Journal of Innovative Technology and Sustainability Education
Homepage : https://journal.i-ros.org/index.php/JITSE
Email : jitse@i-ros.org

e-ISSN 3109-2454
Vol. 2, No. 1, April 2026

Digital Learning Factory for Developing 21st-Century Competencies in Physics Teacher Education toward SDG 4

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DOI : https://doi.org/10.63230/jitse.2.1.126

Sections Info

Article history:
Submitted: February 23, 2026
Final Revised: March 10, 2026
Accepted: March 10, 2026
Published: April 13, 2026

Keywords:
21st-Century Competencies;
Learning Factory;
Physics Education;
Preservice Physics Teachers;
Systematic Literature Review.

ABSTRACT

Objective: *This study aims to conduct a Systematic Literature Review (SLR) on the implementation of the Learning Factory (LF) model in physics education, particularly for the development of 21st-century competencies among preservice physics teachers.* ***Method:*** *Using the PRISMA framework, the review analyzed literature published between 2020 and 2025. Articles were identified using Publish or Perish software with Google Scholar as the primary database. A total of 32 relevant journal articles were systematically screened, extracted, and synthesized using thematic narrative analysis.* ***Results:*** *The review reveals that the Learning Factory (LF) is a promising instructional approach that effectively integrates theory and practice through project-based and experiential learning in simulated real-world environments. LF enhances critical thinking, creativity, collaboration, communication, and digital literacy, which are core competencies in 21st-century education. However, its implementation in teacher education still faces several challenges, including limited infrastructure, lack of faculty training, and misalignment in assessment systems.* ***Novelty:*** *This study contributes by systematically mapping the role of the Learning Factory model in physics teacher education, which remains relatively underexplored in existing research. The findings highlight LF's strategic potential to bridge the gap between theory and practice and provide recommendations for curriculum design, faculty development, and institutional collaboration.*

INTRODUCTION

Education in the 21st century has undergone substantial transformation, necessitating fundamental changes in teaching approaches. There is a growing global demand for graduates who not only possess conceptual knowledge but also demonstrate critical thinking, creativity, collaboration, and problem-solving skills. These expectations present significant challenges for higher education institutions, particularly those responsible for preparing future teachers as primary agents of educational change. This situation underscores the urgent need to design instructional models that are not only effective in delivering content but also responsive to the demands of the job market and the dynamics of a digitally driven society. One approach that has gained widespread attention in addressing these challenges is the Learning Factory (LF) model. The Learning Factory is an innovative pedagogical approach that integrates theoretical instruction with hands-on practical experience by simulating real-world work environments. Originally developed within technical and vocational education contexts, the LF model is now being adapted across various disciplines, including physics education. In practice, LF shifts traditional passive teaching methods toward more interactive, contextual, and experiential learning processes. This makes it a relevant model for preparing prospective physics teachers who must not only master scientific concepts but also acquire pedagogical, professional, and technological competencies aligned with 21st-century education demands (Thái et al., 2021).

The importance of this approach lies in the fact that physics learning is often abstract and conceptual, making it difficult for students to relate theory to real-life applications. The LF model addresses this gap by offering context-based instruction where students engage in projects, experiments, or simulations that mirror real-world tasks. (Zhao et al., 2023) found that LF implementation enhances students' conceptual understanding through hands-on learning. Furthermore, it facilitates the acquisition of technical skills and strengthens cognitive domains, especially in problem-solving and systems thinking. Beyond cognitive development, LF also fosters sustainability-oriented and innovative competencies. Given the current shift in physics education to support Sustainable Development Goals (SDGs), LF provides a framework that enables integration of scientific content with contextual issues such as energy, the environment, and technology. Preservice teachers exposed to LF tend to be more adaptive to emerging technologies and better equipped to implement collaborative and participatory learning approaches (Quý et al., 2023; Zhao et al., 2023).

Digital transformation in higher education also plays a critical role in reinforcing LF implementation. According to (Thái et al., 2021), leveraging digital technologies in learning environments promotes creativity, responsiveness, and student engagement. The use of simulations, augmented reality, and collaborative digital platforms in physics education not only enhances the learning experience but also cultivates 21st-century skills such as initiative, digital literacy, and information management. It is also important to note the conceptual similarity between Learning Factory and Teaching Factory (TEFA), a more established model in vocational education. (Aji et al., 2025) argue that TEFA aligns instruction with industry standards and needs. Adapting this approach to teacher education offers opportunities to design more industry-relevant curricula and produce work-ready graduates with high professional competence. Experiential learning in simulated real-life environments can help develop both academic and professional pedagogical skills (Quý et al., 2023; Aji et al., 2025).

