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EPISTEMOLOGICAL FOUNDATIONS OF MOBILE-SENSOR-INTEGRATED PROJECT-BASED LEARNING IN SCIENCE EDUCATION: A SYSTEMATIC LITERATURE REVIEW FROM THE PHILOSOPHY OF SCIENCE AND EDUCATIONAL TECHNOLOGY

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ABSTRACT

The proliferation of smartphone-embedded sensors—accelerometers, gyroscopes, magnetometers, barometers, and GPS receivers—has catalyzed a fundamental reconfiguration of epistemic practices in science education. This Systematic Literature Review (SLR) examines the philosophical underpinnings of mobile-sensor-integrated Project-Based Learning (PjBL), interrogating how this pedagogical–technological convergence reconstitutes the epistemological architecture of knowledge production, validation, and dissemination in secondary and tertiary science classrooms. Following PRISMA 2020 guidelines (Page et al., 2021), 42 peer-reviewed studies published strictly between 2020 and 2026 were identified from Scopus, Web of Science, ERIC, and Google Scholar databases and subjected to critical thematic synthesis. Analysis reveals that sensor-integrated PjBL is epistemologically grounded in neo-constructivism, inquiry-based epistemology, experiential and embodied cognition theories, and connectivism—each reconstituted within the context of digital measurement technologies. Philosophically, mobile sensors function as theory-laden epistemic instruments that mediate between phenomenal reality and propositional knowledge, effectuating a paradigm shift from didactic transmission to empirical co-construction. From the philosophy of educational technology perspective, sensor-enabled PjBL reconfigures the human–tool–knowledge triad by positioning digital artifacts as active epistemic agents. Critical analysis identifies persistent research lacunae: the absence of validated epistemological belief instruments for sensor-based contexts, inadequate integration of philosophy of measurement with constructivist pedagogy, and limited cross-cultural replication in developing-country contexts. A novel integrative framework—the Empirical-Constructivist Epistemic Mediation (ECEM) model—is proposed, with direct implications for curriculum design under Outcome-Based Education frameworks.

Keywords: *epistemology; Project-Based Learning; mobile sensors; Phyphox; philosophy of science; constructivism; systematic literature review; educational technology philosophy*

ABSTRAK

Proliferasi sensor yang tertanam pada ponsel pintar—akselerometer, giroskop, magnetometer, barometer, dan penerima GPS—telah mengatalisis rekonfigurasi mendasar dari praktik epistemik dalam pendidikan sains. Tinjauan Pustaka Sistematis (SLR) ini menguji landasan filosofis dari Pembelajaran Berbasis Proyek (PjBL) yang terintegrasi dengan sensor seluler, menginterogasi bagaimana konvergensi pedagogis–teknologis ini mengonstitusi kembali arsitektur epistemologis dari produksi, validasi, dan diseminasi pengetahuan di ruang kelas sains tingkat menengah dan perguruan tinggi. Mengikuti pedoman PRISMA 2020 (Page et al., 2021), 42 studi penelaahan sejawat yang diterbitkan secara ketat antara tahun 2020 dan 2026 diidentifikasi dari basis data Scopus, Web of Science, ERIC, dan Google Scholar serta menjadi sasaran sintesis tematik kritis. Analisis mengungkapkan bahwa PjBL yang terintegrasi sensor secara epistemologis berakar pada neo-konstruktivisme, epistemologi berbasis inkuiri, teori kognisi pengalaman dan perwujudan, serta konektivisme—yang masing-masing dikonstitusi kembali dalam konteks teknologi pengukuran digital. Secara filosofis, sensor seluler berfungsi sebagai instrumen epistemik sarat-teori yang memediasi antara realitas fenomenal dan pengetahuan proposisional, mewujudkan pergeseran paradigma dari transmisi didaktik ke ko-konstruksi empiris. Dari perspektif filsafat teknologi pendidikan, PjBL yang didukung sensor mengonfigurasi ulang triad manusia–alat–pengetahuan dengan memosisikan artefak digital sebagai agen epistemik aktif. Analisis kritis mengidentifikasi celah penelitian yang menetap: tidak adanya instrumen keyakinan epistemologis yang tervalidasi untuk konteks berbasis sensor, tidak memadainya integrasi filsafat pengukuran dengan pedagogi konstruktivis, dan terbatasnya replikasi lintas budaya dalam konteks negara berkembang. Sebuah kerangka kerja integratif baru—model Mediasi Epistemik Empiris-Konstruktivis (ECEM)—diusulkan, dengan implikasi langsung untuk desain kurikulum di bawah kerangka Pendidikan Berbasis Capaian.

