Exploring Teachers' Approaches to Developing Complex Problem-Solving Skills in Science.

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ABSTRACT

This article presents a systematic review of 20 peer-reviewed studies focusing on pedagogical innovations in science education at the secondary and higher education levels. The objective was to determine the dominant instructional approaches, assess their documented effects on student learning, and identify the conditions that contribute to their successful implementation. The selected studies, published between 2000 and 2023, span diverse geographical contexts, including Asia, Europe, and North America. Learner-centered, inquiry-based, and project-based methods emerge as the most frequently adopted pedagogical frameworks. These approaches are consistently associated with improved student engagement, enhanced conceptual understanding, and strengthened problem-solving and critical thinking abilities. Autonomy and creativity also appear as recurrent outcomes, particularly in environments that integrate digital tools and structured scaffolding. More than 80% of the studies reported positive effects, although certain limitations were acknowledged, such as unequal access to technological resources, high demands in instructional design, and the necessity of teacher preparedness. Several enabling factors were identified, including active teacher facilitation, use of formative feedback mechanisms, collaborative group structures, and the implementation of authentic learning tasks. The effective use of technology-enhanced environments was also reported as a contributing element when supported by coherent pedagogical planning. The results underscore the importance of institutional support, professional development, and curricular flexibility in sustaining innovative teaching practices. Reinforcing these components appears essential for promoting meaningful learning and equipping students with competencies aligned with the demands of contemporary science education.

Keywords: Science education, Pedagogical innovation, Inquiry-based learning, Learner-centered instruction, Technology integration, Systematic review

1. Introduction

Science education has increasingly shifted from traditional teacher-centered instruction toward active, inquiry-based, and learner-centered approaches designed to develop critical thinking, creativity, and problem-solving skills [1], [2]. Rather than focusing solely on knowledge transmission, contemporary science education aims to prepare students to apply scientific concepts in complex and unfamiliar situations. In this context, the ability to solve complex scientific problems has become a key educational objective, requiring learners to engage in inquiry, collaboration, and reflective thinking [4].

Teachers play a central role in fostering these competencies through the design of learning environments that encourage exploration, reasoning, and knowledge construction [3], [4]. Research has demonstrated that learner-centered pedagogies enhance motivation, creativity, and academic achievement while promoting autonomy and intellectual engagement [1], [5], [6]. Similarly, inquiry-based, project-based, and discovery learning approaches support deeper conceptual understanding and the transfer of knowledge to new contexts [2], [7], [12].

Technological innovations, including virtual laboratories, simulations, flipped classrooms, and the 7E Learning Cycle, further enrich science learning by supporting experimentation, collaboration, and scientific reasoning [8], [9], [10]. However, their effectiveness depends on coherent pedagogical design and appropriate teacher guidance [6], [8]. Despite their documented benefits, the implementation of these approaches remains constrained by limited resources, rigid curricula, traditional assessment practices, and insufficient teacher training [3], [7], [11].

Although previous studies have examined various aspects of pedagogical innovation, less attention has been given to how teachers' pedagogical approaches collectively contribute to the development of complex problem-solving skills. Understanding these relationships is essential for improving science education and preparing learners to address contemporary scientific and societal challenges.

In this context, an unavoidable research question arises: How do teachers' pedagogical approaches in science education contribute to the development of students' competence in solving complex tasks?

To address this question, the article is organized into four main sections: the first presents an in-depth review of the literature on the pedagogical approaches used by science teachers to develop complex task-solving skills; the second outlines the methodology used to identify, select, and analyze relevant studies; the third presents and discusses the results, highlighting the most effective practices, recurring themes, and limitations observed in existing research; and finally, the fourth section provides the conclusion, summarizing the main insights of the review, emphasizing implications for teacher education and professional development, and suggesting directions for future research.