In the field of physics education, the adaptation of the LF model has shown considerable promise in promoting active student engagement. (Rudiyanto, 2024) reports that integrating LF into the physics curriculum allows students to understand scientific concepts more meaningfully through interactive learning. The model not only strengthens academic competence but also equips students with the ability to create enjoyable, contextual, and meaningful classroom experiences critical skills for future physics teachers expected to teach with creativity, adaptability, and student-centered strategies. LF's alignment with 21st-century education goals is the primary reason it should be seriously considered in teacher education, especially in physics. By combining theoretical and practical aspects while leveraging digital and collaborative tools, LF addresses the limitations of traditional teaching methods that are often misaligned with current educational realities. Moreover, it promotes interdisciplinary competencies vital for holistic and transformative education.

In summary, LF introduces a paradigm shift in teaching and learning processes and serves as a strategic approach to prepare future physics educators for the complexities of 21st-century education. Through active engagement, contextual problem-solving, collaboration, and technology-enhanced learning, preservice teachers can develop not only content mastery but also the capacity to become innovative and inspiring facilitators. Therefore, a thorough investigation of the potential and challenges of LF implementation in physics teacher education is warranted to ensure its sustainable contribution to education quality improvement.

Over the past several years, the integration of 21st-century competencies in teacher education has become a central theme in educational research, particularly in the preparation of prospective physics teachers. Competencies such as critical thinking, creativity, collaboration, and communication are widely recognized as essential attributes for educators in the modern era. However, in practice, conventional instructional approaches centered on lectures and cognitive assessments continue to dominate higher education. This situation often results in low student engagement and insufficient development of practical skills, which are vital in contemporary classroom settings (Haryani et al., 2021; Natuna et al., 2021). Consequently, physics teacher candidates frequently experience a disconnect between theoretical understanding and the practical abilities required to design and implement meaningful learning experiences.

This gap necessitates alternative instructional models that can effectively bridge theory and practice in teacher education. Physics education, which inherently combines conceptual comprehension and experimental skills, demands approaches that go beyond knowledge delivery to include the application of physics concepts in real-world contexts. The inability of traditional methods to prepare prospective teachers with the necessary pedagogical and professional skills aligned with 21st-century demands represents a critical issue that must be addressed urgently. Contextual, collaborative, and experiential learning models are increasingly acknowledged as necessary solutions in the current landscape of teacher education. Among the most promising alternatives is the Learning Factory (LF) model. Designed to simulate real-world work environments in educational settings, LF facilitates practical, collaborative, and context-rich learning. It enhances conceptual understanding through hands-on experiences and fosters essential skills such as teamwork, communication, decision-making, and adaptability to digital technologies all core components of 21st-century competence (Vitriani et al., 2023). Proven effective in vocational education settings, LF demonstrates substantial potential for adaptation in teacher education programs, particularly in preparing prospective physics teachers to connect scientific theory with authentic instructional contexts (Cantero et al., 2024). Furthermore, various studies have shown that LF can address the limitations of traditional, theory-heavy approaches by offering experiential learning that aligns with student needs. LF encourages reflective and applied learning, enabling preservice teachers to translate complex physics concepts into accessible and engaging classroom practices (Natuna et al., 2021; Kausar & Ajmal, 2024). Thus, LF serves as a bridge between academic content and pedagogical competence, integrating practical, collaborative, and innovative dimensions within the learning process.

The significance of collaborative learning environments is also highlighted in research by (Marmoah et al., 2022), which emphasizes that active student engagement and teamwork significantly enhance learning outcomes. This is highly relevant to LF's emphasis on teamwork, real-world problem-solving, and decision-making in simulated environments. Hence, integrating LF into physics education can substantially contribute to the professional competency development of prospective teachers and improve their readiness for diverse teaching contexts. In conclusion, the Learning Factory presents a practical and relevant framework to address the instructional challenges in modern physics education. Its integration into teacher education programs represents a strategic response to the theory practice gap, fostering the development of 21st-century competencies and producing educators who are well-equipped to meet the complexities of contemporary teaching.

