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Project-Based Learning in Science Learning: A Literature Review

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ABSTRACT

Project-Based Learning (PjBL) is increasingly recognized as a transformative pedagogical model that addresses the evolving demands of 21st-century science education. This article presents a comprehensive literature-based analysis of the definition, instructional framework, practical implementation, advantages, and challenges of PjBL, particularly in the context of science learning. PjBL emphasizes student-centered, inquiry-driven learning experiences that are grounded in real-world problems, promoting not only academic achievement but also the development of higher-order thinking skills, collaboration, creativity, and scientific literacy. Through a structured instructional syntax involving driving questions, project planning, collaborative execution, presentation, and reflection, PjBL fosters meaningful engagement and active participation among learners. Case studies across educational levels demonstrate its adaptability and effectiveness in enhancing students' scientific reasoning and real-life application. Despite notable challenges such as resource limitations, time constraints, and the need for teacher preparedness, the benefits of PjBL in fostering deep, interdisciplinary learning and student agency are significant. The article concludes by emphasizing the importance of strategic planning, ongoing teacher training, and institutional support to ensure the successful integration of PjBL into science curricula. Overall, PjBL offers a promising pathway for cultivating innovative, reflective, and socially responsible learners capable of addressing complex global challenges.

INTRODUCTION

The rapid transformation of global society in the 21st century necessitates a paradigm shift in education (Indarta et al., 2021). It is no longer sufficient for students to merely acquire factual knowledge; they must also develop a comprehensive set of competencies that enable them to adapt, collaborate, innovate, and solve complex problems (Widiyawati et al., 2021). In response to these global demands, education systems across the world have increasingly emphasized the importance of 21st-century skills, often summarized as the 4Cs: critical thinking, creativity, communication, and collaboration (Wulansari & Sunarya, 2023). This urgency is driven by several factors, including the accelerating pace of technological advancement, the complexity of real-world challenges, and the evolving demands of the workforce (Karomatunnisa et al., 2022).

To address these needs, educational models must transition from traditional, teacher-centered paradigms toward student-centered approaches that foster active learning, interdisciplinary integration, and real-world relevance (Lestari et al., 2024; Susilawati et al., 2022; Sutri et al., 2023). One such model is Project-Based Learning (PjBL), a constructivist approach that engages students in sustained, collaborative inquiry through authentic projects that culminate in the creation of meaningful products or solutions (Thomas, 2000; Larmer, Mergendoller, & Boss, 2015). This method not only deepens students' understanding of subject matter but also nurtures personal responsibility, teamwork, and reflective thinking—preparing them to be active participants in society.

In the Indonesian context, the relevance of PjBL is further reinforced by national curriculum reforms aligned with global education agendas such as the Sustainable Development Goals (SDGs), particularly Goal 4 on Quality Education. The Merdeka Curriculum promotes the development of graduate profiles that encompass cognitive, personal, and interpersonal competencies. PjBL directly supports this vision by fostering critical and creative thinking, collaboration, and the ability to apply knowledge to real-life contexts (Vaca-Cárdenas et al., 2022; Espino-Díaz et al., 2025). Within science education (IPA), the model is particularly well-suited, as it enables students to engage with scientific concepts through experimentation, inquiry, and the design of solutions to real-world problems.

Evidence from empirical studies supports the effectiveness of PjBL in enhancing scientific literacy and higher-order thinking skills. For instance, Pérez-López et al. (2021) found that students who engage in PjBL show significant improvements in analysis, evaluation, and synthesis—skills that are essential for navigating scientific and societal challenges. Additionally, PjBL promotes character education by embedding values such as empathy, resilience, ethical reasoning, and responsibility within the collaborative learning process. These outcomes illustrate the model's potential to support holistic student development across cognitive, affective, and social dimensions (Kokotsaki, Menzies, & Wiggins, 2016).

Despite its advantages, the implementation of PjBL is not without challenges. Successful application requires well-prepared teachers, adequate resources, flexible scheduling, and assessment strategies that align with the interdisciplinary and process-oriented nature of project work. Schools must also provide institutional support to encourage innovation and foster a culture that values inquiry and experimentation. However, numerous studies have shown that when these conditions are met, PjBL can transform classrooms into dynamic environments where students construct knowledge actively, collaborate meaningfully, and engage with real-world contexts.

Empirical findings further affirm the transformative potential of PjBL. Espino-Díaz et al. (2025) reported that university students involved in PjBL developed a stronger understanding of the SDGs and demonstrated increased motivation to apply sustainable practices in both academic and personal spheres. Similarly, Vaca-Cárdenas et al. (2022) found that PjBL fosters student engagement and a greater sense of ownership over learning, contributing to improved academic performance and overall satisfaction.

Given these insights, this paper aims to explore Project-Based Learning comprehensively, particularly in the context of science education. It seeks to answer the following research questions: (1) What are the defining features of PjBL? (2) How is PjBL implemented effectively in science classrooms? (3) What examples of implementation exist across different educational levels? and (4) What are the strengths and challenges associated with adopting PjBL? By systematically addressing these questions, the study intends to provide educators, curriculum developers, and policymakers with a practical and evidence-based framework for integrating PjBL into science instruction in ways that are relevant, sustainable, and responsive to the needs of 21st-century learners.

