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# Supporting Conceptual Understanding in Electricity and Magnetism: A Systematic Review and the DIS Heuristic

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**Abstract:** This systematic review synthesises 37 empirical studies published between 2019 and 2024 regarding secondary school teaching and learning in electricity and magnetism. Following PRISMA 2020 procedures, screening reliability was assessed (κ = 0.76–0.83), although the protocol was not formally registered. The review examines research across five analytically linked dimensions: topical scope, diagnostic practices, instructional mediation, conceptual change, and contextual factors. Findings indicate that research continues to concentrate on electric circuits (n = 28, 76%), while magnetism and electromagnetic induction are underrepresented (n = 5, 14%), thus limiting generalisability across the field. Diagnostic and assessment practices are predominantly outcome-focused, relying on pre-test/post-test instruments (n = 25, 68%), with few process-oriented or formative approaches that capture students' reasoning trajectories. Instructional strategies, including simulations, inquiry, and modelling, demonstrate contingent effectiveness: meaningful conceptual gains predominantly emerge when teachers provide structured guidance and pedagogical mediation. Evidence of sustained conceptual change is scarce, and contextual factors, including equity considerations, are seldom integrated into study designs. In response, this review proposes the Diagnose–Intervene–Sustain (DIS) heuristic, which foregrounds diagnostic assessment, evidence-informed instructional mediation, and reinforcement to support conceptual learning. Equity is positioned as a cross-cutting dimension of the heuristic, reflecting its role as a mediating condition in instructional effectiveness. Implications highlight the necessity for broader content coverage, systematic teacher mediation, process-oriented diagnostics, and attention to equity to enhance electricity and magnetism instruction.

***Keywords:*** Electricity, magnetism, misconceptions, conceptual change, inquiry-based learning, simulations, equity in STEM .

## 1. Introduction

Electricity and magnetism are fundamental areas within secondary school physics, forming the basis for students' understanding of natural phenomena, technological systems, and scientific models. From early experimental demonstrations to the formalisation of electromagnetic theory, these concepts have been central to the development of physics as a discipline (Baigrie, 2006). In contemporary curricula, electricity and magnetism are expected to enhance not only procedural competence but also conceptual reasoning, abstraction, and explanatory coherence (Baptista & Martins, 2023). Despite their significance in the curriculum, students have consistently faced difficulties and misconceptions across generations and educational contexts (Shipstone et al., 1988; Carlton, 1999; Engelhardt & Beichner, 2004; Moodley & Gaigher, 2019). Research shows that students often confuse current with voltage, view electrical components as consumers of current, and struggle to understand system-level behaviour in series and parallel circuits (Hart, 2008; Suryadi et al., 2020; Listianingrum et al., 2024). Similar challenges are evident in magnetism and electromagnetism, where learners must grapple with abstract fields, interactions at a distance, and dynamic

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relationships between electric and magnetic phenomena (Thurn et al., 2020; Mbonyiryivuze et al., 2022). Importantly, these difficulties frequently persist even after instruction that includes hands-on activities or digital simulations (Jaakkola et al., 2011; Dorji Tenzin et al., 2024). This persistence indicates that the limited learning gains cannot be attributed solely to conceptual challenges.

In response, instructional research has increasingly promoted approaches such as inquiry-based learning, model-based reasoning, analogical instruction, and digital simulations to support conceptual understanding (Taber et al., 2006; Burde & Wilhelm, 2020; Sengul, 2023). Tools such as PhET simulations are widely employed to visualise abstract processes and facilitate exploratory learning (Jaakkola et al., 2011; Ramnarain & Penn, 2021). However, empirical findings remain inconsistent. While some studies report substantial conceptual gains, others show modest or inconsistent effects, particularly when instructional guidance is limited (Manunure et al., 2020; Dorji Tenzin et al., 2024). These inconsistencies indicate challenges that extend beyond the selection of instructional tools. A growing body of work suggests that instructional effectiveness in electricity and magnetism is mediated by teachers' pedagogical decisions and representational choices. Constructs such as Pedagogical Content Knowledge and Technological Pedagogical Content Knowledge are frequently referenced to explain variations in instructional outcomes (Shulman, 1986; Mishra & Koehler, 2006). However, across studies, these constructs are rarely operationalised or examined systematically. As a result, technology integration is often reported descriptively rather than analytically, limiting insight into how pedagogical mediation shapes learning (Ramnarain & Penn, 2021; Papalazarou et al., 2024).

Similarly, conceptual change is often inferred from pre-test and post-test gains rather than examined as a process that unfolds during instruction. While Conceptual Change Theory emphasises the restructuring of learners' existing conceptions (Posner et al., 1982), many studies rely on summative assessments, which provide limited insight into students' reasoning trajectories (Engelhardt & Beichner, 2004; Liu et al., 2022). As a result, instructional success is frequently inferred from score improvements rather than documented shifts in conceptual understanding.

Despite an expanding body of empirical literature, existing reviews of electricity and magnetism instruction often focus on specific content areas or instructional tools, with many pre-dating recent developments in digital learning environments. Few reviews systematically examine how diagnostic practices, instructional mediation, and the sustainability of conceptual learning are interconnected across contemporary studies. Additionally, limited attention has been given to how methodological choices and contextual factors, including resource constraints, influence instructional effectiveness in secondary school settings.

In response, this systematic review synthesises empirical studies published between 2019 and 2024 on secondary-level teaching and learning in electricity and magnetism, following PRISMA 2020 procedures (Page et al., 2021). Rather than merely cataloguing instructional approaches, the review investigates structural patterns across studies related to topical scope, diagnostic and assessment practices, instructional mediation, conceptual sustainability, and contextual conditions. Through this analysis, the review aims to identify constraints on conceptual learning and to inform more coherent and effective instructional design.

