes in moisture, gas composition, or ambient conditions; biomedical studies relied on optical or mechanical sensing; and semiconductor or material-characterization studies used

ultrasound and dielectric responses. These were retained or tagged according to measurable physical observables, rather than automatically excluded on the basis of application setting. Nevertheless, in some cases the scientific contribution focused on monitoring, classification, or hardware modification instead of traceable physical metrology, a distinction flagged in the extraction matrix.

Evidence of Measurement Performance, Calibration, and Uncertainty

Performance reporting varied substantially among candidate abstracts. Some presented quantitative comparisons against reference instruments, relative errors, uncertainties, precision values, or operating bounds. Others emphasized functional prototypes, linear sensor responses, stable operation, or improved signals without supplying a metrological error budget. Such differences are themselves observable reporting characteristics, but they do not demonstrate that an unreported assessment was absent from the full article.

Table 10. Selected quantitative performance results explicitly reported in abstracts

ID	Approach	Reported value	Appropriate interpretation
Chen et al. (2026)	Ultrasonic imaging	Echo amplitude: 142 to 216 mV (+52%); gradient +93%	Signal/imaging enhancement
Placidi et al. (2023)	Impedance meter	Maximum capacitance error +6.12%; conductance error +5.6%	Electrical measurement error
Lujan et al. (2026)	Environmental logger	Reported operation: −2 to 12 °C; relative humidity 4–100%	Operating conditions, not accuracy
Jakob et al. (2021)	Photon detection	SNR improvement >100-fold; 98% of dark counts filtered	Signal quality, not metrological accuracy
Merla et al. (2017)	Permittivity measurement	RRMSE <5%; expanded uncertainty <3%	Reference comparison and uncertainty
Pan et al. (2026)	Tactile sensing	Force range up to 5 N; sensitivity 4.08 N^{-1}; accuracy 5.82%; repeatability error <3.42%	Multiple distinct sensor performance metrics
Zhao et al. (2026)	Thickness estimation	Mean absolute error 0.77 nm	Dimensional estimation error
Grossi et al. (2020)	NIR solid-fat measurement	R^2 >0.9 compared with DSC	Association; not directly accuracy
Rousseau et al. (2026)	Luminescence imaging	Temperature precision ±1 °C (1σ); spatial resolution 500 µm; 7 Hz	Precision, resolution, temporal rate
Kuo et al. (2026)	NIR plastic analysis	Classification accuracy 99.17% lab; 75% field	Classification accuracy, not sensor accuracy
do Couto and da Silva (2021)	Electrical quantities	0.4558 ± 0.0004 V; 81.7100 ± 0.1118 µA	Reported value with uncertainty; definition requires verification

Placidi et al. (2023) and Merla et al. (2017) illustrate the clearest explicit numerical examples of instrument-to-reference performance in the extracted evidence. Placidi et al. (2023) reported maximum errors for capacitance and conductance relative to an LCR-meter benchmark, whereas Merla et al. (2017) reported relative root-mean-square error and expanded uncertainty for complex permittivity measurement. Pan et al. (2026) provided multiple mechanical sensor descriptors, including sensitivity, accuracy, and repeatability. In contrast, the Jakob et al. (2021) SNR and dark-count reductions quantify photon-detection signal quality, not accuracy of a physical measurand; Kuo et al. (2026) quantified plastic classification and revealed a laboratory-to-field drop in the reported classification score.

Two further contrasts emerged. First, broad environmental operating ranges (Lujan et al., 2026) and strong correlation with a reference procedure (Grossi et al., 2020) are informative but do not independently establish measurement uncertainty or calibration traceability. Second, the presence of a ± notation (Rousseau et al. (2026), do Couto and da Silva (2021)) does not by itself make uncertainty estimates comparable: definitions, coverage factors, repetitions, and reference conditions may differ. Given that the source material contains only abstracts, the extent of documented calibration chains, statistical uncertainty budgets, and reproducibility tests remains unresolved for much of the corpus.