2. Literature Review

Science education has progressively shifted from traditional teacher-centered instruction toward active and learner-centered approaches that emphasize inquiry, collaboration, and critical thinking. In this perspective, teachers act as facilitators who design learning experiences that promote autonomy, creativity, and problem-solving skills [10]. Research highlights that pedagogical innovation strengthens the connection between theory and practice, encouraging students to actively construct knowledge through exploration and scientific inquiry [2].

Learner-centered pedagogies have been shown to enhance creativity, intellectual flexibility, and critical thinking, all of which are essential for addressing complex scientific problems [1], [3]. Similarly, the integration of twenty-first-century skills, including communication, collaboration, and creativity, supports meaningful learning and engagement [4]. Inquiry-based and discovery learning approaches further contribute to conceptual understanding and scientific reasoning by promoting experimentation and active investigation [8], [12].

Technological innovations, such as flipped classrooms, virtual laboratories, and interactive simulations, provide additional opportunities for collaboration, experimentation, and knowledge construction [5], [6]. However, their effectiveness depends on coherent pedagogical design and appropriate teacher guidance [10], [11]. Despite their benefits, active pedagogies face challenges related to limited resources, teacher preparation, and curricular constraints [7]. Consequently, successful implementation requires supportive educational environments that encourage innovation, creativity, and reflective practice [2], [9].

1. Theoretical Frameworks and Conceptual Foundations

1.1. The Evolution of Pedagogical Paradigms in Science Education

Science education has progressively evolved from a transmissive model, where teachers were considered the primary source of knowledge, toward constructivist and socio-constructivist approaches that place learners at the center of the educational process. In these paradigms, knowledge is actively constructed through interaction, inquiry, and reflection, while teachers act as facilitators who support exploration and learning [10]. This shift promotes autonomy, intrinsic motivation, critical thinking, and creativity, which are essential for scientific learning and problem-solving [11].

Socio-constructivist perspectives further emphasize collaboration and the co-construction of knowledge through dialogue and peer interaction. Learner-centered and collaborative approaches have been shown to enhance creativity, knowledge transfer, and scientific reasoning, enabling students to apply knowledge in authentic contexts [1], [4], [9]. In addition, technological innovations such as flipped classrooms and digital learning environments reinforce active participation and inquiry-based learning when integrated within coherent pedagogical frameworks [5], [6].

However, the implementation of these approaches depends on adequate teacher preparation, institutional support, and access to resources [2], [7]. Overall, contemporary science education aims not only to transmit knowledge but also to develop learners capable of reasoning, innovating, collaborating, and addressing complex real-world challenges [12].

1.2. The Competence of Complex Problem-Solving in Science Education

Complex problem-solving is a key objective of contemporary science education. It involves the ability to analyze unfamiliar situations, integrate diverse knowledge, and develop reasoned and creative solutions through reasoning, self-regulation, perseverance, and curiosity [5]. Research suggests that this competence is best developed through authentic and inquiry-based learning experiences that encourage reflection, collaboration, and evidence-based reasoning [4]. Effective learning environments balance guidance and autonomy, supported by formative feedback, scaffolding, and differentiated instruction [3]. Inquiry-based and discovery learning, as well as the 7E Learning Cycle, further strengthen scientific reasoning and knowledge transfer [8], [12]. Technology-enhanced environments can support experimentation and conceptual understanding when integrated within coherent pedagogical frameworks [5], [6], [10]. However, successful implementation requires adequate resources, teacher training, and institutional support [2], [7], [11].

2. Pedagogical Approaches that Foster Complex Problem-Solving in Science

Contemporary science education increasingly promotes active learning models that emphasize knowledge construction, collaboration, and creativity. Developing complex problem-solving skills requires learners to analyze unfamiliar situations, apply interdisciplinary knowledge, and engage in critical reasoning [1]. The literature identifies three complementary approaches that support these competencies: learner-centered pedagogies, inquiry-based learning, and technology-enhanced innovation.