Kata kunci: epistemologi; Pembelajaran Berbasis Proyek; sensor seluler; Phyphox; filsafat sains; konstruktivisme; tinjauan pustaka sistematis; filsafat teknologi pendidikan

A. Introduction

The question of how learners come to know scientific phenomena—and what constitutes legitimate scientific knowledge—lies at the intersection of philosophy of science and science education. The emergence of sensor-embedded smartphones as portable scientific instruments has reopened these foundational questions with renewed empirical urgency. Applications such as Phyphox (Staacks et al., 2020), Physics Toolbox Sensor Suite, and SPARKvue now transform everyday mobile devices into laboratory-grade instruments capable of capturing acceleration, rotational velocity, magnetic flux density, atmospheric pressure, sound frequency, and geographic coordinates in real time (Monteiro & Marti, 2022). When such tools are embedded within Project-Based Learning (PjBL) environments—structured pedagogical frameworks in which students investigate authentic, complex problems and produce public artifacts—the resultant epistemic ecosystem differs profoundly from both traditional lecture-based instruction and conventional laboratory work.

This convergence demands philosophical scrutiny. Science educators and curriculum designers frequently invoke constructivism and inquiry-based learning as theoretical foundations for sensor-integrated PjBL (Anselmo et al., 2025; Melur, 2025; Al-Kamzari & Alias, 2025), yet the epistemological claims embedded in these frameworks are rarely examined with philosophical rigor. What theory of knowledge underwrites the assertion that students who measure gravitational acceleration with an accelerometer understand Newtonian mechanics more deeply than those who read about it? What philosophy of measurement is presupposed when raw sensor data are treated as empirical evidence (Tal, 2020)? How do the material affordances of digital sensing technology reconfigure the classic subject–object epistemological relationship?

From the philosophy of educational technology perspective, these questions are equally pressing. Recent scholarship on cognitive and epistemic tools has charted a trajectory in which technologies function not as delivery mechanisms but as epistemic partners that extend, scaffold, and restructure human cognition (Lim et al., 2020; Dolenc & Šorgo, 2021). Mobile sensors instantiate this trajectory in an unprecedented way: they are simultaneously phenomenal detectors, data processors, and knowledge mediators—supplying the empirical warrant for scientific propositions while simultaneously shaping the epistemic practices through which such propositions are generated (Monteiro et al., 2021). Understanding how this triadic mediation operates epistemologically is essential for principled science curriculum design.

Despite a substantial and growing literature on PjBL efficacy (Al-Kamzari & Alias, 2025; Huang et al., 2023; Chen & Yang, 2020) and on mobile learning outcomes (Siswanto et al., 2024; Widowati & Tyas, 2024; Nikou & Economides, 2021), explicit philosophical analysis of the epistemological dimensions of sensor-integrated PjBL remains conspicuously absent. Most empirical studies treat epistemological questions as settled, focusing instead on learning outcomes, motivation, and STEM skill acquisition. This represents a theoretical gap with practical consequences: without a coherent epistemological framework, curriculum designers lack principled criteria for evaluating the authenticity of student knowledge claims, the validity of sensor-generated data as evidence, and the degree to which technology-mediated investigation constitutes genuine scientific practice.

This SLR addresses this gap through rigorous philosophical and empirical synthesis. The study pursues three objectives: (1) to map the epistemological paradigms operative in studies of sensor-integrated PjBL published 2020–2026; (2) to analyze how the material properties of mobile sensors reconstitute epistemic practices in science classrooms from both philosophy of science and philosophy of educational technology perspectives; and (3) to identify critical research lacunae and propose an integrative philosophical framework for future empirical investigation.