### 1.1 Problem statement

This systematic review aims to examine contemporary research on the teaching and learning of electricity and magnetism within secondary school contexts, with particular emphasis on how instructional design, teacher knowledge, and assessment practices either support or constrain conceptual understanding. Rather than treating instructional strategies, technologies, or misconceptions as isolated variables, the review adopts an integrative perspective that foregrounds diagnostic practices, pedagogical mediation, and the sustainability of conceptual change.

Guided by this focus, the review addresses the following research questions:

- What dominant thematic emphases characterise research on electricity and magnetism education at the secondary school level, published between 2019 and 2024, and how are these emphases distributed across various content domains?
- What methodological approaches underpin recent empirical studies in the instruction of electricity and magnetism, and how are these frameworks operationalised?
- In what ways do instructional strategies influence students' conceptual understanding of electricity and magnetism, and what role does teacher pedagogical reasoning play in mediating the effectiveness of these strategies?
- What assessment and diagnostic tools are utilised to evaluate conceptual understanding and misconceptions in electricity and magnetism, and to what extent do these tools effectively capture processes of conceptual change?
- What gaps emerge in the literature concerning sustained conceptual development, equity, and contextual responsiveness, particularly in relation to resource constraints, learner diversity, and underrepresented topics within electricity and magnetism?

## 2. Conceptual and Historical Significance of Electricity and Magnetism

Electricity and magnetism hold a unique position in secondary school physics, both due to their historical development and their conceptual structure. Unlike mechanics, which is based on directly observable phenomena, electricity and magnetism require learners to engage with abstract concepts, mathematical symbols, and system-level relationships. Historically, the formalisation of electrical and magnetic phenomena predated the widespread use of field-based representations, leading to explanatory approaches that focused more on effects than on mechanisms (Baigrie, 2006). These epistemic origins continue to shape the way electricity and magnetism are presented in school curricula and instructional materials.

Conceptually, these subjects necessitate coordinated reasoning across various representations, including circuit diagrams, symbolic equations, verbal explanations, and graphical models. Students must reconcile local interactions with global system behaviour, such as understanding how changes in one component impact the entire circuit. Research consistently demonstrates that learners struggle to integrate these representations, often resorting to linear or substance-based reasoning that contradicts scientific models (Shipstone et al., 1988; Carlton, 1999; Hart, 2008). These reasoning patterns are not merely misconceptions; they represent coherent alternative frameworks that are resistant to change.

The persistence of misconceptions in electricity and magnetism has been observed across educational levels and cultural contexts (Badmus & Jita, 2024; Engelhardt & Beichner, 2004; Moodley & Gaigher, 2019; Suryadi et al., 2020). Even when instruction includes practical activities or digital simulations, students may not restructure their conceptual understanding if instructional tasks do not explicitly address their underlying reasoning (Jaakkola et al., 2011; Dorji Tenzin et al., 2024). This indicates that the conceptual difficulties in electricity and magnetism are not solely due to the complexity of the content but are also influenced by how learners' ideas are elicited, challenged, and refined during instruction.

From an instructional standpoint, these challenges impose significant demands on teachers' pedagogical reasoning. Effective teaching of electricity and magnetism requires more than just accurate content knowledge. Teachers must anticipate common misconceptions, select representations that clarify abstract relationships, and sequence learning experiences to support conceptual coherence (Shulman, 1986; Coetzee et al., 2022). When digital tools such as simulations are introduced, teachers must also integrate technological affordances with pedagogical intent and content-specific goals (Mishra & Koehler, 2006; Ramnarain & Penn, 2021; Chen et al., 2023). Without this integration, instructional innovations risk fostering superficial engagement rather than promoting genuine conceptual understanding.

These conceptual and historical characteristics elucidate why research on electricity and magnetism often yields uneven instructional outcomes. Diagnostic practices frequently fail to accurately capture the structure of students' reasoning. Furthermore, instructional strategies may place undue emphasis on activities or technologies without adequate pedagogical mediation. Opportunities for follow-up to reinforce and stabilise newly formed concepts are seldom examined. Consequently, comparing instructional effectiveness across studies proves challenging, and generalising successful interventions is problematic. Understanding electricity and magnetism as a domain characterised by historically rooted abstractions, representational complexity, and resistant alternative conceptions provides a necessary framework for this review. Rather than addressing misconceptions, instructional strategies, or technologies in isolation, this review investigates how diagnostic reasoning, instructional mediation, and sustained conceptual development are approached across recent empirical studies. This perspective informs the subsequent synthesis and aids in identifying structural patterns that influence learning outcomes in electricity and magnetism education.

## 3. Methodology

This study employed a systematic review design guided by the PRISMA 2020 framework (Page et al., 2021) to ensure transparency, rigour, and replicability in the identification, screening, and synthesis of pertinent literature. The review concentrated on empirical studies investigating the teaching and learning of electricity and magnetism within secondary school contexts. A review protocol delineating the scope, eligibility criteria, and analytical procedures was developed prior to data collection and served to guide the review process. Formal registration was not undertaken due to time constraints; however, this limitation is acknowledged in the Limitations section.

### 3.1 Search strategy and data sources

The systematic search was conducted from 15 July 2024 to 30 August 2024. A systematic literature review was undertaken across multiple databases frequently utilised in science education research, including Scopus, Web of Science, ERIC, and Google Scholar. Scopus and Web of Science were employed to capture citation-indexed research in physics education, while ERIC was included for education-focused studies. Google Scholar served as a supplementary source to identify relevant publications that may not be consistently indexed in other databases. The results from Google Scholar were limited to the first 200 entries sorted by relevance; no additional records meeting the eligibility criteria were identified through this supplementary search. Search terms were constructed using combinations of keywords pertaining to electricity and magnetism, secondary education, and instructional strategies. The full search strings for each database are detailed in Appendix A. The search was restricted to peer-reviewed articles published between 2019 and 2024 and reported in English. This time frame was selected to encompass recent instructional practices and assessment approaches in secondary school publications concerning electricity and magnetism, particularly in relation to the increasing integration of digital tools and contemporary pedagogical designs.