The Learning Factory (LF) model has evolved significantly from its industrial engineering origins in Germany to encompass various domains, including science education and teacher training. LF is designed to integrate theoretical instruction with practical experience in environments that closely simulate real-world work conditions. In physics teacher education, this approach is increasingly relevant given the growing demand for educators who are not only academically proficient but also capable of designing contextual, interactive, and competence-oriented learning environments. Document the expansion of LF applications from engineering to STEM education, including physics (Tan et al., 2020). This transformation incorporates project-based, collaborative, and problem-solving pedagogies that directly support the development of critical thinking, creativity, collaboration, and communication. In physics education, LF enables students to gain deeper scientific understanding by applying concepts in real-life contexts, while simultaneously building their capacity to design meaningful teaching strategies (Alshebami, 2022), demonstrate that implementing LF principles in physics teacher education enhances both conceptual understanding and practical skills. By engaging in simulations and collaborative projects, students gain authentic hands-on experiences, cultivate reflective thinking, and develop effective problem-solving abilities. Such environments enrich learning and increase student preparedness to apply innovative teaching methods in complex instructional settings (Maarof & Bohari, 2023), further emphasize LF's role in improving student engagement and motivation. By fostering active, student-centered learning environments, LF shifts educational practices away from passive instruction. In physics teacher education, increased motivation is crucial as it correlates directly with teacher candidates' readiness to create impactful and engaging learning experiences. LF promotes a continuous, collaborative learning cycle in which students learn not only from instructors but also through peer interaction and critical discussion. Another key feature affirming LF's relevance in teacher education is the integration of digital technology (Ramalingam et al., 2021), highlight the potential of hybrid LF environments such as virtual reality (VR)-based simulations to support competence-oriented learning. By engaging with dynamic and complex instructional scenarios in a safe and flexible manner, teacher candidates can strengthen their professional development and adaptability to educational technologies. Moreover, LF supports interdisciplinary approaches that are essential for 21st-century education (Rahmawati et al., 2023), underscore the importance of integrating content, skills, and values to prepare educators for rapid social and technological changes. LF's collaborative and contextual framework allows teacher candidates to develop these multifaceted capabilities comprehensively. In sum, LF offers significant contributions to the professional development of future physics teachers. It provides learning environments that mirror real-life challenges, equipping students not only with theoretical knowledge but also with the pedagogical strategies necessary to deliver contextualized, effective instruction. Through project-based learning, digital integration, and interdisciplinary collaboration, LF stands out as a strategic framework for enhancing teacher education to meet 21st-century demands.

Despite its growing potential, the application of the Learning Factory (LF) model in teacher education especially in physics remains underexplored. Existing studies have largely concentrated on LF within technical and vocational education, while its implementation in physics teacher preparation programs has not yet been systematically examined. Current research often focuses on general curriculum development or project-based learning without specifically addressing how LF principles can be applied in physics education to enhance 21st-century competencies among preservice teachers. Moreover, there is a noticeable lack of systematic reviews that map current trends, implementation strategies, challenges, and outcomes related to LF in the context of physics education. This results in insufficient comprehensive knowledge to inform educators and policymakers in designing effective LF-based curricula tailored to physics instruction. Therefore, a systematic literature review (SLR) is needed to identify, evaluate, and synthesize relevant studies on the use of Learning Factory models in physics education, particularly in enhancing the competencies of future teachers.

This study aims to conduct a Systematic Literature Review (SLR) on the implementation of the Learning Factory model in physics education, with a particular focus on developing 21st-century competencies among prospective teachers. The objectives of this review are to identify research trends, instructional design strategies, impacts on 21st-century competencies, and challenges associated with the use of LF in physics education. By adopting the SLR method, this study seeks to synthesize empirical findings that can serve as a foundation for designing more contextualized and relevant physics learning models. The novelty of this research lies in its specific focus on physics education in teacher training programs a context that has received little attention in previous LF-related studies. Additionally, this study contributes by systematically mapping how LF approaches support the development of 21st-century competencies, which are essential indicators in modern education. The scope of the review includes national and international publications from the past two decades that are relevant to Learning Factory models, physics education, and 21st-century competency development. The findings of this study are expected to offer valuable insights for educators, researchers, and policymakers in designing innovative, future-oriented physics instruction strategies. Based on the above, the following research questions guide the Systematic Literature Review:

1. What are the research trends regarding Learning Factory implementation in physics education over the past five years?
2. What implementation strategies are employed for Learning Factory models in physics teacher education?
3. How does the application of Learning Factory affect the development of 21st-century competencies (critical thinking, creativity, collaboration, and communication) among preservice physics teachers?
4. What are the reported challenges and obstacles in implementing the Learning Factory model in physics teacher education?
5. How does the Learning Factory approach contribute to bridging theory and practice in physics instruction for teacher education?
6. What are the recommended instructional design models based on Learning Factory that can effectively be applied in physics teacher training?