Reporting Completeness, Ambiguities, and Evidentiary Gaps

Three recurring reporting gaps were identifiable at the abstract level. The first concerns cost: explicit prices or standardized cost comparisons were rarely represented in the extraction fields, despite repeated low-cost framing. The second concerns metrological detail: several abstracts referred to successful deployment or improved signals without providing both a quantitative performance metric and a specified reference. The third concerns comparability: the corpus mixed absolute and relative errors, precision, signal-to-noise ratio, imaging contrast, classification accuracy, resolution, and uncertainty, none of which can be treated as interchangeable measures of accuracy.

Other ambiguity involved the unit of analysis. A low-cost component improvement may be part of an expensive measurement arrangement (Chen et al., 2026); a prototype containing inexpensive components may not qualify as a low-cost measuring instrument (do Couto and da Silva, 2021); and an emulated circuit response may not demonstrate experimental measurement of a real physical system (Guerrero-rodríguez et al., 2021). These cases were retained or flagged because the abstract-level design intentionally favors transparent uncertainty over premature exclusion. Their inclusion in the evidence map does not constitute verification of eligibility for a conventional full-text systematic review.

The resulting evidence map therefore supports a taxonomy of instrument architectures, measurement mechanisms, application contexts, and reported performance descriptors. It does not permit conclusions about pooled accuracy, comparative cost effectiveness, standard-compliant calibration, or prevalence of unreported methods within complete articles. The 22-record corpus should be interpreted as a structured mapping of available Scopus abstract evidence under the stated query and filters.

Discussion

The evidence map reveals that low-cost instrumentation for physical measurements is not a single technological class but a collection of strategies for converting physical interactions into usable experimental information. The substantial representation of optical, electrical, and mechanical approaches reflects this diversity rather than a hierarchy of technical superiority. Across the mapped records, an inexpensive or accessible architecture could refer to simplified components, localized fabrication, portable assembly, open acquisition interfaces, or adaptation of established physical principles. These distinctions are consequential because the price of a sensing component cannot establish the affordability of a complete measurement chain, including reference calibration, data processing, maintenance, and long-term use. Open scientific hardware literature similarly associates accessibility with transparency, modifiability, and reduced barriers to apparatus construction, rather than with a universally low purchase price (Pearce, 2012; Fisher & Gould, 2012; Baden et al., 2015).

Examples from the mapped studies clarify how cost-oriented design takes different forms. Placidi et al. (2023) developed an impedance-based system for soil-water evaluation, whereas Merla et al. (2017) considered a portable approach to complex-permittivity measurements. Yang et al. (2021) integrated dielectric sensing into polymer-curing monitoring, and Mazini et al. (2026) employed readily available materials to demonstrate capacitive measurement principles. These applications share an emphasis on accessible instrument configurations, but neither the target measurand nor the technical demand is equivalent. A portable dielectric meter, an embedded process sensor, and a hands-on capacitor device consequently require different standards of practical utility, calibration, and acceptable error. This observation complicates broad claims that low-cost systems are inherently interchangeable with commercial instruments.

The relationship between transduction physics and reported measurands provides a second, more fundamental interpretation. Electrical impedance can be the quantity measured directly or a proxy for changes in water content, polymer state, or mechanical geometry. The dielectric studies of Placidi et al. (2023), Yang et al. (2021), Merla et al. (2017), and Mazini et al. (2026) exemplify how comparable electrical responses may represent materially different physical properties. Such conversion requires a model relating sensor response to the quantity of interest; the quality of the resulting measurement depends on the validity of that model under the intended operating conditions. The metrological vocabulary distinguishes the measurand, indication, and calibration relationship, while measurement-model guidance makes explicit that model inadequacy and input-quantity uncertainty influence the reported result (JCGM, 2012, 2020).

Optical instruments demonstrate a similarly broad range of physical transformations. Runyan et al. (2025) applied stereo imaging to underwater geometry, Gugliandolo et al. (2024) used transmitted-light behavior for microplastic identification, Grossi et al. (2020) examined near-infrared responses related to solid-fat content, and Rousseau et al. (2026) developed luminescence-lifetime imaging for multiple sensed quantities. Jakob et al. (2021) addressed photon-detection signal processing, whereas Zhao et al. (2026) used a physics-informed computational approach to infer nanoscale thickness. Kuo et al. (2026) combined

low-cost near-infrared spectroscopy and edge-based classification. These studies cannot be reduced to a common optical-accuracy concept: spatial reconstruction, photon counting, spectral estimation, lifetime sensing, and categorical recognition all rely on different inference models and reference quantities.