2.1. Learner-Centered Approaches

Learner-centered approaches position students as active participants in the learning process while teachers act as facilitators [10]. Such approaches foster autonomy, motivation, critical thinking, and creativity, all of which are essential for addressing complex scientific problems [1], [11]. Collaborative activities, including discussions, debates, and group projects, further strengthen knowledge transfer and long-term understanding [4], [9]. By encouraging exploration and co-construction of knowledge, these approaches create favorable conditions for developing higher-order thinking skills.

2.2. Discovery and Inquiry-Based Learning

Inquiry-based learning engages students in observation, experimentation, and hypothesis testing, helping them develop scientific reasoning and conceptual understanding [12]. The 7E Learning Cycle provides a structured framework that guides learners through exploration, explanation, and evaluation stages, promoting reflective thinking and problem-solving [8]. However, effective implementation requires pedagogical scaffolding, formative feedback, and appropriate learning conditions [3]. Institutional barriers such as limited resources and overloaded curricula may also constrain the adoption of inquiry-based practices [4], [7].

2.3. Pedagogical Innovation and the Integration of Technology

Technology-enhanced approaches, including virtual laboratories, simulations, and flipped classrooms, support motivation, engagement, and conceptual learning [5], [6]. When integrated into coherent pedagogical frameworks, digital tools facilitate inquiry, collaboration, and autonomous learning [2], [10]. Furthermore, technology can improve formative assessment and provide continuous feedback that strengthens knowledge transfer and problem-solving skills [9], [11].

2.4. Toward an Integrative Science Pedagogy

Recent research advocates an integrative approach that combines learner-centered, inquiry-based, and technology-enhanced pedagogies. Such a model promotes creativity, collaboration, and critical thinking while connecting theoretical knowledge with authentic experiences [4]. Nevertheless, its effectiveness depends on teacher training, institutional support, and adequate resources [3], [7], [11].

3. Pedagogical Innovation and the Integration of Technology

The teaching of science is currently undergoing a profound transformation driven by pedagogical and technological innovations. These changes go far beyond a simple modernization of tools; they reflect a redefinition of the teacher's role, the status of knowledge, and the very nature of learning itself. In this context, active approaches, flipped classrooms, digital integration, and innovative strategies based on creativity have become essential levers for developing students' complex problem-solving skills.

3.1. The Flipped Classroom and the Redefinition of the Teacher's Role

Pedagogical innovation in science education increasingly promotes learner-centered approaches in which students actively construct knowledge while teachers act as facilitators [1]. The flipped classroom is a notable example of this transformation, allowing students to acquire theoretical content independently and use classroom time for discussion, collaboration, and problem-solving. Research indicates that this model enhances conceptual understanding, autonomy, and peer interaction, while encouraging the development of critical thinking and inquiry skills [2], [5]. Its effectiveness, however, depends on careful instructional planning, formative assessment, and teacher guidance [3]. Consequently, teachers are increasingly viewed as designers of learning environments that foster collaboration, exploration, and the development of twenty-first-century competencies [4].

3.2. The Use of Educational Technologies and Digital Learning Environments

Educational technologies, including virtual laboratories, simulations, and interactive platforms, support motivation, autonomy, and conceptual understanding in science education [6]. When integrated into structured approaches such as the 7E Learning Cycle, these tools strengthen scientific literacy and inquiry skills [8], [12]. Nevertheless, their effectiveness depends on equitable access, teacher training, and meaningful pedagogical integration [10], [11].

3.3. Innovative Strategies and Creativity in Science Classrooms

Innovative strategies such as project-based learning, gamification, scientific debates, and collaborative activities enhance engagement, creativity, and higher-order thinking skills [7], [9]. By encouraging exploration, hypothesis generation, and authentic problem-solving, these approaches strengthen cognitive flexibility and scientific reasoning [2], [8]. However, their successful implementation requires sufficient resources, time, and institutional support [3], [4].