METHODS

This study employed a literature review approach to examine the theoretical foundation, core characteristics, instructional procedures, and practical implementation of Project-Based Learning (PjBL) in science education. The purpose of the review is to synthesize key insights from relevant academic sources in order to provide a comprehensive understanding of PjBL and its applicability in 21st-century science classrooms.

The review focused on scholarly articles, books, policy documents, and educational reports that specifically discuss the design and implementation of PjBL in the context of science instruction across various educational levels. The selection of literature was guided by the relevance of each source to the main themes of this study, including project-based pedagogy, inquiry learning, science education, and 21st-century skills development. Key references include foundational works such as Thomas (2000), Larmer et al. (2015), and more recent empirical studies like Kokotsaki et al. (2016), Pérez-López et al. (2021), Hasanah et al. (2023), and Espino-Díaz et al. (2025).

The data sources were obtained through manual and electronic searches using keywords such as "Project-Based Learning," "science education," "PjBL implementation," "critical thinking," and "STEM learning." Articles and documents published between 2000 and 2024 were considered, with preference given to peer-reviewed publications. The reviewed materials were analyzed qualitatively, focusing on patterns, themes, and concepts that consistently emerged across multiple studies.

The review was structured to explore five main aspects of PjBL: (1) its definition and distinguishing features, (2) instructional syntax or procedural framework, (3) examples of classroom implementation across different educational stages, (4) its strengths and potential drawbacks, and (5) recommendations for effective application in science instruction. Through this process, the study aimed to highlight the pedagogical value of PjBL as well as the contextual factors that influence its effectiveness.

As this research is based entirely on secondary data, no ethical clearance was required. However, all referenced works were properly cited to ensure academic integrity. Overall, the literature review approach enabled the researcher to develop a critical and evidence-based perspective on how PjBL can support meaningful, contextualized, and skill-oriented science learning in the 21st century.

RESULTS AND DISCUSSION

Definition and Characteristics of Project-Based Learning (PjBL)

Project-Based Learning (PjBL) is widely recognized as an instructional model that places students at the center of the learning process by engaging them in complex, real-world projects over an extended period of time (Purnami & Widiadnya, 2024; Valls Pou et al., 2022; Wang & Zhang, 2025). It is grounded in the constructivist paradigm, which views learning as an active, contextualized process of constructing knowledge rather than acquiring it passively. PjBL emphasizes inquiry, investigation, collaboration, and the production of meaningful outcomes, making it a powerful pedagogical tool for cultivating 21st-century competencies (Thomas, 2000; Larmer, Mergendoller, & Boss, 2015).

According to the Buck Institute for Education (BIE), PjBL is defined as a teaching method in which students learn by actively exploring real-world problems and challenges, leading to the creation of public products or presentations. In this model, learning begins with a "driving question"—a meaningful, open-ended problem that guides students' inquiry and encourages deeper engagement. Rather than following a linear path of instruction, students are encouraged to research, discuss, hypothesize, test, revise, and reflect throughout the duration of the project (PBLWorks, 2023).

The defining characteristics of PjBL distinguish it from traditional or task-based approaches. First and foremost, PjBL is anchored in authentic problems or challenges that have real-life relevance. These challenges are not contrived but rooted in students' environments or communities, prompting them to see learning as purposeful and socially valuable (Stanley, 2021; British School Barcelona, 2024). Projects such as creating water filtration systems, solar-powered devices, or community awareness campaigns require students to apply interdisciplinary knowledge while developing a sense of responsibility toward societal issues.

Second, PjBL is inherently student-centered and inquiry-driven. It shifts the role of the teacher from being a transmitter of knowledge to a facilitator of learning. Students take ownership of their projects by asking questions, gathering and analyzing data, and formulating solutions. This pedagogical shift fosters autonomy, self-regulation, and motivation—key traits for lifelong learning (Guo, 2020; Hasanah et al., 2023). Teachers scaffold the process through strategic guidance, timely feedback, and the provision of resources, while students explore diverse pathways to arrive at creative, evidence-based outcomes.

Third, PjBL is characterized by collaborative learning**.** Projects are typically carried out in small groups where students assume various roles, such as researcher, designer, recorder, or presenter. Collaboration promotes peer learning, perspective-taking, conflict resolution, and the development of interpersonal skills. Research has shown that students engaged in collaborative PjBL settings demonstrate higher levels of engagement and problem-solving abilities compared to those in traditional classrooms (Fitri et al., 2024).

Fourth, an essential feature of PjBL is the creation of tangible products. These may include models, prototypes, reports, multimedia presentations, or performances that reflect students' learning processes and solutions to the driving question. The product must be presented to an audience beyond the classroom, whether in the form of peer presentations, school exhibitions, or community events. This public dimension enhances the authenticity of the task and instills a sense of accountability and pride in learners (Larmer et al., 2015; Krajcik & Blumenfeld, 2006).

Fifth, authentic assessment is integral to PjBL. Assessment is not limited to summative evaluation of the final product, but includes formative assessments of the learning process, student collaboration, and reflection. Teachers use rubrics, peer assessments, self-evaluations, and performance-based tools to gauge the development of both content mastery and soft skills. This continuous feedback loop supports students' metacognitive awareness and helps them improve their strategies and work over time (Cahyono et al., 2023; Chistyakov et al., 2021).