This heterogeneity also highlights the distinction between measuring physical quantities and performing classification or prediction using physical signals. Spectroscopy generates a physical response, but classification accuracy describes how frequently a classification model assigns the intended label, not how closely a measured spectrum matches a traceable reference. Accordingly, the laboratory-to-field classification contrast reported by Kuo et al. (2026) informs model robustness under changed conditions, whereas the response comparisons in Grossi et al. (2020) speak to a different form of analytical association. The imaging-based dimensional work of Zhao et al. (2026) further raises questions about the relationship between computational inference and reference measurements. Treating all three approaches as interchangeable examples of sensor accuracy would obscure precisely the methodological differences that give the evidence map interpretive value.

Mechanical and hybrid systems extend this point beyond electronics and photonics. Pan et al. (2026) used a piezoresistive tactile architecture, Laferrière and Payeur (2017) addressed proximity and contact responses in robot interaction, and Vaquero-Martínez et al. (2026) presented a homemade gravimetric lysimeter. Miranda-Martínez et al. (2022) connected resonant sensing and viscosity-related information, whereas Scariot et al. (2025) examined weight-based observation of activity. Each system illustrates the importance of differentiating a primary physical signal from the application-specific attribute inferred from it. For example, a force response, a variation in mass, and a modeled rheological index may all be obtained with accessible equipment, but they are neither the same measurand nor subject to an identical validation protocol.

One of the clearest cross-study findings is the non-equivalence of commonly reported performance indicators. Placidi et al. (2023) expressed electrical error against a reference, Merla et al. (2017) reported root-mean-square error and uncertainty, and Pan et al. (2026) presented sensor sensitivity, accuracy, and repeatability characteristics. Conversely, Jakob et al. (2021) emphasized improvements in signal-to-noise performance, and Chen et al. (2026) reported enhanced ultrasound echo and gradient responses. Higher signal strength or improved image contrast can be technically useful without establishing the accuracy of a subsequent physical measurement. The Guide to the Expression of Uncertainty in Measurement requires uncertainties to be associated with specified measurands and evaluation models, rather than inferred from qualitatively favorable instrument behavior (JCGM, 2008).

The broader sensor-evaluation literature supports this interpretation. Kang et al. (2022) showed that performance assessments of affordable environmental sensors depend on the statistics reported, reference instruments, and operating environments. Li et al. (2020) evaluated multiple low-cost particulate-matter monitors, illustrating the value of comparison across devices rather than relying on nominal sensor specifications. Hayward et al. (2024) further emphasized biases, corrections, and comparability limitations in field sensor applications. Although

these studies concern air-quality monitoring rather than every physics instrument represented in the mapping, their methodological implication is transferable: evaluation must specify what is being measured, what acts as the reference, which error statistic is reported, and whether the conditions correspond to the intended application. Cross-domain transfer should apply to assessment principles, not numerical error thresholds.

A related issue is that repeatability, trueness, resolution, and uncertainty represent different properties of a measurement process. Good repeatability may coexist with systematic bias, and high numerical resolution does not by itself demonstrate agreement with a reference. In the mapped corpus, Rousseau et al. (2026) reported temperature precision alongside spatial and temporal resolution, while do Couto and da Silva (2021) illustrated uncertainty calculation for electrical quantities. These examples are informative but cannot be combined without knowing the underlying models, coverage conventions, and sources of uncertainty. Metrological terminology and uncertainty guidance consequently offer a more rigorous interpretive framework than generic assertions that a device is reliable or accurate (JCGM, 2008, 2012).

Calibration should therefore be understood as part of the measurement system, not merely as a correction applied after data collection. Liang (2021) reviewed techniques and challenges of calibrating low-cost ambient sensors, while Liang and Daniels (2022) demonstrated how algorithm selection, calibration duration, and explanatory variables can alter calibrated sensor performance. Concas et al. (2021) critically considered field monitoring and calibration strategies, and Narayana et al. (2022) examined sustainable low-cost monitoring arrangements. These sources collectively suggest that an instrument architecture should be evaluated alongside its reference procedure, expected interferences, calibration domain, and maintenance burden. In particular, a calibration that performs well under a restricted environment cannot automatically be assumed to transfer to other measurement conditions.