2. Methodology

This study employed a Systematic Literature Review (SLR) guided by the PRISMA 2020 framework to investigate innovative pedagogical strategies in science education. The review focused on learner-centered approaches, hands-on learning, and technology-enhanced pedagogies. A structured search was conducted across Scopus, Web of Science, Google Scholar, and ScienceDirect. From an initial corpus of 200 studies, 20 peer-reviewed articles published between 2020 and 2025 were selected according to predefined eligibility criteria.

2.1. Research Objectives

The review aimed to: (RO1) identify innovative pedagogical strategies in science education, (RO2) evaluate their effects on student engagement, conceptual understanding, and higher-order thinking skills, and (RO3) examine challenges related to implementation, including resource limitations, teacher training, and curriculum adaptation.

2.2. Eligibility Criteria

Only peer-reviewed studies published between 2020 and 2025 in English or French were included. The review focused on empirical research addressing innovative pedagogical approaches in science education and reporting learning or engagement outcomes. Studies unrelated to science education, theoretical papers without empirical data, and non-peer-reviewed publications were excluded.

Table 1. Inclusion and exclusion criteria for study selection.

Criterion	Inclusion	Exclusion
Publication period	Articles published between 2020 and 2025	Articles published before 2020
Language	Publications in French or English	Other languages
Source type	Peer-reviewed scientific articles	Grey literature, reports, books
Theme	Innovative pedagogical strategies in science education	Topics unrelated to science pedagogy

Methodology	Empirical studies (quantitative, qualitative, or mixed)	Purely theoretical studies without data
Educational context	Primary, secondary, or higher education	Vocational or technical training
Evaluation	Studies including measures of learning or engagement	Absence of evaluation of pedagogical effects

2.3. Search Strategy

A structured search strategy was developed to identify relevant studies on pedagogical innovation in science education. Searches were conducted in Scopus, Web of Science, Google Scholar, and ScienceDirect using combinations of keywords related to active learning, learner-centered approaches, project-based learning, technology integration, and assessment strategies. Boolean operators and truncation techniques were applied to refine the search process. Selected studies were categorized into three themes: learner-centered and collaborative approaches, inquiry-based and experiential learning, and technopedagogical innovations. Publications were coded according to methodology, educational level, interventions, targeted skills, outcomes, and limitations. Continuous monitoring until June 2025 ensured the inclusion of the most recent evidence.