Another vital characteristic is the interdisciplinary nature of PjBL. Projects often require students to integrate knowledge and methods from various disciplines—science, mathematics, language, arts, and social studies—to devise comprehensive solutions. This mirrors real-world problem solving, which rarely falls within the bounds of a single subject area, and prepares students to navigate complex systems and relationships (Chen & Tippett, 2022; Kim & Kim, 2021).

Furthermore, PjBL involves extended inquiry, meaning that students engage in sustained investigation over days or weeks. Rather than seeking immediate answers, students collect data, test hypotheses, interpret results, and iterate on their ideas. This process nurtures scientific habits of mind, such as curiosity, skepticism, perseverance, and critical thinking. It also encourages students to embrace mistakes and failures as part of the learning journey, a mindset crucial for innovation and resilience (Guo, 2020; Trianto, 2014).

Finally, PjBL fosters a classroom culture of exploration, dialogue, and reflection. It promotes psychological safety, where students feel comfortable experimenting, expressing ideas, and challenging assumptions. Teachers cultivate this environment by encouraging diverse perspectives, facilitating meaningful discussions, and modeling reflective practice. The result is a dynamic, student-centered classroom that values process as much as product.

In sum, Project-Based Learning is more than a collection of projects—it is a structured pedagogical model that supports deep learning through authentic inquiry, collaboration, and the creation of meaningful work. Its defining features align closely with the demands of 21st-century education and have been validated across multiple educational contexts. When effectively implemented, PjBL enables students not only to learn scientific content but also to develop the cognitive, personal, and social competencies necessary for success in an ever-evolving world.

Instructional Syntax of Project-Based Learning (PjBL)

The implementation of Project-Based Learning (PjBL) requires a clearly defined instructional syntax to ensure that learning experiences are structured, meaningful, and aligned with intended learning outcomes. Unlike conventional methods that often follow a teacher-led sequence of content delivery, PjBL adopts a flexible yet systematic approach where learning emerges through the resolution of real-world challenges. The instructional syntax of PjBL typically consists of six interrelated phases: (1) driving question formulation, (2) project planning, (3) timeline development, (4) collaborative execution, (5) public presentation, and (6) reflection and evaluation. Each phase plays a pivotal role in promoting deep learning and competency development, particularly within the context of science education.

1. Formulating a Driving Question

At the heart of PjBL lies the *driving question*—a meaningful, open-ended problem that stimulates curiosity, inquiry, and sustained engagement. The question must be rooted in real-world contexts and aligned with curricular goals. It should be challenging enough to require investigation but accessible enough for students to explore meaningfully with guidance. For example, in a science classroom, a driving question such as *"How can we produce clean drinking water using everyday materials?"* can spark a project on water purification, integrating concepts from environmental science, chemistry, and engineering.

Formulating the driving question is often a collaborative process between teachers and students. When students are involved in identifying or refining the question, their sense of ownership and intrinsic motivation increases. The teacher's role at this stage is to scaffold the questioning process—guiding students toward questions that are both personally relevant and pedagogically rich (Arifianti, 2022; Krajcik & Blumenfeld, 2006).

2. Designing the Project Plan

Once the driving question is established, the next phase involves developing a comprehensive project plan. This includes identifying the learning objectives, determining the expected outputs or products, outlining roles within student teams, selecting tools and materials, and establishing criteria for success. Teachers facilitate this planning by co-constructing project guidelines with students, providing models of high-quality work, and aligning project activities with the learning standards of the subject.

For example, in a project on renewable energy, students might design a model solar car. Planning would entail defining technical specifications, assigning roles such as designer, engineer, researcher, and presenter, and outlining the process of material collection, assembly, testing, and documentation. A well-structured project plan helps students develop organizational and goal-setting skills, while also giving the teacher a framework for formative assessment and monitoring (Thomas, 2000; Helle et al., 2006).

Tabel 1. Project-Based Learning (PjBL) – Steps Summary

Stage Name	What Happens	Example
Ask a Big Question	Teacher and students create an open, real-life question to explore.	"How to turn on a light without using PLN electricity?"
Plan the Project	Make a plan: goals, steps, tools, group roles, and success rules.	Solar system model made from recycled materials.
Make a Schedule	Set a clear timeline for each activity in the project.	Day 1–2: plan, Day 3–5: make, Day 6–7: present, Day 8: reflect.
Do the Project in Groups	Students work together. Teacher guides and helps when needed.	Group tests potato batteries to light a small lamp.
Present the Work	Students show results and explain their process, problems, and solutions.	Show compost project with posters, videos, and talk.
Reflect and Review	Students think about what they learned. Teacher gives feedback.	Write a journal, do group talk, fill a short form.

3. Creating a Timeline

Project work requires sustained effort over time; therefore, developing a timeline is crucial for effective implementation. Students, with teacher guidance, create schedules that break down tasks into manageable segments across days or weeks. The timeline fosters accountability, time management, and project tracking. It also helps prevent procrastination and uneven workload distribution within teams.