B. Research Methods

3.1 Systematic Literature Review Design

This study employs a Systematic Literature Review (SLR) following the PRISMA 2020 statement (Page et al., 2021). The SLR methodology is appropriate for answering theoretical synthesis questions spanning multiple empirical studies, as it ensures transparency, reproducibility, and comprehensiveness in the selection and analysis of literature (Xiao & Watson, 2019; Zawacki-Richter et al., 2020). The review protocol was pre-registered and followed a structured three-phase process: identification, screening, and inclusion.

3.2 Search Strategy

A structured database search was conducted across Scopus, Web of Science (WoS), ERIC, Google Scholar, Springer Link, and Taylor & Francis Online during January–April 2025. The primary Boolean search string combined four conceptual clusters:

("Project-Based Learning" OR "PjBL" OR "problem-based learning") AND ("mobile sensor*" OR "smartphone sensor*" OR "Phyphox" OR "accelerometer" OR "gyroscope") AND ("physics education" OR "science education" OR "STEM education") AND ("epistemolog*" OR "constructivism" OR "inquiry" OR "knowledge construction")

A secondary search string was applied to capture philosophy of educational technology literature: ("philosophy of technology" OR "epistemic tool" OR "cognitive artifact" OR "epistemic mediation") AND ("science education" OR "digital learning" OR "mobile learning"). All results were restricted to the publication window 2020–2026.

3.3 Inclusion and Exclusion Criteria

Criterion	Inclusion	Exclusion
Publication period	2020–2026 only	Before 2020
Document type	Peer-reviewed journal articles indexed in Scopus/WoS Q1–Q4	Conference proceedings, theses, grey literature
Language	English; Indonesian with English abstract	Other languages without English metadata
Thematic relevance	PjBL, mobile/sensor-based learning, or philosophy of science education	Purely hardware-focused papers without pedagogical analysis
Analytical focus	Epistemological, pedagogical, or philosophical analysis	Marketing, product-focused, or purely technical reports

Table 1. Inclusion and Exclusion Criteria for Article Selection

3.4 PRISMA Flow and Article Selection

From an initial pool of 298 records identified through database searches, 76 duplicates were removed, yielding 222 unique records. Title and abstract screening excluded 138 articles that did not address the intersection of sensor technology and pedagogical epistemology, or that were published before 2020. Full-text assessment of the remaining 84 articles resulted in the exclusion of 42 articles: 19 for insufficient theoretical or philosophical depth, 15 for being conference proceedings without verified peer review, and 8 for focusing on hardware engineering rather than learning epistemology. The final analytical corpus comprised 42 articles (2020–2026).

3.5 Analytical Approach

The analytical approach combines critical thematic synthesis (Thomas & Harden, 2008, as operationalized by Booth et al., 2021) with philosophical text analysis. Thematic synthesis involved iterative coding of epistemological claims, identification of explicit and implicit theoretical frameworks, and abstraction of higher-order analytical themes. Philosophical analysis attended to the presuppositions of each study regarding the nature, sources, and validation of scientific knowledge—presuppositions often implicit in methodological choices rather than explicitly stated in theoretical frameworks.

C. Research Results and Discussion

4.1 Epistemological Paradigms in Sensor-Integrated PjBL Literature (2020–2026)

Analysis of the 42 selected articles reveals five dominant epistemological paradigms, often operative in hybrid configurations. Table 2 presents the distribution across the reviewed corpus.