### 3.2 Eligibility criteria

Studies were included in the review if they met the following criteria: empirical research studies published in peer-reviewed journals; focused on the teaching or learning of electricity and magnetism; conducted in secondary school or equivalent educational contexts; reported data on student learning outcomes, instructional processes, or teacher practices; and were published between 2019 and 2024. Studies were excluded if they focused exclusively on primary or tertiary education, were theoretical papers, editorials, or conference proceedings, did not report empirical data, or addressed physics topics unrelated to electricity and magnetism.

### 3.3 Study selection process

The study selection process involved three stages: title screening, abstract screening, and full-text review. All records retrieved from the database searches were first screened by title to eliminate clearly irrelevant studies. The abstracts of the remaining articles were then reviewed against the eligibility criteria. Full texts were obtained for studies that met the inclusion criteria or where eligibility was unclear. To enhance reliability, screening was conducted independently by two reviewers. Inter-rater agreement for title screening was 94.3% ($\kappa = 0.83$), and for abstract screening, it was 89.7% ($\kappa = 0.76$). Disagreements were resolved through discussion and consensus. The final set of included studies was documented using a PRISMA flow diagram (see Figure 1).

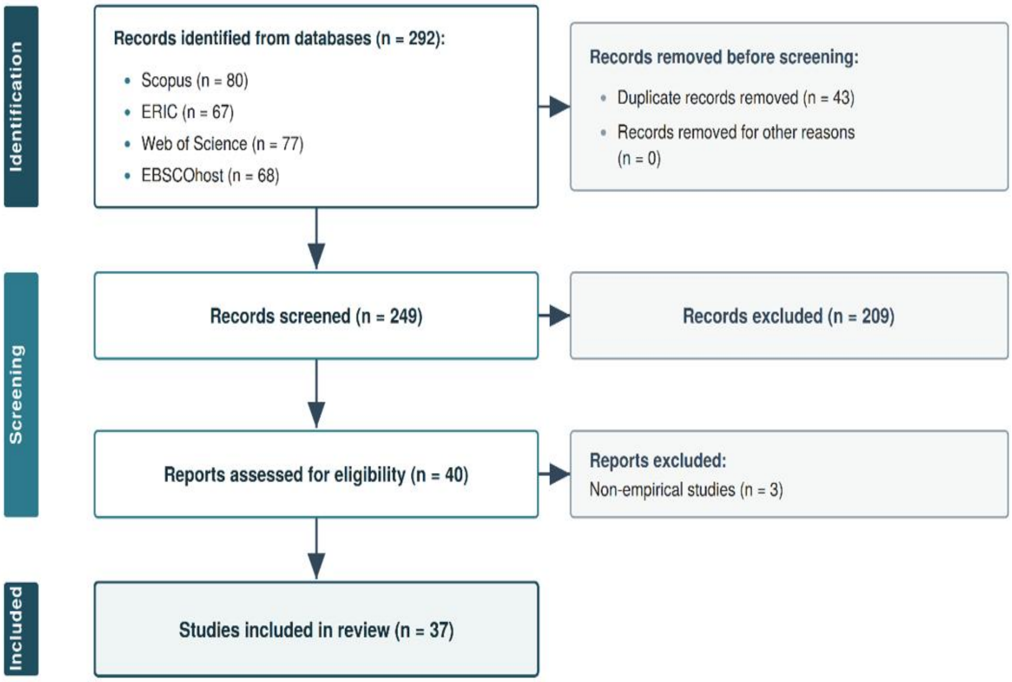


***Figure 1:*** *PRISMA flow diagram of the study selection process (n=37)*

Figure 1 presents the PRISMA flow diagram for study selection. A total of 292 records were identified from Scopus (n = 80), ERIC (n = 67), Web of Science (n = 77), and EBSCOhost (n = 68). Following the removal of 43 duplicate records, 249 records remained for screening. Of these, 209 were excluded based on a review of titles and abstracts. The remaining 40 studies proceeded to full-text assessment, which resulted in the exclusion of three non-empirical studies. Consequently, 37 studies fulfilled the inclusion criteria and were retained for the final review and synthesis (see Appendix B).

### 3.4 Data extraction and reliability

Data extraction was conducted utilising a structured framework developed in alignment with the research questions. For each included study, information was systematically collected regarding publication characteristics and research context, the specific electricity and magnetism concepts addressed, instructional strategies and learning environments employed, theoretical perspectives underpinning the study, assessment and diagnostic approaches utilised, and the reported learning outcomes and study limitations. Extracted data were analysed using thematic synthesis. Initial coding was performed deductively based on the research questions, followed by inductive refinement to capture emerging patterns across the studies. This approach facilitated a systematic comparison of instructional practices, theoretical assumptions, and assessment strategies.

### 3.6 Quality and contextual considerations

Quality and contextual factors were meticulously considered throughout the synthesis process. Although no formal instrument for assessing risk of bias or quality appraisal was employed, variations in research design, sample size, and assessment rigour were taken into account when interpreting the findings. Moreover, contextual variables such as resource availability, instructional setting, and learner diversity were documented when reported. Particular attention was paid to how contextual constraints influenced instructional approaches and learning outcomes, especially within under-resourced educational settings. The absence of a formal quality appraisal process is acknowledged as a limitation of this review.

## 4. Results

This section presents the findings of the systematic review of secondary school electricity and magnetism (E&M) education research published between 2019 and 2024. Organised around the research questions, the analysis synthesises evidence from the 37 included studies regarding thematic trends, methodological approaches, instructional strategies, assessment practices, conceptual change, contextual factors, and emerging research gaps.