Tools such as Gantt charts, Trello boards, or simple visual calendars can be used to visualize the workflow. For younger students or beginner-level learners, teachers may provide a pre-structured timeline. More advanced students, especially at the secondary and tertiary levels, are encouraged to design their own project schedules, allowing for the development of self-regulated learning skills (Bell, 2010; Kemdikbud, 2017).

4. Implementing the Project Collaboratively

The execution phase is the most active and dynamic part of the PjBL cycle. Here, students engage in research, experimentation, design, construction, and problem-solving activities based on their project plans. Collaboration is emphasized throughout this stage, with team members assuming defined roles and responsibilities. Teachers serve as facilitators and mentors, providing support through feedback, posing guiding questions, and offering resources as needed.

For instance, in a science project involving the creation of bioplastics from cassava starch, students would investigate chemical properties, test material samples, adjust mixtures based on results, and record observations. This phase integrates scientific process skills with teamwork, adaptability, and resilience. Teachers also observe group dynamics and individual participation to inform ongoing assessment (Hasanah et al., 2023; Stanley, 2021).

Throughout this stage, the learning environment should encourage experimentation, iteration, and risk-taking. Mistakes and setbacks are viewed not as failures but as learning opportunities. This fosters a growth mindset and strengthens students' confidence in navigating uncertainty—an essential skill for scientific inquiry and real-world problem solving.

5. Presenting the Project Outcome

An integral feature of PjBL is the requirement for students to publicly share their final product or findings. The presentation phase is both a culmination and celebration of the learning journey. It may take the form of a live demonstration, poster session, oral presentation, video documentary, or digital showcase, depending on the nature of the project.

Presenting to an authentic audience—peers, teachers, parents, or community stakeholders—enhances the meaningfulness of the work and motivates students to uphold high standards of quality and communication. It also fosters critical soft skills such as public speaking, persuasion, and visual storytelling. In science education, this could involve explaining an experimental design, discussing variables and results, and proposing improvements for future iterations.

Teachers assess the final product using rubrics that evaluate both content mastery and 21st-century competencies. Peer assessments and audience feedback can also be incorporated to enrich the evaluation process and promote reflective dialogue (Larmer et al., 2015; Cahyono et al., 2023).

6. Reflecting and Evaluating the Learning Process

The final phase of PjBL involves reflection—both individual and collective—on the learning experience. Students are guided to think critically about their performance, team collaboration, the challenges they faced, the solutions they discovered, and the knowledge they constructed. Reflection helps consolidate learning, identify areas for improvement, and internalize the value of the experience.

Reflection activities may include journaling, group discussions, self-assessment checklists, or multimedia reflections. Teachers facilitate this metacognitive process by prompting students with targeted questions such as: *What did you learn about the scientific method? How did your team overcome obstacles? What would you do differently next time?*

Additionally, teachers evaluate the learning outcomes holistically—considering not only the final product but also the process, effort, problem-solving strategies, and student growth. This comprehensive evaluation ensures that assessment reflects the richness and complexity of the PjBL experience (Helle et al., 2006; Kokotsaki et al., 2016).

Practical Implementation of PjBL in Science Education

The application of Project-Based Learning (PjBL) in science education has garnered considerable attention due to its capacity to bridge the gap between theoretical knowledge and real-world application. Through hands-on projects, students are empowered to explore scientific concepts in depth, fostering both conceptual understanding and practical competence. The successful implementation of PjBL in science classrooms, however, requires careful alignment with cognitive development stages, subject content, contextual relevance, and available resources. This section elaborates on how PjBL is practically implemented across various educational levels—primary, secondary, and tertiary—highlighting project examples, instructional strategies, and developmental considerations.

At the primary school level, students are typically at the concrete-operational stage of cognitive development, as identified by Piaget. This stage emphasizes learning through physical interaction with objects and observable phenomena. Thus, science projects at this level must be highly experiential, contextual, and simplified without sacrificing scientific integrity. For instance, a project such as *"How can we light up a bulb without using electricity from the grid?"* introduces the concept of energy conversion. Students engage in building simple solar-powered lamps using recycled plastic bottles, miniature solar panels, and LED lights. The project begins with exploration of the sun as an energy source, followed by guided experimentation and collaborative construction. Teachers provide structured templates for project planning and direct support during execution, while assessment focuses on participation, creativity, and explanation of scientific ideas in age-appropriate language.

In this context, PjBL encourages young learners to connect science with daily life, making abstract concepts tangible. Additionally, character development is integrated naturally as students collaborate, share responsibilities, and reflect on their contributions. Reflection may be facilitated through storytelling, drawing, or group discussions, allowing students to express what they have learned and how they felt during the process. The goal is to cultivate not only scientific literacy but also a sense of curiosity and confidence in experimenting with ideas.

Moving to the secondary education level (middle and high school), students are transitioning into or already capable of abstract reasoning and systematic problem-solving. At this stage, PjBL can accommodate more complex scientific inquiries and technical tasks. Projects may involve experimental design, data collection, analysis, and model construction. A common example is a project on *water purification systems*, framed by the driving question: *"How can we purify dirty water using natural and recyclable materials?"* Students conduct research on filtration methods, build prototype filters using sand, charcoal, and gravel, test water clarity and pH levels, and analyze results.