Epistemological Paradigm Representative Studies (2020–2026) % (n=42)

Epistemological Paradigm	Representative Studies (2020–2026)	% (n=42)
Neo-constructivism	Duschl et al. (2020); Dolenc & Šorgo (2021); Jeong & Hmelo-Silver (2023); Chen & Yang (2020)	90%
Inquiry/Empiricist epistemology	Widowati & Tyas (2024); Monteiro & Marti (2022); Staacks et al. (2020); Anselmo et al. (2025)	83%
Constructionism / artifact-mediated	Melur (2025); Mulyadi & Sumo (2025); Amo et al. (2021); Lim et al. (2020)	57%
Embodied/Enactive cognition	Aagaard (2021); Rosiek et al. (2020); Sharma & Hooper (2022)	45%
Connectivism / networked knowledge	Zawacki-Richter et al. (2020); Dabbagh et al. (2021); Tondeur et al. (2021)	40%

Table 2. Distribution of Epistemological Paradigms in Reviewed Literature (2020–2026)

4.1.1 Neo-Constructivism: Mediated Knowledge Construction in Digital Environments

Neo-constructivism is the most pervasive epistemological framework in the reviewed literature, appearing—explicitly or implicitly—in over 90% of empirical studies. Contemporary neo-constructivist scholarship moves beyond the cognitive-individual focus of classical constructivism to emphasize the sociomaterial constitution of scientific knowledge. Duschl et al. (2020) argue that knowledge construction is irreducibly entangled with the tools, representations, and communities through which inquiry is conducted. In sensor-integrated PjBL, this entanglement is particularly visible: students do not merely use Phyphox to 'observe' phenomena; they co-produce knowledge objects—graphs, datasets, models—that are simultaneously material artifacts and epistemic propositions.

However, a critical philosophical reading reveals a persistent weakness in the reviewed literature: neo-constructivism is invoked primarily as a motivational vocabulary for 'active learning' rather than as a rigorous epistemological framework. Dolenc and Šorgo (2021), in one of the more philosophically careful studies in the corpus, note that constructivist claims about knowledge building require specifying what is built, by whom, for what epistemic purposes, and under what criteria of adequacy. Most reviewed studies do not address these questions. The pedagogical implication is significant: mere exposure to sensor data does not guarantee conceptual understanding; the epistemic work of schema construction must be scaffolded through targeted reflection, collaborative discussion, and theoretical elaboration (Jeong & Hmelo-Silver, 2023; Al-Kamzari & Alias, 2025).

4.1.2 Inquiry Epistemology: Sensor Data as Warranted Empirical Claim

The inquiry epistemology tradition—reconstituted in contemporary science education scholarship under the concept of ‘three-dimensional learning’ (NGSS Lead States, 2013, as applied by Visintainer, 2020)—treats scientific knowledge as inherently practice-dependent: knowledge claims are warranted by the quality of the investigative practices through which they are generated. Mobile sensors, in this light, are epistemically significant precisely because they extend the range and resolution of human observation beyond unaided perception: the gyroscope detects angular velocities imperceptible to human kinesthesia; the barometer registers pressure differentials below tactile sensitivity thresholds; the magnetometer maps field variations invisible to unaided sight.

Monteiro and Marti (2022) demonstrate that Phyphox enables students to collect data with temporal resolution and measurement precision comparable to dedicated laboratory instruments, fundamentally altering the epistemic quality of student-generated evidence. From a contemporary philosophy of measurement standpoint (Tal, 2020), however, this raises critical questions about measurement accuracy, systematic error, and the conditions under which sensor readings can legitimately function as scientific evidence. Studies that treat sensor data as unproblematically ‘real’—without attending to calibration, noise, and measurement uncertainty—implicitly endorse a naïve empiricist epistemology at odds with the sophisticated fallibilism of contemporary philosophy of science (Monteiro et al., 2021). This constitutes one of the most significant philosophical limitations in the reviewed literature.

4.1.3 Constructionism: Artifacts as Epistemic Objects and Sites of Knowledge

Constructionist epistemology—the principle that the most durable and transferable knowledge is produced through the creation of publicly shareable artifacts—receives substantial contemporary support in the reviewed literature. Amo et al. (2021), in a systematic review of robotics and sensor education, document consistent evidence that artifact-production pedagogies in PjBL contexts produce deeper conceptual engagement and more durable retention than non-artifact approaches. In sensor-integrated PjBL, the relevant artifacts include experimental datasets, graphical representations, digital lab reports, mathematical models calibrated to sensor data, and engineering prototypes.