Application context helps explain why no uniform performance hierarchy emerges from the mapped abstracts. Lujan et al. (2026) addressed a high-mountain environmental logging application, Izett and Tortell (2021) investigated a dissolved-gas tracing approach, and Chilcott and Kjærgaard (2021) described monitoring of an ultracold-atom apparatus. Their physical settings differ markedly in environmental variability, sampling frequency, signal conditioning, and practical consequences of measurement error. The deployment-focused literature similarly shows that ambient conditions and sensor-to-sensor variation can affect comparability (Li et al., 2020; Hayward et al., 2024). A defensible definition of adequate performance must therefore be conditional on the measurand, measurement range, purpose, and operating environment.

These contrasts also underscore that affordability and field robustness are partly independent design objectives. An instrument optimized for low component count may remain sensitive to drift or interference; conversely, additional reference measurements and protective components may increase cost while improving confidence in results. The comprehensive evaluation perspective offered by Kang et al. (2022) and the calibration analysis of Liang and Daniels (2022) suggest that long-term utility depends on more than prototype functionality. For systems such as

the open-source logger of Lujan et al. (2026) or the underwater imaging platform of Runyan et al. (2025), this implies a need to distinguish proof-of-operation from evidence of reproducibility and performance across operating contexts. Such implications extend the abstract findings but are not presented as unreported experimental outcomes of those individual studies.

The evidence map further exposes an important ambiguity in what constitutes the instrument under review. A low-cost modification to an acoustic measurement chain does not establish that the entire chain is inexpensive, as the application of a transmission-line coating in Chen et al. (2026) illustrates. Similarly, uncertainty analysis of a low-cost photovoltaic prototype is relevant to measurement quality but does not necessarily demonstrate that the measuring apparatus itself is low-cost (do Couto & da Silva, 2021). Circuit emulation using an embedded platform may reproduce expected responses without independently validating measurements of a real physical system (Guerrero-Rodríguez et al., 2021). Such boundary cases are scientifically informative, but they should not be treated as equivalent evidence of validated, affordable physical instrumentation.

This ambiguity is especially relevant to the educational and biomedical margins of the corpus. The hands-on capacitor systems considered by Mazini et al. (2026) and the homemade lysimeter discussed by Vaquero-Martínez et al. (2026) highlight accessibility for experimentation, whereas Pan et al. (2026), Miranda-Martínez et al. (2022), and Scariot et al. (2025) applied sensing techniques to surgical, fluid-characterization, or behavioral questions. The common physical basis does not erase differences in evidence required for the intended use. Where the task is conceptual demonstration, repeatable physical response may be central; where the task involves quantitative decisions, calibration and uncertainty may become considerably more consequential. It follows that a useful literature synthesis needs to preserve context rather than equating all reported successes.

A third interpretive contribution concerns reporting completeness. Across the abstracts, cost figures, detailed calibration chains, and explicit uncertainty budgets were not consistently visible. This is properly understood as limited information in the abstract-level corpus, not proof that complete papers omitted those analyses. The distinction is essential because indexed abstracts are written to summarize study aims and selected results, and the information they contain depends on reporting priorities. The present mapping can therefore identify how authors frame low-cost design and which performance metrics they foreground, but it cannot establish the prevalence of missing methods across full reports. Nor can it rank the underlying studies by metrological quality or derive pooled cost-effectiveness estimates from their heterogeneous descriptions.

The mapped evidence nevertheless points to a constructive way of comparing future studies: a minimum reporting structure should identify the complete measurement chain, the specific measurand, the sensor or transduction principle, the measurement model, the reference procedure, the relevant operating range, and the uncertainty associated with the reported result. Cost reporting should distinguish component price from total system cost and expenses associated with calibration and maintenance. Such elements align with metrological requirements for clear definitions and credible inference (JCGM, 2012, 2020), while practical open-hardware scholarship emphasizes documentation and reproducible

construction as enabling conditions for accessible science (Pearce, 2012; Baden et al., 2015). These elements constitute a proposal derived from the synthesis, not an instrument-quality checklist formally validated by this review.