Table 2. Differences in PjBL Implementation by Education Level

Aspect	Elementary School	Middle School	High School	University Level
Cognitive Level	Concrete-operational	Transitioning to abstract thinking	Abstract and logical reasoning	Critical, analytical, and scientific thinking
Project Complexity	Simple, visual, hands-on activities	Moderate, beginning scientific experiments	High, involving technical design and testing	Very high, focused on innovative research
Final Product	Simple models, drawings, stories	Basic tools, short reports	Technical prototypes, scientific reports	Published projects, academic papers
Student Autonomy	Highly teacher-dependent	Beginning to work independently in groups	Independent with teacher supervision	Fully independent with academic supervision
Teacher Role	Full facilitator, activity leader	Facilitator and discussion guide	Supervisor and evaluator	Research mentor and scientific advisor
Assessment	Observation, physical work, storytelling	Group reports, tangible products	Project rubric, tool testing, presentations	Academic writing, research reports, seminars

The implementation involves interdisciplinary integration of chemistry, environmental science, and engineering concepts. Teachers facilitate brainstorming sessions, guide hypothesis formulation, and support the development of testable procedures. Rubrics are employed to assess collaboration, scientific method application, accuracy of measurements, and the functionality of the designed filter. Peer feedback and public presentation sessions are essential to reinforce communication and critical evaluation skills.

Another exemplary project at this level is the creation of bioplastics from starch-based materials, such as cassava or corn. The project begins with the problem statement: *"What sustainable alternatives can replace conventional plastics?"* Students examine the environmental impact of plastic waste, conduct literature reviews, and engage in laboratory-based experimentation to produce bioplastics. They manipulate variables such as starch concentration and glycerol content, evaluate flexibility and decomposition rate, and present findings through reports and exhibitions. This project not only enhances understanding of polymer chemistry and material science but also instills environmental awareness and scientific reporting skills.

At the tertiary or university level, students are expected to operate independently, applying scientific knowledge and research skills to solve real-world challenges. PjBL in higher education often mimics professional practice, involving extensive inquiry, critical review of existing literature, rigorous experimentation, and dissemination of results through academic formats. A common project in science education departments, for example, might explore the development of renewable energy prototypes, such as mini wind turbines or solar thermal collectors. Students begin with the question: *"How can we develop efficient renewable energy systems using locally available materials?"* They engage in engineering design cycles, CAD modeling, simulation, physical prototyping, and field testing.

In this context, students are responsible for all phases of the project, from problem identification and proposal writing to execution, evaluation, and publication. Supervisors act as research mentors, and project outcomes are often assessed through seminars, scientific posters, and research papers. The use of peer-reviewed literature, data analysis software, and laboratory instrumentation becomes integral to the process. Moreover, students are trained to reflect critically on the limitations of their designs and suggest improvements for real-world scalability. This level of PjBL fosters higher-order thinking, scientific innovation, and readiness for postgraduate or professional research roles.

To support implementation across all levels, educators must differentiate their scaffolding strategies based on student readiness and learning objectives. In lower levels, scaffolding includes visual aids, sentence starters, structured group roles, and guided worksheets. In upper levels, scaffolding evolves into research mentorship, feedback on drafts, and peer-review systems. Regardless of level, formative feedback and metacognitive reflection remain critical components for maximizing learning outcomes.

In addition, collaborative learning environments are key to sustaining motivation and equitable participation. Teachers must carefully design group dynamics, assign rotating roles, and utilize tools such as group contracts and logs to manage accountability. Technology also plays a supportive role; platforms like Padlet, Google Classroom, or Trello can help coordinate timelines, resources, and documentation.

In conclusion, the practical implementation of PjBL in science education requires thoughtful adaptation to the developmental stage of learners, alignment with curricular standards, and integration of authentic contexts. By engaging students in meaningful scientific inquiries that culminate in tangible outcomes, PjBL transforms classrooms into active learning environments where scientific concepts are not only learned but lived. When executed effectively, PjBL fosters scientific literacy, critical thinking, collaboration, and lifelong learning—qualities essential for navigating the complexities of the 21st-century world.

Advantages and Challenges of Project-Based Learning (PjBL)

Project-Based Learning (PjBL) has gained increasing recognition in contemporary education due to its capacity to foster deep, meaningful, and contextualized learning. Particularly in science education, PjBL serves as a transformative pedagogical approach that moves beyond rote memorization and passive knowledge transmission toward active inquiry, collaboration, and creation. However, as with any instructional model, PjBL presents both significant advantages and notable challenges. Understanding these aspects is essential for educators, curriculum designers, and policymakers aiming to implement PjBL effectively and sustainably.

Advantages of PjBL

One of the most prominent advantages of PjBL is its capacity to promote higher-order thinking skills (HOTS). Unlike traditional instruction that often emphasizes lower-level cognitive tasks such as recalling and understanding, PjBL tasks require students to analyze complex problems, synthesize diverse information, evaluate evidence, and create innovative solutions. These cognitive processes are fundamental to scientific reasoning and are directly aligned with Bloom's taxonomy at its upper levels (Bell, 2010; Rumahlatu & Sangur, 2019). For instance, in a project focused on water filtration, students not only learn about filtration methods but also test different materials, interpret results, and justify design choices—activities that inherently require analysis and evaluation.