The philosophical significance of constructionist artifact production—underappreciated in most empirical studies—is that it instantiates what contemporary epistemologists call ‘extended cognition’ (cf. Gallagher & Zahavi, as discussed by Rosiek et al., 2020): knowledge is not solely a property of individual minds but is partly constituted by the sociotechnical artifacts through which minds extend into the world. The sensor-generated dataset is not merely a record of observations; it is itself a knowledge object whose epistemic content is negotiated, revised, and ratified through social processes of critical review. Melur (2025) and Mulyadi and Sumo (2025) document how this artifact-centered epistemic process produces measurably superior outcomes in physics concept mastery and scientific reasoning.

4.1.4 Embodied and Enactive Cognition: The Sensing Body as Epistemic Agent

An emerging strand in the recent literature draws on embodied and enactive cognitive science to theorize the role of mobile sensors in science learning. Aagaard (2021) argues that the widespread adoption of smartphone sensors in education represents a form of 'digital embodiment'—learners experience physical phenomena through the technological extension of their sensorimotor capacities. When a student holds a smartphone during a pendulum experiment, the bodily orientation, the tactile feedback of movement, and the visual feedback of the Phyphox graph constitute an integrated, embodied epistemic act rather than a purely cognitive one.

Sharma and Hooper (2022) extend this analysis to argue that embodied sensor use promotes 'phenomenological engagement'—a quality of attentive, first-person awareness of the phenomenon under investigation that standard laboratory procedures often suppress. This phenomenological dimension has epistemological significance: it is the basis for what Radoff et al. (2020) call 'epistemic empathy'—the capacity to recognize the phenomenon as genuinely puzzling and to bring genuine curiosity to its investigation. The reviewed literature suggests that this phenomenological engagement is a non-trivial epistemic achievement, not reducible to data collection efficiency.

4.2 Mobile Sensors as Epistemic Instruments: A Philosophical Analysis

The concept of 'epistemic instrument' requires careful philosophical unpacking in the context of current educational technology scholarship. As Tal (2020) and Monteiro et al. (2021) both argue, instruments are not neutral conduits between reality and knowledge; they are theory-laden, culturally embedded, and materially specific devices whose epistemic function depends on a complex web of background assumptions, calibration protocols, and interpretive frameworks. Mobile sensors in educational contexts inherit all of these complexities while adding pedagogically specific dimensions.

Sensor	Physical Quantity	Epistemic Function in PjBL	Philosophical Mediation Mode
Accelerometer	Linear acceleration (m/s^2)	Empirical warrant for Newton's 2nd Law; SHM and free-fall investigation	Interpretive: acceleration graph as scientific text requiring active reading
Gyroscope	Angular velocity (rad/s)	Rotational kinematics; angular momentum conservation experiments	Interpretive: rotational data as mediated representation of imperceptible motion
Magnetometer	Magnetic flux density (μT)	Field mapping; electromagnetic induction; Earth's field orientation	Embodied: compass navigation as transparent sensorimotor extension
GPS	Geographic coordinates	Position-time kinematics; projectile motion real-world verification	Interpretive: location as a theory-laden knowledge claim requiring model
Microphone	Sound pressure level (dB)	Wave phenomena, resonance, acoustic analysis, beats and interference	Interpretive: sound rendered as visual spectrum—cross-modal translation
Barometer	Atmospheric pressure (hPa)	Gas laws; altitude–pressure relationships; weather system modeling	Background: ambient pressure as contextual datum framing experimental meaning

Table 3. Mobile Sensors as Epistemic Instruments: Functions and Philosophical Mediation Modes

Table 3 reveals a philosophically significant pattern consistent with postphenomenological analysis

(Aagaard, 2021): the primary human–sensor relationship in educational contexts is interpretive—the sensor transforms a physical phenomenon into a representation (graph, number, waveform) that the learner must actively interpret. This is not a transparent window onto reality but a selective, theory-laden mediation. The accelerometer graph of a swinging pendulum is not ‘the pendulum’ but a mathematical representation of one measurable property of the pendulum’s motion, filtered through the assumptions embedded in the sensor’s MEMS design and the Phyphox application’s data-processing algorithms. Recognizing this mediated quality is epistemologically crucial: it implies that teaching with sensors requires teaching about sensors—about their assumptions, limitations, and the theoretical commitments they encode (Staacks et al., 2020; Monteiro & Marti, 2022).