### 4.1 Scope and topical distribution of the literature

The corpus of 37 studies included in this review demonstrates a sustained scholarly interest in electricity and magnetism education in secondary schools between 2019 and 2024. The publication output during this period was relatively stable, with no pronounced upward or downward trend. Geographically, research was concentrated in Asia (n = 15, 40%), Europe (n = 12, 32%), North America (n = 6, 16%), and Africa (n = 4, 12%). In terms of content focus, the literature exhibited a strong concentration on electric circuits. Twenty-eight studies (76%) examined student understanding of direct current circuits, including series and parallel circuit configurations, current flow, voltage, and resistance. In contrast, magnetism, electromagnetic induction, and field-based reasoning were addressed far less frequently (n = 5, 14%). The remaining four studies (11%) investigated integrated or cross-cutting topics that addressed both electrical and magnetic phenomena or focused on broader conceptual frameworks spanning multiple electricity and magnetism content areas. This imbalance highlights a narrow topical focus, indicating that findings derived predominantly from circuit studies may not generalise to other electricity and magnetism topics. Consequently, the field's ability to draw comprehensive conclusions about conceptual learning across the full spectrum of electricity and magnetism content remains constrained.

***Table 1:*** *Methodological orientation of secondary electricity and magnetism research (2019–2024)*

| Methodological Orientation | Number of Studies | Percentage of Corpus |
|---|---|---|
| Quantitative(Experimental/Quasi-Experimental/Survey) | 19 | 51.4% |
| Qualitative Case Study | 9 | 24.3% |
| Mixed Methods | 6 | 16.2% |
| Design-Based Research | 3 | 8.1% |
| **Total** | **37** | **100%** |

As evidenced in Table 1, the methodological distribution indicates a pronounced focus on outcome-oriented measurement, with more than half of the studies utilising quantitative pre-test and post-test designs. In contrast, qualitative and design-based methodologies, which are more adept at investigating instructional processes, teacher mediation, and conceptual development over time, are relatively underrepresented. This methodological imbalance may restrict the understanding of how students cultivate reasoning across various topics within electricity and magnetism, particularly in less-explored domains such as magnetism and induction.

### 4.2 Diagnostic and assessment practices in electricity and magnetism research

Across the reviewed studies, diagnostic and assessment practices were predominantly outcome-oriented, concentrating on measuring conceptual gains rather than examining students' reasoning processes. A significant number of studies (n = 25, 68%) utilised pre-test and post-test designs, generally employing standardised or researcher-developed concept inventories to identify misconceptions and evaluate learning outcomes. These instruments were administered prior to and following instruction, with limited emphasis placed on assessments integrated within the instructional process.

***Table 2:*** *Diagnostic and assessment approaches in reviewed electricity and magnetism studies (2019–2024)*

| Diagnostic Approach | No. of Studies | Percentage of Corpus | Typical Instruments / Methods | Key Focus |
|---|---|---|---|---|
| Pre-/Post-Test Concept Inventories | 25 | 68% | Standardised tests, researcher-designed inventories | Outcome measurement, misconceptions identification |
| Formative / Process-Oriented Assessment | 5 | 14% | Observational protocols, embedded tasks, iterative questioning | Capturing reasoning during instruction |
| Qualitative Diagnostics | 7 | 19% | Interviews, open-ended written responses | Exploration of student reasoning, conceptual conflicts |
| Mixed / Combined Approaches | 4 | 11% | Integration of quantitative and qualitative measures | Bridging outcome measurement with reasoning insight |

*Note: Some studies used multiple diagnostic approaches; percentages sum >100%*

As demonstrated in Table 2, the majority of studies (68%) utilised pre-/post-test concept inventories, whereas formative and qualitative diagnostics were comparatively less prevalent. This distribution underscores a pronounced emphasis on quantifiable outcomes and the relative paucity of methodologies that capture real-time reasoning.

### 4.3 Outcome-oriented diagnostics

Concept inventories focused on electric circuits were the most frequently employed instruments. These inventories typically assessed well-established misconceptions, such as the confusion between current and voltage or erroneous interpretations of circuit behaviour. Although these tools facilitated cross-study comparisons, they primarily measured response accuracy, thereby providing limited insights into the evolution of students' conceptual frameworks during instruction. As a result, the diagnostic data predominantly captured "what students answered correctly" rather than "how students reasoned."

### 4.4 Formative and process-oriented approaches

Formative and process-oriented diagnostics were rare. Only a small number of studies (n = 5, 14%) employed observational protocols, embedded tasks, or iterative questioning to examine student thinking as instruction progressed. Even in studies using simulations or inquiry-based methods, assessment measures were typically external to the learning environment and administered post-instruction. This separation limited the ability to capture moments of conceptual conflict, sense-making, or knowledge revision.

### 4.5 Qualitative diagnostics

Qualitative methods, such as interviews or open-ended written responses, were applied in a limited subset of studies (n = 7, 19%). These methods revealed students' persistent reliance on everyday reasoning and linear causal explanations that conflicted with scientific models. However, findings from qualitative diagnostics were seldom integrated systematically with quantitative results, which reduced their impact on interpretations of instructional effectiveness.

### 4.6 Instructional strategies and pedagogical mediation

Instructional strategies identified in the reviewed studies encompassed simulations, inquiry-based learning, modelling activities, and analogical instruction. Notably, digital simulations emerged as the most frequently investigated, frequently serving as tools for visualising abstract electrical and magnetic phenomena. However, the effectiveness of these simulations varied significantly, contingent upon the level and quality of teacher mediation. A consistent pattern emerged: instructional strategies yielded stronger conceptual gains when accompanied by structured teacher guidance. Explicit scaffolding, guided questioning, and targeted explanations enhanced the efficacy of both simulations and inquiry-based learning. In contrast, minimally guided or fully autonomous approaches frequently yielded modest or inconsistent improvements, underscoring the conditional effectiveness of these strategies. The role of teacher knowledge was often cited as influential, yet it was rarely examined empirically. Pedagogical Content Knowledge (PCK) and Technological Pedagogical Content Knowledge (TPACK) were occasionally referenced to elucidate differences in outcomes; however, most studies did not operationalise or measure these constructs. Consequently, the mechanisms through which teacher decisions shape learning remain largely inferred.