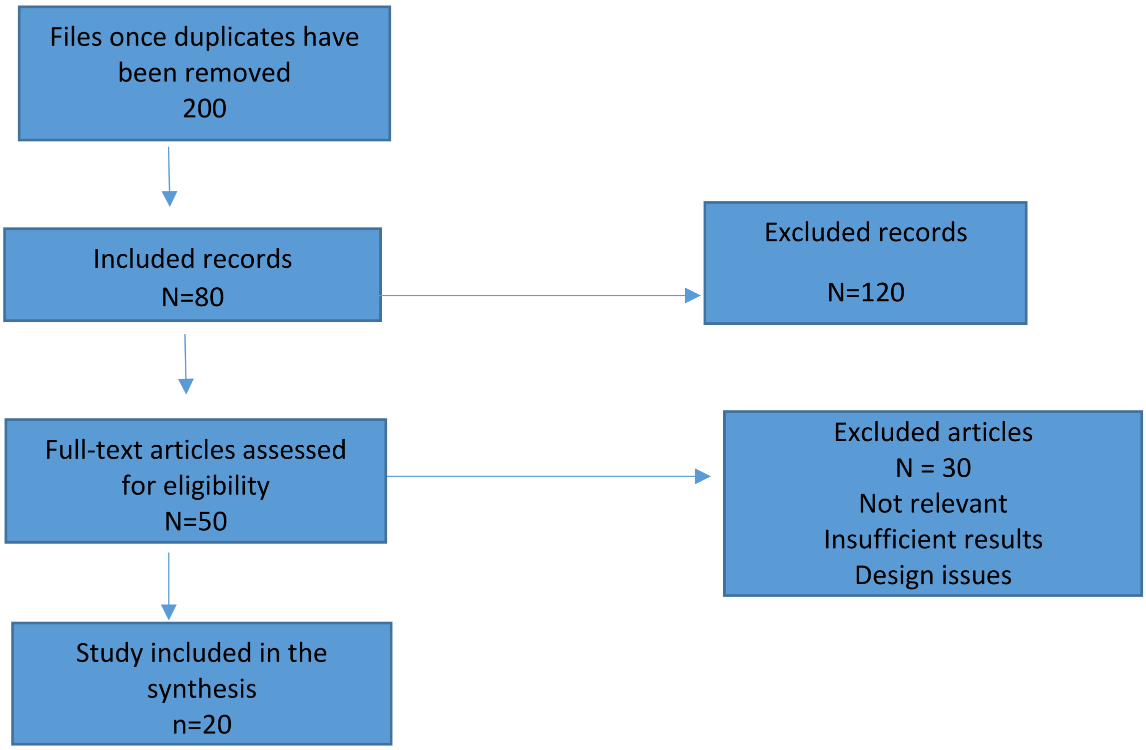

Figure 1. PRISMA diagram.

3. Results

Among the 20 selected studies, empirical research predominated, reflecting a strong interest in examining pedagogical innovations within authentic classroom settings. Qualitative studies represented 45% of the corpus (9/20), focusing on classroom interactions, student engagement, and teacher mediation. Quantitative studies accounted for 30% (6/20) and primarily assessed the effects of pedagogical interventions on outcomes such as motivation, engagement, and conceptual understanding through measurable indicators. Mixed-methods studies comprised 25% (5/20), combining qualitative and quantitative data to provide a more comprehensive understanding of learning processes. Overall, the corpus demonstrates methodological diversity while maintaining a common focus on classroom-based science education research.

Table 1. General Characteristics of the 20 Included Studies

Study ID	Author(s)	Year	Country/Region	Education Level	Methodology	Pedagogical Approach	Key Focus
[1]	Aytaç & Kula	2020	Turkey	Secondary	Quantitative (Meta-analysis)	Learner-centered	Creativity, divergent thinking
[2]	Bugtai et al.	2020	Philippines	Secondary	Qualitative	Flipped classroom, creativity	Engagement, autonomy
[3]	Goksoy	2020	Turkey	Secondary	Quantitative	Mastery learning	Feedback, confidence
[4]	Haryani et al.	2021	India	Secondary	Mixed	21st-century skills integration	Collaboration, critical thinking
[5]	Joy et al.	2022	India	Higher education	Quantitative	Flipped classroom	Active learning, autonomy
[6]	Kerimbayev et al.	2021	Kazakhstan	Secondary	Mixed	Virtual labs & simulations	Digital tools, motivation
[7]	Kilag et al.	2022	Philippines	Secondary	Qualitative	Project-based learning	Retention, critical thinking
[8]	Lisao et al.	2023	Philippines	Secondary	Mixed	7E Learning Cycle	Inquiry, structured reasoning
[9]	Sarkar & Chakraborty	2022	India	Secondary	Qualitative	Gamification, collaboration	Motivation, problem-solving
[10]	Tang	2023	China	Secondary	Theoretical & Observational	Tech integration, inquiry	Teacher role, pedagogy
[11]	Wang	2023	China	Secondary	Quantitative	Learner-centered	Motivation, engagement
[12]	Winarni et al.	2023	Indonesia	Secondary	Experimental	Discovery learning	Scientific reasoning
[13]	Vygotsky	1978	Global	Theoretical	Theoretical	Social constructivism	Zone of proximal development, mediation
[14]	Linn & Eylon	2011	USA	Higher education	Theoretical	Knowledge integration	Technology-enhanced learning
[15]	Krajcik & Blumenfeld	2006	USA	Secondary	Theoretical	Project-based learning	Deep understanding, motivation
[16]	Chi	2009	USA	Cross-level	Theoretical	Active/constructive/interactive model	Differentiation of learning activities
[17]	De Jong	2006	Netherlands	Secondary	Theoretical	Inquiry learning + technology	Scientific reasoning