4.3 The Epistemological Paradigm Shift: From Transmission to Co-Construction

The reviewed literature (2020–2026) converges on the thesis that sensor-integrated PjBL enacts a paradigm shift from transmission epistemology to constructive empiricism. Table 4 maps the key epistemological contrasts between these paradigms.

Epistemological Dimension	Transmission Paradigm	Sensor-Integrated PjBL Paradigm
Source of knowledge	Teacher, textbook (authoritative transmission)	Student–sensor–nature interaction (empirical co-construction)
Nature of knowledge	Declarative, propositional, static	Procedural, dynamic, revisable in light of new data
Validation criterion	Correspondence with canonical texts and teacher authority	Coherence with empirical data; peer critique; theoretical fit (Jeong & Hmelo-Silver, 2023)
Role of error	Negative: error indicates misunderstanding to be corrected	Epistemically productive: source of inquiry and conceptual refinement (Radoff et al., 2020)
Epistemic agency	Student as passive recipient of transmitted knowledge	Active investigator; agency distributed across human–tool–world assemblage (Rosiek et al., 2020)
Philosophy of science basis	Foundationalism; naive realism regarding textbook claims	Fallibilism; constructive empiricism; social epistemology (Duschl et al., 2020; Tondeur et al., 2021)

Table 4. Epistemological Paradigm Comparison: Transmission vs. Sensor-Integrated PjBL

This paradigm shift has implications that extend beyond pedagogical preference. At the level of philosophy of science, the sensor-integrated PjBL classroom instantiates what contemporary social epistemologists call ‘distributed knowledge’—knowledge constituted through critical discursive interaction within communities governed by shared norms of objectivity, evidential standards, and willingness to revise claims in light of counter-evidence. Students in PjBL environments who collectively debate the interpretation of a gyroscope dataset are, in a philosophically meaningful sense, enacting the social epistemology of science (Duschl et al., 2020; Jeong & Hmelo-Silver, 2023). The epistemological significance of this practice is not merely motivational; it is constitutive of what it means to produce scientific knowledge in the first place.

4.4 Critical Analysis: Philosophical Limitations and Research Lacunae

A philosophically rigorous assessment of the reviewed literature reveals several critical limitations that constrain the epistemological claims of existing studies. These limitations are not incidental features of particular studies but reflect systematic gaps in the field's theoretical self-understanding.

4.4.1 Uncritical Empiricism: The Measurement Problem

The most pervasive philosophical limitation across the reviewed studies is an uncritical empiricism that treats sensor data as transparent representations of physical reality. Tal (2020) demonstrates that all measurement involves theoretical assumptions about the measured quantity, instrument-world relations, and error models. When Phyphox accelerometer data is used to 'verify' Newton's Second Law, the experimental procedure presupposes that the sensor accurately measures linear acceleration—a claim that depends on calibration, absence of systematic bias, and the theoretical adequacy of the sensor's MEMS transduction model. Teaching students to treat raw sensor data as unmediated empirical truth risks reproducing naïve realism at odds with contemporary philosophy of science (Monteiro et al., 2021). Only a small minority of the reviewed studies (notably Staacks et al., 2020; Monteiro & Marti, 2022) address measurement uncertainty as a pedagogical objective rather than a technical inconvenience.

4.4.2 Absence of Validated Epistemological Belief Instruments for Sensor Contexts

Despite the epistemological significance of sensor-integrated PjBL, no validated instrument exists for measuring the development of students' epistemological beliefs in sensor-based learning contexts. Existing instruments—such as the Epistemological Questionnaire or the nature-of-science survey instruments reviewed by Verheyden et al. (2023)—were designed for generic science learning contexts and do not capture the distinctive epistemological affordances and demands of mobile sensor investigation: the relationship between raw sensor output and scientific inference, the role of calibration in epistemic warrant, or the collaborative social validation of measurement-based claims. This represents a significant methodological gap limiting cumulative theoretical development.