***Table 3:*** *Instructional strategies, teacher mediation, and observed effectiveness (2019–2024)*

| Instructional Strategy | No. of Studies | Teacher Mediation Level | Typical Pedagogical Support | Observed Effectiveness |
|---|---|---|---|---|
| Simulations | 15 | High: 9, Low: 6 | Guided questioning, scaffolding, and explanation | Conceptual gains higher with guidance |
| Inquiry / Modelling | 8 | High: 5, Low: 3 | Model construction support, iterative feedback | Deeper understanding with active guidance |
| Analogical / Narrative Instruction | 5 | Moderate | Story analogies, real-world links | Conceptual clarity mixed |
| Minimal Guidance / Autonomous Exploration | 4 | Low | Minimal scaffolding | Learning gains uneven |

*Note: Some studies employed multiple strategies; numbers may overlap.*

Few studies have integrated diagnostic practices that capture instructional mediation in real time. Most have relied on post-test assessments, which primarily measure learning outcomes rather than reasoning or sense-making processes. Consequently, the influence of teacher mediation on the development of students' conceptual frameworks is often inferred rather than directly observed. Although studies employing formative or embedded diagnostics are limited, they have revealed that teacher scaffolding significantly influences how students reconcile misconceptions and construct scientific models.

### 4.7 Conceptual change and sustainability of learning

A central focus in the reviewed literature was the extent to which instructional interventions promoted not only immediate conceptual gains but also a deeper conceptual understanding of electricity and magnetism concepts. Across the studies, evidence suggests that while short-term learning improvements are common, sustained conceptual change remains limited. Most studies assessed learning through pre-test and post-test measures administered immediately before and after the interventions. These designs effectively capture immediate outcomes but rarely measure the persistence of conceptual understanding. Only a few studies included delayed post-tests or follow-up assessments to evaluate long-term retention. When such longitudinal measures were applied, gains often decayed over time, indicating inconsistent conceptual change, particularly for complex topics such as electromagnetic induction and field-based reasoning. Reinforcement practices, such as repeated application, integration across contexts, or iterative problem-solving, were not frequently reported. In studies where reinforcement occurred, conceptual understanding tended to be more robust, suggesting that sustainable learning depends on repeated and contextually varied engagement with core electricity and magnetism concepts.

***Table 4:*** *Evidence of conceptual change and retention (2019–2024)*

| Study Focus | Assessment Timing | Observed Gains | Retention Evidence | Notes |
|---|---|---|---|---|
| Electric Circuits | Immediate Post-Test | High | Few delayed assessments | Gains often short-lived |
| Electric Circuits | Delayed Post-Test (1–4 weeks) | Moderate | Retention reduced | Requires reinforcement |
| Magnetism & Induction | Immediate Post-Test | Moderate | Rare, delayed measures | Fragile understanding |
| Magnetism & Induction | Delayed Post-Test | Low | Conceptual decay observed | Limited instructional scaffolding |

*Note: Some studies included multiple content areas or assessments; numbers may overlap*

A limited subset of studies employed mixed-method or process-oriented assessments to examine the evolution of student reasoning over time. These studies highlighted that students often temporarily adopt scientifically accurate explanations without fully restructuring their underlying mental models. Misconceptions, particularly those rooted in everyday reasoning or prior experiences, frequently re-emerged when interventions lacked sustained engagement or explicit reinforcement. Overall, the reviewed literature indicates that instructional interventions can yield measurable conceptual gains in energy and matter (E&M), particularly in the short term. However, the sustainability of learning is inconsistent, constrained by limited longitudinal assessments, inadequate reinforcement practices, and underdeveloped mechanisms for fostering deep conceptual restructuring.

### 4.8 Contextual and equity-related patterns

The reviewed literature indicates that contextual factors and equity considerations significantly influence the teaching and learning of electricity and magnetism; however, they are frequently regarded as peripheral rather than structural elements within instructional research.

***Table 5:*** *Contextual and Equity Considerations in Reviewed Studies (2019–2024)*

| Contextual Factor | Number of Studies Reporting | Observed Impact on Learning | Key Notes |
|---|---|---|---|
| Resource Availability | 8 | Limited hands-on experimentation in low-resource settings | Digital simulations partially mitigated gaps |
| Teacher Preparation (CK/PCK) | 11 | Strong mediator of instructional effectiveness | Effective scaffolding depended on teacher expertise |

| | | | |
|---|---|---|---|
| Learner Diversity (gender, prior knowledge, SES) | 6 | Uneven engagement and misconceptions | Few studies systematically analysed differential outcomes |
| Technology Access | 5 | Digital tools enhanced visualisation but introduced disparities | Equity gaps in access influenced learning gains |

*Note: Studies may address multiple contextual factors; numbers are not mutually exclusive*

Table 5 indicates that contextual and equity-related factors were addressed inconsistently across the reviewed literature and were rarely treated as central analytical variables. Teacher preparation, particularly in relation to content knowledge and pedagogical content knowledge, was the most frequently reported contextual factor and emerged as a robust mediator of instructional effectiveness. In contrast, resource availability and access to technology were cited in relatively few studies, with findings suggesting that digital simulations could partially mitigate the impact of limited physical resources, albeit not without introducing new access-related disparities. Learner diversity, encompassing gender, prior knowledge, and socioeconomic status, was the least systematically examined; when these factors were mentioned, analyses predominantly remained descriptive rather than explanatory.