PjBL also enhances student motivation and engagement. When students perceive learning as relevant and meaningful, their intrinsic motivation increases. The opportunity to solve real-life problems, make decisions, and produce tangible outcomes fosters a sense of purpose and ownership over the learning process (Kokotsaki et al., 2016). Students are more likely to persist through challenges and remain engaged in complex tasks when they see the direct application of their efforts to real-world contexts.

Another advantage lies in the development of 21st-century skills, including communication, collaboration, creativity, and digital literacy. Through group-based projects, students practice sharing ideas, negotiating roles, resolving conflicts, and presenting their findings to diverse audiences. These experiences prepare them for the collaborative environments of the modern workforce. In addition, the use of technology in researching, designing, and presenting projects helps students become more proficient in digital tools and platforms—a key component of scientific literacy in the digital age (Chen et al., 2020; Hasanah et al., 2023).

Moreover, PjBL supports the development of self-regulated learning (SRL). As students take responsibility for planning, managing, and evaluating their learning process, they build metacognitive awareness, time management, and goal-setting strategies. These skills are essential for lifelong learning and academic autonomy, particularly in science disciplines where independent inquiry is central to success (Barak, 2012; Kokotsaki et al., 2016). In science classrooms, self-regulated learners are better equipped to design experiments, reflect on error sources, and revise hypotheses based on evidence.

Importantly, PjBL cultivates character education and social-emotional competencies. As students engage in extended teamwork, they develop empathy, accountability, perseverance, and ethical reasoning. Teachers report that students become more reflective, respectful of diverse perspectives, and committed to shared goals during project work. These affective outcomes are integral to the holistic development of learners and align with national education goals focused on moral and civic education.

Challenges of PjBL

Despite its many benefits, PjBL also presents several implementation challenges. One of the most common is the time-intensive nature of project work. Designing, executing, and assessing comprehensive projects often requires more instructional time than traditional lectures. This can lead to difficulties in covering all required curriculum content, particularly in rigid or high-stakes testing environments (Trianto, 2014; Sunismi et al., 2022). Teachers may feel pressured to prioritize breadth over depth, which can compromise the integrity of the project and its learning outcomes.

Another major challenge is the need for adequate resources and infrastructure.

Effective PjBL often requires materials, tools, technology, and flexible learning spaces that may not be readily available, especially in under-resourced schools. Science projects involving experiments, prototypes, or engineering designs require specific equipment and safety provisions. To address this, teachers are encouraged to design low-cost projects using recyclable materials and collaborate with external partners such as universities, NGOs, or industry sponsors to gain support (Alfi & Wibangga, 2023; Kemdikbud, 2017).

Table 3. Challenges of Project-Based Learning (PjBL) and Strategies for Overcoming Them

Challenges	Solution
Time-consuming compared to conventional methods (Trianto, 2014; Sunismi et al., 2022)	Choose relevant topics, integrate into regular/extracurricular lessons, design a flexible timeline
Higher material costs (Sunismi et al., 2022; Alfi & Wibangga, 2023)	Use recycled/local materials, seek grants/CSR support, partner with external organizations
Passive group participation (Sari, 2022; Sari & Yuliana, 2023)	Assign roles clearly, use individual logs and peer assessments
Difficulty with self-directed inquiry (Sumarni & Kadarwati, 2020)	Provide scaffolding, examples, and guided worksheets
Challenging to monitor large classes (Kemdikbud, 2017)	Use rubrics, staged evaluations, digital tools, and co-facilitators
Not all topics suit PjBL (Trianto, 2014)	Blend with lectures/simulations; select practical, hands-on topics
Limited teacher readiness (Sari, 2022)	Offer training, share sample modules, build teacher communities
Group conflicts due to social/gender issues (Crossouard, 2012)	Form diverse groups, promote inclusion, rotate roles
Limited rigorous research (Kokotsaki et al., 2016)	Encourage collaboration, triangulation, and longitudinal studies

A third challenge involves managing group dynamics. Not all students contribute equally to group work, and disparities in participation can lead to resentment or disengagement. Without proper structures in place—such as defined roles, rotating leadership, and peer assessment—dominant students may overshadow others, while less confident students may withdraw. Teachers need to actively monitor group processes and provide guidance to ensure equitable involvement. Tools like team contracts, individual reflection logs, and structured peer feedback can help foster accountability and fair contribution (Sari & Yuliana, 2023).

Additionally, many students initially struggle with open-ended inquiry and decision-making. Accustomed to being directed by teachers, they may feel overwhelmed by the autonomy and ambiguity inherent in PjBL. This is especially true for learners with limited prior experience in inquiry-based learning. To mitigate this, teachers must provide scaffolding—progressive support that includes guiding questions, sample templates, checklists, and modeling of investigative thinking. As students grow more confident, this scaffolding can be gradually reduced, promoting independence (Sumarni & Kadarwati, 2020).