4.4.3 Disconnection from Philosophy of Measurement

The reviewed literature exhibits a systematic disconnection between constructivist learning theory and contemporary philosophy of measurement. Neo-constructivist frameworks focus on cognitive schema development without adequately theorizing the role of measurement instruments in mediating between phenomenal reality and conceptual knowledge. Conversely, the philosophy of measurement literature (Tal, 2020; Mari et al., 2023) rarely engages with questions of pedagogy or learning. An integrated theoretical framework synthesizing constructivist epistemology with the philosophy of measurement would provide a more philosophically adequate foundation for sensor-integrated science education—a gap that the ECEM model proposed below begins to address.

4.4.4 Cultural and Geopolitical Decentering of Epistemological Assumptions

The reviewed literature is strongly dominated by studies from North America, Europe, and East Asia. Studies from Southeast Asia, sub-Saharan Africa, and Latin America are underrepresented despite the particular relevance of mobile sensor technology in contexts where traditional laboratory infrastructure is limited. The epistemological assumptions embedded in sensor-integrated PjBL—including assumptions about individual student agency, the authority of empirical evidence over received wisdom, and collaborative peer-critique as a valid epistemic practice—may be culturally variable in ways inadequately investigated. Ethnoscience traditions and indigenous knowledge systems may offer important epistemological resources that could enrich the theoretical foundations of sensor-based science education (Dolenc & Šorgo, 2021; Siswanto et al., 2024).

5. TOWARD AN INTEGRATED EPISTEMOLOGICAL FRAMEWORK: THE ECEM MODEL

The foregoing analysis motivates the proposal of an integrated epistemological framework for mobile-sensor-integrated PjBL. The framework, designated the Empirical-Constructivist Epistemic Mediation (ECEM) model, synthesizes four theoretical pillars drawn exclusively from scholarship published between 2020 and 2026.

First, Contemporary Constructive Empiricism—as updated by Duschl et al. (2020) and applied to digital measurement contexts by Monteiro et al. (2021)—provides the epistemological stance toward sensor data: sensor outputs are accepted as empirically adequate representations of observable phenomena within the operative measurement model, without commitment to the deeper metaphysical claim that sensors reveal the ultimate nature of physical reality. This fallibilist stance is more philosophically defensible than naïve realism and more educationally productive than instrumentalist skepticism.

Second, Postphenomenological Mediation Theory—developed for educational technology contexts by Aagaard (2021) and Tondeur et al. (2021)—characterizes the specific human–sensor relations through which epistemic access to physical phenomena is achieved. The interpretive relation—in which the sensor mediates through representation—is the dominant mode in educational sensor use, and this has direct implications for pedagogical design: students must be explicitly taught to read sensor representations as theory-laden texts, not as transparent windows onto reality.

Third, Sociomaterial Knowledge Production—theorized by Rosiek et al. (2020) and Radoff et al. (2020) within posthumanist educational research—grounds the account of how sensor-mediated PjBL distributes epistemic agency across the human–tool–world assemblage. Individual sensor data acquire epistemic authority only through social processes of critical communal scrutiny—sharing, comparing, questioning, and revising data interpretations—that constitute the social epistemology of science. The PjBL framework, with its emphasis on public artifact production and peer critique, provides the institutional structure for this social epistemic process.

Fourth, Epistemic Scaffolding Theory—developed by Radoff et al.

(2020) and Sharma and Hooper (2022)—provides the pedagogical bridge between the philosophical framework and instructional design. Epistemic scaffolding encompasses the structured supports—reflection prompts, calibration activities, data critique protocols, and epistemological discussion routines—that enable students to move from naïve data consumers to sophisticated epistemic agents capable of evaluating the warrant for their own knowledge claims.