### 4.9 Geographical and resource contexts

Research was predominantly focused on middle- and high-resource regions of Asia and Europe, with a notable scarcity of studies conducted in low-resource contexts within Africa. Investigations undertaken in under-resourced settings identified significant challenges, including limited access to laboratory equipment, simulation resources, and teacher training or professional development. These constraints significantly influenced both the design of interventions and the observed learning outcomes. For instance, students in resource-limited classrooms frequently depended on teacher-mediated demonstrations rather than engaging in hands-on experimentation, thereby restricting opportunities for active engagement with fundamental concepts.

### 4.10 Teacher preparation and knowledge

Teacher expertise, encompassing both content knowledge (CK) and pedagogical content knowledge (PCK), significantly mediates instructional effectiveness. Numerous studies have documented that educators with incomplete CK or limited familiarity with diagnostic tools are less capable of scaffolding complex concepts, such as electromagnetic induction. In instances where teacher preparation is inadequate, instructional strategies, even those demonstrated to be effective in controlled settings, result in modest or inconsistent student learning gains.

### 4.11 Learner diversity and equity

Few studies have explicitly examined learner diversity in terms of prior knowledge, socioeconomic status, or gender. Where reported, these factors have been correlated with variations in conceptual understanding and responsiveness to instructional strategies. For instance, interventions that rely on technology-based simulations have demonstrated unequal benefits for students with limited digital literacy or prior exposure. Similarly, studies conducted in gender-segregated classrooms have reported disparities in engagement and misconceptions, particularly in hands-on or inquiry-driven activities.

In summary, these findings indicate that equity should not be regarded as an add-on but rather as a mediating condition that influences the efficacy of instructional strategies. Neglecting contextual variability risks overgeneralising results and misinterpreting conceptual gains. Furthermore, the interaction between teacher mediation, resources, and student diversity suggests that interventions must be adaptively designed to local contexts to achieve meaningful learning outcomes.

## 5. Discussion of Findings

This section delineates the findings of the review based on the 37 studies incorporated into the final corpus. The results are organised according to the research questions and synthesise evidence pertaining to thematic trends, methodological approaches, instructional practices, assessment methods, conceptual change, and contextual factors in secondary school education concerning electricity and magnetism.

### 5.1 Overview and synthesis

The reviewed literature underscores persistent trends and gaps in secondary electricity and magnetism (E&M) education research from 2019 to 2024. The studies predominantly addressed electric circuits, with a specific focus on direct current series and parallel configurations (e.g., Burde & Wilhelm, 2020; Demirçali & Selvi, 2023; Sengul, 2023). Diagnostic practices predominantly employed pre-test/post-test designs and concept inventories, with insufficient attention dedicated to reasoning processes (e.g., Liu et al., 2022; Ivanjek et al., 2021). Instructional strategies encompassed simulations, inquiry-based learning, modelling activities, and analogical instruction, with the effectiveness of these approaches being contingent upon teacher mediation (e.g., Burde & Wilhelm, 2020; Gottschlich et al., 2024; Jaakkola & Veermans, 2020). Evidence for sustained conceptual change was minimal, and studies seldom addressed equity explicitly (e.g., Mbonyiryivuze et al., 2022; Lombard & Simayi, 2019). Overall, these findings reflect an expanding research base characterised by uneven coverage of content and pedagogical practices.

### 5.2 Linking findings to conceptual learning in electricity and magnetism

Electric circuits have predominated the literature, while magnetism, electromagnetic induction, and field-based reasoning have been underrepresented (e.g., Büyükbayraktar & Dilber, 2022; Kaliampos et al., 2021). This emphasis constrains the generalisability of findings across the entirety of electromagnetic (E&M) topics. Studies focusing on circuits yield valuable insights into misconceptions pertaining to current, voltage, and resistance (Ball & Tofel-Grehl, 2020; Burde & Wilhelm, 2020); however, they fail to address the conceptual challenges associated with magnetism or induction. Future research should investigate these underrepresented domains to attain a comprehensive understanding of secondary students' conceptual learning in E&M.

### 5.3 Diagnostic practices and student reasoning

Diagnostic methods have emphasised the measurement of outcomes rather than the processes of reasoning. Concept inventories have been widely employed to address misconceptions, such as confusion between voltage and current and misinterpretations of circuit behaviour (Alanazı, 2020; Ouahi et al., 2024; Taslidere & Yıldırım, 2023). However, few studies have incorporated formative or process-oriented assessments, including embedded tasks, iterative questioning, or interviews (Degirmenci, 2022; Coetzee et al., 2022). When qualitative methods were utilised, they revealed a persistent reliance on everyday reasoning and linear causal explanations (Carpendale & Hume, 2020; Poti et al., 2022). The limited integration of qualitative findings with quantitative results constrains the interpretation of instructional effectiveness and renders student reasoning largely invisible. These findings underscore the importance of the Diagnose stage in the DIS heuristic, highlighting the necessity of identifying prior conceptions and misconceptions to inform instructional practices.

### 5.4 Instructional mediation and pedagogical reasoning

Instructional strategies were conditionally effective. Simulations produced positive outcomes primarily when accompanied by structured guidance and scaffolding (Dandl et al., 2024; Jaakkola & Veermans, 2020). Minimally guided interventions produced modest or inconsistent gains (Liu et al., 2024). Inquiry-based and modelling approaches demonstrated efficacy when educators actively facilitated conceptual alignment and the selection of representations (Demirçali & Selvi, 2023; Maričić et al., 2024). Teacher knowledge, encompassing both Pedagogical Content Knowledge and Technological Pedagogical Content Knowledge, significantly influenced outcomes yet was rarely operationalised (Salar & Uğurel, 2020; Saputro et al., 2019). These findings are consistent with the Intervene stage of the DIS heuristic, underscoring the necessity for intentional instructional design that responds to diagnostic insights and fosters sense-making.