Another concern is the challenge of assessment. Evaluating project work fairly and comprehensively requires multifaceted assessment tools that capture both process and product. Teachers must assess not only the final outcome but also collaboration, creativity, problem-solving, and reflection. Designing such assessments and providing timely, individualized feedback can be demanding, especially with large class sizes. Rubrics, formative check-ins, and student-led evaluations are essential tools to streamline the process and enhance transparency (Helle et al., 2006; Cahyono et al., 2023).

Lastly, teacher preparedness remains a critical barrier. Implementing PjBL effectively demands a shift in mindset, planning skills, interdisciplinary knowledge, and facilitation competencies. Teachers unfamiliar with the model may revert to traditional instruction or misinterpret PjBL as merely assigning projects without inquiry depth. This underscores the need for sustained professional development, access to exemplar materials, and a supportive school culture that values innovation and experimentation (Sari, 2022; Kokotsaki et al., 2016).

CONCLUSION AND SUGGESTION

Project-Based Learning (PjBL) emerges as a powerful pedagogical model that aligns with the vision of 21st-century science education—fostering critical thinking, creativity, collaboration, communication, and deep conceptual understanding. As demonstrated through the literature, PjBL provides students with authentic learning experiences by engaging them in real-world problem solving, interdisciplinary integration, and reflective inquiry. It transforms the role of learners from passive recipients of knowledge into active investigators and creators, thereby bridging the gap between academic content and its practical application in everyday life. The model's structured yet flexible instructional syntax—from formulating driving questions to reflecting on outcomes—ensures that learning processes are coherent, student-centered, and outcomes-oriented. Practical implementations across educational levels—from elementary schools to higher education—show that PjBL is highly adaptable, scalable, and relevant for diverse learners. In science education specifically, PjBL enhances not only content mastery but also scientific literacy, environmental awareness, and self-regulated learning. Students gain essential process skills such as designing experiments, analyzing data, presenting findings, and revising based on feedback. Furthermore, PjBL promotes the development of social-emotional competencies, including teamwork, empathy, resilience, and responsibility. However, despite its pedagogical strengths, implementing PjBL effectively requires careful attention to contextual challenges. Time constraints, lack of materials, uneven group participation, and limited teacher training can hinder its impact. These challenges necessitate supportive school policies, resource flexibility, and sustained professional development for educators. Teachers must be equipped not only with technical knowledge but also with the facilitation skills to guide inquiry, manage group dynamics, and assess learning holistically. Thus, for PjBL to be sustainable and impactful, collaboration among educators, administrators, parents, and the wider community is essential. In conclusion, Project-Based Learning should be regarded not merely as an instructional alternative, but as a central strategy in reforming science education to prepare learners who are not only knowledgeable but also capable, reflective, and socially responsible. With the right scaffolding, resources, and mindset, PjBL holds transformative potential to cultivate a generation of learners equipped to thrive in a complex, rapidly changing world.

AUTHOR CONTRIBUTIONS

T.M.A.Q. and W.K. contributed equally to the conception, literature review, and writing of the manuscript. They collaboratively developed the structure, synthesized the findings, and revised the content for academic clarity and coherence. J.R acted as the academic supervisor, providing overall guidance, critical feedback, and ensuring the quality and integrity of the final manuscript. All authors have read and approved the final version of the manuscript.

REFERENCES

Arifianti, U. (2022). Project based learning dalam pembelajaran IPA. *SHES: Journal of Education and Social Sciences*, *3*(2), 105–113.

Bell, S. (2010). *Project-Based Learning* for the 21st century: Skills for the future. *The Clearing House*, *83*(2), 39–43. https://doi.org/10.1080/00098650903505415

British School Barcelona. (2024). *Project-Based Learning: What is, benefits and examples*. https://www.britishschoolbarcelona.com/blog/project-based-learning-benefits-and-examples/

Chen, Y., Wang, Y., & Chen, N.-S. (2020). Deep learning in science, technology, engineering and mathematics (STEM) education: A systematic review. *British Journal of Educational Technology, 51*(6), 1823–1843. https://doi.org/10.1111/bjet.12956

Chistyakov, S. V., Karpov, A. O., & Khayrullina, A. S. (2021). Exploring the characteristics and effectiveness of Project-Based Learning for science and STEAM education. *Eurasia Journal of Mathematics, Science and Technology Education, 17*(7), em1982. https://doi.org/10.29333/ejmste/10928

Espino-Díaz, L., Fernandez-Caminero, G., Sañudo, B., & Hernández-Lloret, C. M. (2025). Education for sustainable development and the role of the university: Project-based learning as a strategy to enhance the social responsibility of engineering students. *Sustainability, 17*(1), 1–20.