[18]	Ertmer & Simons	2006	USA	K–12	Qualitative	PBL implementation	Teacher support, barriers
[19]	Jonassen	2000	USA	General	Theoretical	Problem-solving design	Cognitive strategies
[20]	Hmelo-Silver	2004	USA	Secondary	Theoretical review	Problem-based learning	Learning processes, outcomes

The reviewed studies reveal considerable methodological and contextual diversity. Most studies (75%, 15/20) were conducted at the secondary education level, indicating a strong interest in pedagogical innovation during key stages of learner development. Theoretical contributions accounted for 35% of the corpus (7/20), highlighting the importance of conceptual frameworks in science education research. Qualitative and quantitative studies each represented 25% (5/20), while mixed-methods designs accounted for 15% (3/20). Geographically, the studies spanned Asia, Europe, the Middle East, and North America. Pedagogically, the corpus reflected a balance between learner-centered, inquiry-based, project-based, and technology-enhanced approaches, emphasizing active and meaningful learning.

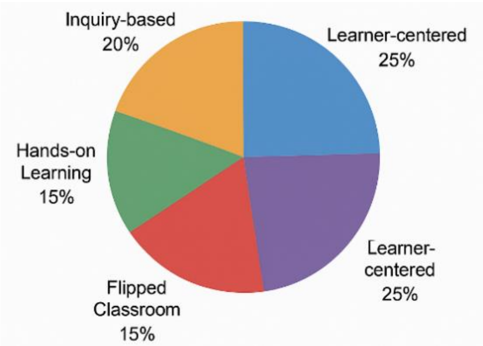

Figure 2 – Distribution of Pedagogical Approaches

Figure 2 shows the distribution of pedagogical approaches across the 20 selected studies. Learner-centered approaches were the most frequently reported (25%), reflecting a strong emphasis on student autonomy, active participation, and personalized learning. Inquiry-based learning accounted for 20%, highlighting the importance of scientific investigation, curiosity, and reasoning in science education. Flipped classrooms and hands-on learning each represented 15%, demonstrating the growing integration of digital technologies and experiential learning. Although some overlap exists between categories, particularly with project-based and constructivist approaches, the overall distribution indicates a clear preference for active learning models designed to promote critical thinking, engagement, and knowledge application.

Table 2. Distribution of Reported Effects According to Pedagogical Approach

Pedagogical Approach	Student Engagement	Conceptual Understanding	Problem-Solving & Critical Thinking	Creativity & Autonomy	Remarks / Limitations
Learner-Centered	Positive	Positive	Positive	Positive	Requires well-trained teachers and structured autonomy

Inquiry-Based Learning	Positive	Positive	Positive	Mixed	Time-consuming; needs careful scaffolding
Hands-on Learning	Positive	Positive	Mixed	Positive	Resource-intensive; access to materials may vary
Flipped Classroom	Positive	Positive	Positive	Mixed	Depends on student preparation and digital access
7E Learning Cycle	Positive	Positive	Positive	Positive	Requires detailed instructional planning
Technology Integration (e.g. VR, simulations)	Mixed	Positive	Mixed	Positive	Effective only with coherent pedagogy and access equity
Gamification / PBL / Other Innovative Strategies	Positive	Positive	Positive	Positive	Motivation-driven, but sustainability in large classes uncertain

Table 2 highlights the learning effects associated with different pedagogical approaches across engagement, conceptual understanding, problem-solving, critical thinking, creativity, and autonomy. Learner-centered and 7E Learning Cycle approaches produced consistently positive outcomes in all domains, emphasizing the importance of structured support and active participation. Inquiry-based learning showed strong effects on engagement and reasoning but required substantial scaffolding and time investment. Hands-on learning and flipped classrooms also generated positive results, although their effectiveness depended on reflection opportunities, student preparation, and access to resources. Technology-based approaches yielded mixed outcomes, while gamification and project-based learning strongly enhanced motivation, participation, and autonomy