### 5.5 Sustainability of learning and conceptual change

Evidence for sustained learning is limited. Most studies report short-term conceptual gains, with few longitudinal assessments (Wheatley et al., 2021; Thurn et al., 2020). Reinforcement practices are rarely described, suggesting that conceptual change may be fragile. These observations support the Sustain stage of the DIS heuristic, emphasising the necessity of iterative engagement, the revisiting of key ideas, and the promotion of knowledge transfer to new contexts in order to maintain conceptual understanding.

### 5.6 Equity and contextual influences

Contextual factors, including resource availability, teacher preparation, and learner diversity, mediated instructional effectiveness (Mbonyiryivuze et al., 2022; Moodley & Gaigher, 2019; Lombard & Simayi, 2019). Research conducted in low-resource or underrepresented contexts remains limited, thereby constraining insights into equity-sensitive Education and Mathematics instruction. Addressing equity necessitates the integration of structural considerations into both research design and pedagogical practice, rather than relegating them to peripheral concerns.

### 5.7 Integrating findings into a heuristic for E&M instruction

The Diagnose–Intervene–Sustain (DIS) Heuristic presented in Figure 2 consolidates the central patterns identified across the reviewed studies into a coherent instructional logic. Rather than proposing a new method or tool, the heuristic addresses structural limitations consistently observed in the literature, including narrow diagnostic practices, variable instructional effectiveness, and limited attention to the depth of conceptual learning.

The Diagnose stage foregrounds the necessity of moving beyond reliance on pre-test and post-test instruments as the primary means of understanding student learning. Across the reviewed studies, diagnostic practices were largely summative and outcome-oriented, often obscuring how students reasoned about electrical and magnetic phenomena during instruction. This stage, therefore, emphasises the systematic elicitation of student conceptions through formative probes, open tasks, and iterative checks that render reasoning visible and instructionally actionable.

The Intervene stage highlights the consistent finding that instructional strategies in electricity and magnetism are conditionally effective. Simulations, inquiry activities, and modelling tasks lead to better learning outcomes when teachers intentionally mediate them by aligning representations, sequencing, and questioning with identified conceptual needs. This stage positions instructional design as responsive rather than generic, placing emphasis on pedagogical mediation and representational coherence rather than merely on the selection of tools.

The Sustain stage addresses a recurring weakness in the reviewed literature: the fragility of reported conceptual gains. Many studies have documented short-term improvements without investigating whether understanding persisted or if knowledge transferred beyond the immediate instructional context. This stage underscores the importance of reinforcing learning by revisiting core ideas, applying concepts across various contexts, and helping students coordinate multiple representations over time. Sustaining learning is seen as an instructional responsibility rather than an assumed outcome.

The DIS heuristic explicitly positions equity as a central dimension rather than a peripheral consideration (see Figure 2). Factors such as resource availability, teacher preparation, learner diversity, and contextual elements are acknowledged as mediating conditions that influence the effectiveness of each stage of the instructional cycle. Addressing equity is not an additional aspect but a fundamental requirement for meaningful and generalisable instructional design in electricity and magnetism education.

In summary, the DIS heuristic serves both as a synthesis of empirical patterns and as a guiding framework for future research and practice. It reframes effective instruction in electricity and magnetism as a continuous process that connects diagnosis, pedagogical decision-making, and sustained conceptual development, rather than as a series of isolated interventions.

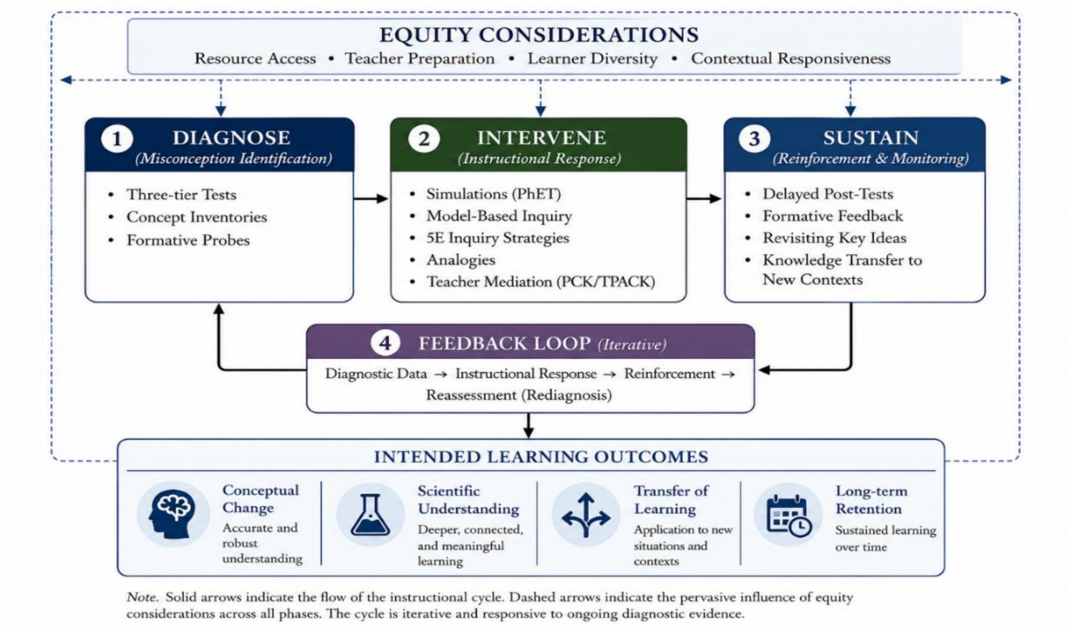


***Figure 2:*** *Integrated E & M instructional heuristic*

### 5.8 Recommendations for research and practice

Future research should extend beyond circuits to encompass underrepresented topics such as magnetism and electromagnetic induction. Diagnostic approaches ought to integrate process-oriented and qualitative methods to effectively capture reasoning and conceptual evolution. Empirical examination of teacher knowledge and mediation is essential, and longitudinal designs are necessary to evaluate sustainability. Moreover, equity considerations must be embedded in both research and instructional design to enhance learning outcomes across diverse contexts.