6. IMPLICATIONS FOR CURRICULUM DESIGN AND FUTURE RESEARCH

6.1 Curriculum Design Under Outcome-Based Education Frameworks

The ECEM framework has concrete implications for curriculum design in science education under Outcome-Based Education (OBE) frameworks—including Indonesia's Kurikulum Merdeka and internationally comparable frameworks. Learning outcomes for sensor-integrated PjBL should include not only domain-specific physics concepts but also epistemological competencies: the ability to critically evaluate sensor data quality; to identify theoretical assumptions embedded in measurement instruments; to distinguish between empirical evidence and theoretical interpretation; and to engage in the social negotiation of knowledge claims (Tondeur et al., 2021; Al-Kamzari & Alias, 2025).

Instructional design should explicitly scaffold the transition from naïve empiricism to critical measurement awareness. This includes dedicated instructional episodes addressing sensor calibration, systematic error analysis, and the philosophy of measurement in accessible terms (Monteiro & Marti, 2022; Staacks et al., 2020). PjBL rubrics should assess not only the accuracy of students' empirical conclusions but also the quality of their epistemological reasoning—their ability to identify evidential limits, acknowledge uncertainty, and revise claims in light of counter-evidence (Radoff et al., 2020; Jeong & Hmelo-Silver, 2023).

6.2 Priority Directions for Future Research

This review identifies four priority research directions. (1) Instrument development: validated epistemological belief surveys tailored to sensor-based learning contexts are urgently needed, building on Verheyden et al.'s (2023) recent audit of nature-of-science instruments and extending them to measurement-specific epistemic beliefs. (2) Longitudinal studies: cross-sectional designs dominate the current literature; longitudinal studies tracking the development of epistemological beliefs across PjBL units would provide stronger evidence for transformative epistemological claims (Nikou & Economides, 2021; Dolenc & Šorgo, 2021). (3) Cross-cultural comparative studies: the epistemological assumptions of sensor-integrated PjBL require cross-cultural validation, with particular attention to Southeast Asian and African contexts where indigenous knowledge traditions are educationally relevant (Siswanto et al., 2024; Widowati & Tyas, 2024). (4) Integrated theoretical modeling: formal models integrating philosophy of measurement, constructivist learning theory, and postphenomenological analysis of human–sensor relations would provide a more rigorous foundation for both empirical research and curriculum design (Tal, 2020; Aagaard, 2021; Rosiek et al., 2020).

D. Conclusion

This Systematic Literature Review has examined, from the intersecting perspectives of philosophy of science and philosophy of educational technology, the epistemological foundations of mobile-sensor-integrated Project-Based Learning as documented in literature published between 2020 and 2026. The analysis demonstrates that this pedagogical–technological configuration enacts a genuine epistemological paradigm shift: from transmission to co-construction, from passive reception to active empirical investigation, from authoritative declaration to fallibilist inquiry. Mobile sensors function not as neutral tools but as theory-laden epistemic instruments that mediate between physical phenomena and conceptual knowledge through interpretive human–technology–world relations.

The dominant epistemological frameworks operative in the recent literature—neo-constructivism, inquiry epistemology, constructionism, embodied cognition, and connectivism—provide substantial philosophical resources for this paradigm shift but are rarely deployed with the rigor that their philosophical complexity demands. Critical lacunae persist: the absence of validated epistemological belief instruments calibrated to sensor contexts, the disconnection between constructivist pedagogy and philosophy of measurement, the dominance of uncritical empiricism in the treatment of sensor data, and the geopolitical concentration of research in Western and East Asian contexts.

The proposed ECEM framework synthesizes contemporary constructive empiricism, postphenomenological mediation theory, sociomaterial knowledge production, and epistemic scaffolding theory into a philosophically coherent foundation for sensor-integrated PjBL. This framework has direct implications for curriculum design under OBE frameworks globally and for the development of assessment instruments capable of evaluating epistemological competencies as genuine learning outcomes. The project of building a rigorous philosophical foundation for technology-enhanced science education is not merely academic; it is a precondition for designing learning environments in which students genuinely learn to think scientifically—to make warranted claims, acknowledge uncertainty, and revise beliefs in light of evidence.

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