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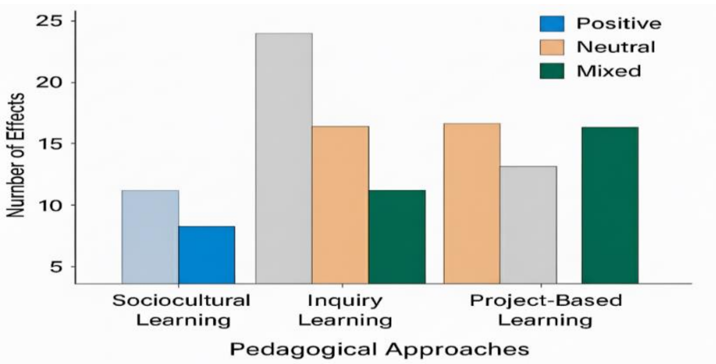
Figure 2: Types of effects across pedagogical approaches



The reported effects varied across pedagogical approaches. Inquiry-based learning showed the highest number of positive outcomes, particularly in student engagement, conceptual understanding, and critical thinking, although some mixed and neutral effects suggest challenges related to implementation, scaffolding, and time constraints. Project-based learning also generated substantial positive results, especially in autonomy and problem-solving, but its effectiveness appeared sensitive to instructional design and classroom management. Sociocultural approaches produced fewer overall effects and a higher proportion of neutral outcomes, indicating the importance of effective teacher mediation and structured interaction. Overall, the findings suggest that successful pedagogical innovation depends on contextual adaptation, clear objectives, and adequate support mechanisms.

Table 3. Factors Contributing to the Effectiveness of Pedagogical Approaches

Facilitating Factor	Description	Frequently Associated Approaches	Studies Referenced
Active Teacher Facilitation	Teachers guiding learning through scaffolding, questioning, and adaptive support	Inquiry-based learning, sociocultural approaches, flipped classroom	Vygotsky (1978), Chi (2009), Joy et al. (2022), Tang (2023)
Use of Technology-Enhanced Environments	Integration of simulations, virtual labs, or flipped content to support engagement and conceptual understanding	Inquiry learning, blended learning, knowledge integration	Linn & Eylon (2011), Kerimbayev et al. (2021), Wang (2023)
Collaborative Learning Structures	Structured group tasks fostering peer interaction and knowledge co-construction	Project-based learning, problem-based learning, gamification	Hmelo-Silver (2004), Sarkar & Chakraborty (2022), Kilag et al. (2022)
Formative Assessment and Feedback	Ongoing assessment and feedback helping students regulate and improve learning	Mastery learning, flipped classroom, formative models	Goksoy (2020), Ertmer & Simons (2006), Wang (2023)
Authentic & Real-World Tasks	Tasks connected to students' lives and societal challenges that promote relevance and motivation	Project-based learning, hands-on learning, problem-solving approaches	Jonassen (2000), Krajcik & Blumenfeld (2006), Bugtai et al. (2020)
Student Autonomy and Ownership	Encouragement of self-direction, decision-making, and creativity in learning processes	Learner-centered pedagogies, creativity-oriented models	Aytaç & Kula (2020), Chi (2009), De Jong (2006)
Institutional and Pedagogical Support	Availability of resources, teacher training, leadership backing, and curricular flexibility	All approaches (as enablers, not techniques)	Haryani et al. (2021), Winarni et al. (2023), Joy et al. (2022)

Several facilitating factors were identified across the reviewed studies. Teacher facilitation, particularly through scaffolding and guided learning, was essential for supporting student engagement and conceptual understanding [4], [16], [10]. Technology-enhanced environments, including simulations and virtual laboratories, improved motivation and learning outcomes when aligned with clear pedagogical objectives [14], [11], [6]. Collaborative learning structures promoted problem-solving and knowledge co-construction, especially in project-based and gamified settings [20], [9]. Formative assessment and authentic real-world tasks further strengthened learning and motivation [19], [2]. Finally, learner autonomy and institutional support emerged as critical conditions for sustaining pedagogical innovation and effective implementation [1], [17], [12].