### 5.9 Limitations of the review

Several limitations should be considered when interpreting the findings of this review. First, the review protocol was not formally registered with an open science registry (e.g., PROSPERO, OSF). Although a prespecified protocol was developed and adhered to, formal registration is recommended in systematic review practice to mitigate selective reporting and enhance transparency. Second, no formal risk-of-bias or quality appraisal instrument was applied to the included studies. While attention was devoted to variations in research design, sample size, and assessment rigour during synthesis, the absence of systematic quality scoring may restrict the degree to which findings can be weighted by methodological strength. Third, the search was confined to English-language, peer-reviewed articles indexed in accessible databases, potentially excluding pertinent research in other languages or unpublished formats. Although full per-database search strings are provided in Appendix A, data extraction was conducted by a single reviewer, with verification of a random 20% sample by a second reviewer; fully independent dual extraction was not performed. Fourth, methodological heterogeneity across studies limited direct comparability, and inconsistencies in reporting constrained synthesis. Fifth, this review concentrated on studies published between 2019 and 2024, which may overlook foundational research that could offer important historical context or longitudinal insights into instructional practices in E&M education. Sixth, the reliance on published peer-reviewed studies may introduce publication bias, as studies reporting significant or positive findings are more likely to be published. These limitations should be considered when applying conclusions to broader educational contexts.

## 6. Conclusion

This systematic review underscores that conceptual learning in electricity and magnetism is influenced by multiple interacting factors, including instructional mediation, assessment practices, and contextual conditions. The analysis reveals a persistent focus on electric circuits, while magnetism and electromagnetic induction remain underexplored. Diagnostic practices are predominantly summative, emphasising pre-test and post-test gains, which limits visibility into the reasoning processes that underpin student learning. Instructional strategies such as simulations, inquiry-based learning, and modelling activities demonstrate conditional effectiveness, with teacher guidance and pedagogical mediation serving as critical determinants of success. Contextual factors, including resource availability, teacher preparation, and learner diversity, further influence the outcomes and generalisability of interventions.

The Diagnose–Intervene–Sustain (DIS) heuristic provides a structured approach for integrating diagnostics, instructional design, and reinforcement, offering a practical guide for fostering sustained conceptual change. By prioritising diagnosis, targeted intervention, and reinforcement, this framework addresses deficiencies in current practices and aligns instructional strategies with the developmental trajectories of student understanding. Equity is positioned as a cross-cutting dimension of the heuristic, reflecting its role as a mediating condition in instructional effectiveness. Future research could expand content coverage beyond circuits to include underrepresented domains such as magnetism and electromagnetic induction. It may also adopt process-oriented diagnostic methods that capture reasoning during instruction, systematically investigate the role of teacher mediation, and embed equity considerations into study design. Longitudinal studies are necessary to evaluate the sustainability of conceptual change and the transfer of learning across contexts. By addressing these areas, secondary education in electricity and magnetism can progress towards more comprehensive, evidence-based, and equitable instructional practices.

## 7. Declarations

**Author contributions:** Conceptualisation (L. C. J & O. T. B); Literature review (L. C. & O. T. B); methodology (L. C. J & M. T); software (N/A.); validation (M. D. L & L. C. J); formal analysis (L. C. J & O. T. B); investigation (N/A); data curation (L. C. J & O. T. B) drafting and preparation (L. C. J & O. T. B); review and editing (L. C. J & O. T. B); supervision (N/A); project administration (N/A); funding acquisition (N/A). All authors have read and approved the published version of the article.

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**Conflict of Interest:** The author(s) declare no conflict of interest.

**Data Availability Statement:** This review is based entirely on publicly available data and information sourced from peer-reviewed articles, reports, and other academic publications cited in the manuscript. No new primary data were generated or analysed during this study. Readers may refer to the cited sources for detailed information.

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**Appendix A:** *Full database search strings*

| Database | Search String |
|---|---|
| **Scopus** | TITLE-ABS-KEY(("electricity" OR "magnetism" OR "electromagnetism" OR "electric circuits" OR "electromagnetic induction") AND ("secondary school" OR "high school" OR "secondary education") AND ("teaching" OR "learning" OR "instruction" OR "misconceptions" OR "conceptual understanding")) AND PUBYEAR > 2018 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English")) |
| **Web of Science** | TS=((electricity OR magnetism OR electromagnetism OR "electric circuits") AND ("secondary school" OR "high school") AND (teaching OR learning OR instruction)) Refined by: Document Types: Articles; 2019–2024; English |
| **ERIC (EBSCOhost)** | (DE "Electricity" OR DE "Magnetism" OR DE "Electromagnetism") AND (DE "Secondary Education" OR DE "High Schools") AND (DE "Science Instruction" OR DE "Teaching Methods") AND peer_reviewed:yes AND (pubyear:2019-2024) |
| **EBSCOhost (Academic Search Complete)** | Same as ERIC string with Academic Search Complete database selected |
| **Google Scholar** | allintitle: electricity magnetism "secondary school" OR "high school" (bounded to first 200 results; supplementary use only) |

**Search dates:** 15 July 2024 – 30 August 2024

***APPENDIX B:*** *Included Studies in Systematic Review (n = 37)*


1. Alanazı, F. H. (2020). The Effectiveness of the 4MATteaching approach in enhancing conceptions of electricity in physics for female students in the kingdom of Saudi Arabia. *Journal of Turkish Science Education*, *17*(2), 271-288. https://doi.org/10.36681/tused.2020.26
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