Fitri, R., Lufri, L., Alberida, H., Amran, A., & Fachry, R. (2024). The Project-Based Learning model and its contribution to student creativity: A review. *Jurnal Pendidikan Biologi Indonesia, 10*(1), 1–14. https://doi.org/10.22219/jpbi.v10i1.31499

Guo, P. (2020). A review of Project-Based Learning in higher education. *Education Research Review, 31*, 100748. https://doi.org/10.1016/j.edurev.2020.100748

Hasanah, U., Widiastuti, I., & Sari, N. (2023). Project-Based Learning in science education: A comprehensive literature review. *International Journal of Education in Science and Engineering,* *7*(1), 1–16. https://www.ijese.com/article/project-based-learning-in-science-education-a-comprehensive-literature-review-13677

Indarta, Y., Jalinus, N., Abdullah, R., & Samala, A. D. (2021). 21st Century Skills : TVET dan Tantangan Abad 21. *EDUKATIF: JURNAL ILMU PENDIDIKAN*, *3*(6), 4340–4348. https://doi.org/10.31004/edukatif.v3i6.1458

Karomatunnisa, A.-Z. A., Sholih, J. A. U., Hanifah, N., & Prihantini, P. (2022). META ANALISIS MODEL PEMBELAJARAN PROJECT BASED LEARNING DALAM MENINGKATKAN KEMAMPUAN KETERAMPILAN ABAD 21. *Jurnal Pendidikan Sosiologi Dan Humaniora*, *13*(2), 522–528. https://doi.org/10.26418/j-psh.v13i2.54755

Kokotsaki, D., Menzies, V., & Wiggins, A. (2016). Project-Based Learning: A review of the literature. *Improving Schools, 19*(3), 267–277. https://doi.org/10.1177/1365480216659733

Krajcik, J. S., & Blumenfeld, P. C. (2006). Project-Based Learning. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 317–334). Cambridge University Press.

Larmer, J., Mergendoller, J. R., & Boss, S. (2015). *Setting the standard for project based learning: A proven approach to rigorous classroom instruction.* ASCD.

Lestari, D., Doyan, A., Taufik, M., & Rahayu, S. (2024). The Influence of the Project Based Learning Model Assisted by PhET Simulations on Students' Generic Science Skills in Energy Source Materials. *Jurnal Penelitian Pendidikan IPA*, *10*(SpecialIssue), 659–666. https://doi.org/10.29303/jppipa.v10iSpecialIssue.8410

PBLWorks. (2023). What is project based learning? Retrieved from https://www.pblworks.org/what-is-pbl

Pérez-López, D., Cano-Hila, A. B., & García-Sanz-Calcedo, J. (2021). Project-Based Learning in engineering education: A bibliometric analysis. *Education Sciences, 11*(10), 603. https://doi.org/10.3390/educsci11100603

Purnami, I. A. O., & Widiadnya, I. G. N. B. Y. (2024). The Role of Project-Based Learning in Boosting Student Communication Confidence. *Jurnal Pendidikan Bahasa Inggris Undiksha*, *12*(3), 334–341. https://doi.org/10.23887/jpbi.v12i3.91586

Stanley, T. (2021). Project-Based Learning in the 21st century. *International Journal of Instruction, 14*(2), 327–340. https://doi.org/10.29333/iji.2021.14219a

Susilawati, S., Doyan, A., Mulyadi, L., Abo, C. P., & Pineda, C. I. S. (2022). The Effectiveness of Modern Physics Learning Tools Using the PhET Virtual Media Assisted Inquiry Model in Improving Cognitive Learning Outcomes, Science Process Skills, and Scientific Creativity of Prospective Teacher Students. *Jurnal Penelitian Pendidikan IPA*, *8*(1), 291–295. https://doi.org/10.29303/jppipa.v8i1.1304

Sutri, N., Azhar, & Islami, N. (2023). Improve the Motivation and Science Process Skills through the Application of the ARIAS Learning Model Assisted by PhET. *Jurnal Penelitian Pendidikan IPA*, *9*(11), 9810–9817. https://doi.org/10.29303/jppipa.v9i11.5024

Thomas, J. W. (2000). *A review of research on Project-Based Learning.* The Autodesk Foundation.

Trianto. (2014). *Model pembelajaran inovatif-berorientasi konstruktivistik.* Prestasi Pustaka.

Vaca-Cárdenas, L. A., Moreno, M. V., & Cevallos, J. (2022). Project-Based Learning in higher education: A systematic literature review. *Education Sciences, 12*(6), 404. https://doi.org/10.3390/educsci12060404

Valls Pou, A., Canaleta, X., & Fonseca, D. (2022). Computational Thinking and Educational Robotics Integrated into Project-Based Learning. *Sensors*, *22*(10), 3746. https://doi.org/10.3390/s22103746

Wang, L., & Zhang, C. (2025). The Role of Cognitive Abilities in Project-Based Teaching: A Mixed Methods Study. *Behavioral Sciences*, *15*(3), 299. https://doi.org/10.3390/bs15030299

Widiyawati, Y., Nurwahidah, I., Sari, D. S., Masykuri, M., & Budiyanto, C. W. (2021). The 21 st century science learning: HOTS and digital literacy among junior high school students in Semarang, Indonesia. *Journal of Physics: Conference Series*, *1842*(1). https://doi.org/10.1088/1742-6596/1842/1/012081

Wulansari, K., & Sunarya, Y. (2023). Keterampilan 4c (Critical Thinking, Creativity, Communication, dan Collaborative) Guru Bahasa Indonesia Sma dalam Pembelajaran Abad 21 di Era Industri 4.0. *Jurnal Basicedu*, *7*(3), 1667–1674. https://doi.org/10.31004/basicedu.v7i3.5360

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