4. Discussion

Among the 20 studies reviewed, theoretical contributions represented 35% of the corpus, highlighting the strong conceptual foundations that continue to shape science education research, particularly in constructivist learning, problem-solving design, and interactive learning models [1], [4], [15]. This balance between theoretical and empirical research reflects the ongoing effort to strengthen pedagogical frameworks while evaluating their practical application.

The findings indicate that learner-centered and inquiry-based approaches were among the most frequently reported pedagogical models, accounting for a substantial proportion of the selected studies. Consistent with previous research, these approaches were associated with higher levels of student engagement, conceptual understanding, and critical thinking [2], [5]. However, several studies emphasized challenges related to implementation, including the need for scaffolding, teacher expertise, and sufficient instructional time.

Project-based and problem-based learning approaches also showed positive effects on autonomy, motivation, and knowledge integration, although limitations related to large class sizes and institutional constraints were reported [7], [8]. Similarly, technology-enhanced approaches, including flipped classrooms, virtual laboratories, and simulations, contributed positively to motivation and understanding when supported by coherent pedagogical planning [10], [11]. Nevertheless, their effectiveness remained dependent on equitable access to technology and student preparedness [12].

The results further underline the importance of formative assessment and continuous feedback in supporting self-regulation and deeper learning [13], [14]. Authentic learning tasks connected to real-world contexts were also associated with stronger motivation and knowledge transfer [15], [16]. Overall, the reviewed studies suggest that pedagogical innovation is most effective when combined with collaborative learning, learner autonomy, and adequate institutional support [1], [5], [19], [20].

5. Conclusion

This systematic review highlights the importance of active and student-centered pedagogical approaches in science education. Across the reviewed studies, these approaches consistently promoted student engagement, conceptual understanding, autonomy, and higher-order thinking skills [1], [14]. Inquiry-based and discovery-oriented learning also emerged as effective strategies for fostering scientific reasoning, structured exploration, and transferable skills, although their implementation requires adequate scaffolding and teacher preparation [5], [20].

Innovative models such as flipped classrooms, project-based learning, and gamified environments showed promising outcomes in terms of motivation, participation, and problem-solving. Their effectiveness was particularly evident when supported by coherent pedagogical design, appropriate digital infrastructure, and student readiness [2], [11]. Similarly, technology-enhanced learning, including virtual laboratories and simulations, was found to strengthen motivation and interaction when integrated into meaningful instructional frameworks [10], [12].

The review further emphasizes the importance of formative assessment and continuous feedback in supporting self-regulation, metacognitive development, and individualized learning pathways [8], [13]. Authentic learning tasks connected to real-world contexts also contributed to deeper understanding and increased motivation [15], [16]. In addition, collaborative learning environments and opportunities for student autonomy were repeatedly associated with greater engagement and knowledge co-construction [1], [3], [5], [17].

Finally, the successful implementation of these pedagogical approaches depends on broader institutional conditions, including teacher training, leadership support, and access to material and digital resources [2], [19]. Overall, the findings suggest that effective science education relies on the alignment of pedagogy, technology, assessment, and institutional support to foster meaningful and sustainable learning outcomes. Future research should focus on long-term evaluations and context-sensitive implementation strategies to maximize the impact of these innovations across diverse educational settings.

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Vygotsky 1978 Global Theoretical Theoretical Social constructivism Zone of proximal development, mediation

Linn & Eylon 2011 USA Higher education Theoretical Knowledge integration Technology-enhanced learning

Krajcik & Blumenfeld 2006 USA Secondary Theoretical Project-based learning Deep understanding, motivation

Chi 2009 USA Cross-level Theoretical Active/constructive/interactive model Differentiation of learning activities

De Jong 2006 Netherlands Secondary Theoretical Inquiry learning + technology Scientific reasoning

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