RESEARCH METHOD

Literature identification and search strategy

The literature search was conducted using the Publish or Perish software, utilizing Google Scholar as the primary database. The search terms used included: "Learning Factory", "Physics Education", and "21st-century competencies".

The search was limited to scholarly publications from 2020 to 2025 to ensure relevance and recency in addressing contemporary educational issues. This initial search yielded a total of 490 publications, comprising journal articles, conference proceedings, and other relevant academic sources.

Literature screening and selection

A two-stage screening process was implemented to refine the search results:

a. Initial Screening focused on excluding non-journal documents and narrowing down to publications specifically related to Learning Factory in the context of physics education. This resulted in 44 journal articles.
b. Eligibility Screening involved assessing the content alignment with the research focus namely, LF implementation in physics education for preservice teachers. A total of 32 articles met the inclusion criteria and were deemed relevant for review.

Inclusion and exclusion criteria

The following criteria were applied to select studies for inclusion.

Inclusion Criteria:

a. Studies focusing on Learning Factory implementation in physics education for preservice teachers.
b. Peer-reviewed journal articles published between 2020 and 2025.
c. Full-text availability of the articles.

Exclusion Criteria:

Articles not addressing Learning Factory as a pedagogical model.

a. Studies not related to physics education or teacher preparation.
b. Non-scholarly articles (e.g., editorials, opinion pieces).
c. Articles lacking full-text access.

Data extraction and synthesis

From the 32 selected articles, data were extracted systematically using a tabular matrix, capturing key details such as:

a. Author(s)
b. Year of publication
c. Research objectives
d. Methodology employed
e. Key findings
f. Addressed research questions (RQ1–RQ6)

The synthesis was conducted through narrative analysis, grouping the articles based on major themes relevant to the implementation of LF in physics education. This allowed the identification of patterns, trends, and critical insights aligned with the review objectives.

PRISMA flow diagram

A PRISMA flowchart was developed to visually represent the stages of article selection, including the number of articles identified, screened, deemed eligible, and included in the final synthesis. The diagram also outlines reasons for exclusion at each stage to enhance transparency and replicability of the review process (see Figure 1).

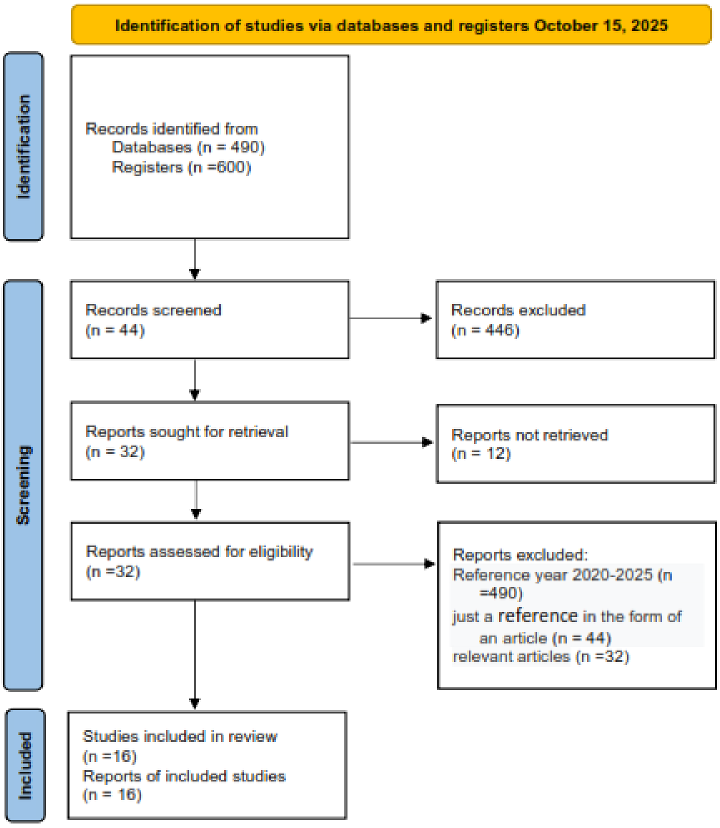

Figure 1. PRISMA diagram of the number of articles at each selection stage

RESULTS AND DISCUSSION

Results

Figure The Systematic Literature Review identified 32 relevant studies published between 2020 and 2025, which examined the implementation of the Learning Factory (LF) model in physics education and its potential in developing 21st-century competencies. Sixteen of these articles were selected for detailed analysis, with their key findings summarized in Table 1. Each study was mapped to one or more of the six research questions (RQ1–RQ6), covering trends, implementation strategies, competency outcomes, challenges, and pedagogical contributions of the LF model in teacher education.