Several methodological boundaries constrain the weight that can be assigned to these interpretations. The review was based on Scopus-indexed titles, metadata, and abstracts under a specific search expression and article-only subject filters; it did not include full-text assessment or independent duplicate screening. Consequently, ten uncertain records were retained for mapping rather than confirmed as eligible primary studies. The mapped sample also included studies primarily concerned with modifications, emulation, or classification rather than traceable physical measurement. These conditions make the synthesis appropriate for identifying categories of instruments and abstract-reported evidence, but not for establishing comprehensive methodological quality, comparative accuracy, or generalizable estimates of the effectiveness of low-cost instruments.

Taken as a whole, the literature suggests that the central scientific question is not whether inexpensive devices can generate usable signals, but under what conditions those signals become defensible measurements. Accessible designs and open architectures broaden the range of experimental applications, yet their credibility depends on properly specified measurands, reliable transduction models, context-sensitive calibration, and transparent uncertainty evaluation. Future work would benefit from direct comparisons between affordable and reference-grade measurement chains, consistent cost accounting, and repeated assessments across realistic operating environments. These priorities are grounded in the contrasts between the mapped studies and the external metrology and calibration literature, rather than in an assumption that low-cost designs necessarily underperform conventional instruments (Fisher & Gould, 2012; Concas et al., 2021; Narayana et al., 2022).

CONCLUSION

This study provides a systematic mapping of the literature concerning low-cost instrumentation for physical measurements, revealing substantial diversity in technological architectures, sensing principles, and measurement applications. Of the 133 records initially identified in Scopus, 22 publications were retained for thematic synthesis following database filtering and literature screening. The findings identified five major instrumentation families: optical and photonic, electrical and dielectric, mechanical, integrated and environmental, and acoustic and ultrasonic systems. Optical and photonic instrumentation represented the largest proportion of the analyzed publications, followed by electrical and dielectric systems. The thematic synthesis further identified five interconnected patterns concerning accessible instrument design, physical transduction, performance validation, application-driven deployment, and the completeness of reported cost and metrological information. These findings demonstrate that low-cost instrumentation encompasses diverse technological approaches rather than a uniform category of measurement devices.

The synthesis indicates that the scientific value of low-cost instrumentation depends not only on the accessibility and simplicity of its technological components but also on the relationship between sensing principles, measured physical quantities, and the reliability of the resulting measurements. Across the reviewed

studies, performance evaluation involved heterogeneous indicators, including measurement error, sensitivity, repeatability, precision, resolution, signal-to-noise ratio, and classification accuracy. These indicators represent distinct measurement characteristics and cannot be interpreted interchangeably or combined into a common measure of instrument performance. The findings also reveal inconsistencies in the availability of information concerning total instrument costs, reference calibration, metrological traceability, and measurement uncertainty. Consequently, claims of affordability and successful instrument operation do not independently establish measurement accuracy, reliability, or equivalence to reference-grade instrumentation.

The principal contribution of this study lies in establishing an integrated thematic understanding of how accessible instrument architectures, physical measurement principles, and performance evaluation practices intersect across different application contexts. The evidence suggests that the development of scientifically credible low-cost instrumentation requires consideration of the complete measurement system, including its physical transduction mechanism, measurement model, calibration requirements, operational conditions, and uncertainty characteristics. Because the synthesis was based on bibliographic metadata and published abstracts rather than full-text assessments, the findings do not establish the comparative accuracy, cost-effectiveness, or metrological quality of individual instruments. Within these methodological boundaries, the study provides a structured foundation for understanding the research landscape of low-cost physical instrumentation and identifying technical and reporting priorities for its further development.

RECOMMENDATION

The integrated mapping of instrumentation architectures, physical measurement principles, and performance evaluation approaches provides a conceptual basis for developing and assessing low-cost measurement systems. Future research should extend this framework through experimental validation across different instrumentation families and application contexts. Particular emphasis should be placed on establishing appropriate calibration procedures, measurement uncertainty, reproducibility, and comparisons with reference-grade instruments. Researchers are encouraged to adopt consistent reporting practices that distinguish technological affordability from measurement reliability, thereby supporting the development of accessible instrumentation capable of producing scientifically credible physical measurements.

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