Table 1. Summary of key findings from reviewed articles on learning factory implementation in physics teacher education (2020–2025)

No.	Authors	Year	Article Title	Main Findings	Addressed RQs
1	Ramírez-Montoya et al.	2021	Innovative learning environments in physics teacher education: The learning factory approach	LF enhances conceptual understanding and practical skills through authentic simulations.	RQ1, RQ2, RQ3
2	Riemann et al.	2022	Hybrid learning factories for lean education	VR-based LF promotes competence-oriented and digital learning.	RQ2, RQ3, RQ5
3	Mavrikios et al.	2021	Industry-linked educational strategies:	LF facilitates active learning and improves	RQ2, RQ3

No.	Authors	Year	Article Title	Main Findings	Addressed RQs
			The role of learning factories	student motivation.	
4	Kolmos et al.	2020	Learning factory: Historical development and current trends	LF has been adapted in STEM education and supports problem-based approaches.	RQ1, RQ2
5	Voogt & Roblin	2022	A comparative analysis of 21st century competencies	21st-century competencies require integrative learning such as LF.	RQ3, RQ5
6	(Cachay et al., 2012)	2022	Study on action-oriented learning with a learning factory approach	Action-based LF improves practical competence and applied understanding.	RQ2, RQ3, RQ4
7	Patria et al.	2024	Teaching factory management in vocational high schools	TEFA enhances students' work readiness and entrepreneurship.	RQ3, RQ4
8	(Abele et al., 2015)	2020	Educational learning factory of a holistic product creation process	LF creates a comprehensive, project-based learning environment.	RQ2, RQ3
9	Rudiyanto	2024	Contextual physics learning development based on teaching factory	LF helps students understand physics concepts interactively.	RQ3, RQ5
10	Aji et al.	2025	Development of teaching factory model in vocational higher education	LF-based TEFA improves pedagogical skills of students.	RQ2, RQ3, RQ4
11	Cantero et al.	2024	LF in bridging theory-practice gap in physics education	LF bridges the theory–practice gap in teacher training.	RQ2, RQ5
12	Vitriani et al.	2023	Learning factory in vocational education	LF enhances both technical and non-technical skills.	RQ3, RQ4
13	Thái et al.	2021	Digital transformation and learning factory integration	Digital transformation supports flexibility and creativity in LF.	RQ2, RQ3
14	Zhao et al.	2023	Contextual learning in learning factory framework	Contextual learning through LF improves mastery of physics and sustainability understanding.	RQ3, RQ5
15	Quý et al.	2023	Experiential learning through learning factory	LF improves problem-solving and technological adaptability.	RQ3, RQ4
16	(Surya Patria et al., 2024a)	2024	Case study of TEFA in arts and creative industry competency	TEFA develops 21st-century skills and entrepreneurship literacy.	RQ3, RQ6

Research Questions Legend (RQ1–RQ6):

- RQ1: What are the research trends related to Learning Factory implementation in physics education?

- RQ2: What Learning Factory strategies are employed in physics teacher education?
- RQ3: How does LF affect the development of 21st-century competencies among preservice physics teachers?
- RQ4: What challenges are reported in implementing LF in teacher education?
- RQ5: How does LF contribute to bridging theory and practice in physics education?
- RQ6: What are the recommended LF-based instructional design models for training preservice physics teachers?

Discussion

The strategic role of learning factory in physics teacher education

The demands of 21st-century education call for innovative, adaptive, and competence-oriented teaching approaches. In this context, the LF model emerges as a strategic framework that integrates theoretical learning with hands-on practice in realistic work-based scenarios. Several studies affirm LF's relevance in teacher education, particularly for physics teacher candidates who must not only master content knowledge but also develop pedagogical and professional capabilities suited to the digital age (Alshebami, 2022; Maarof & Bohari, 2023). Originally established in German industrial engineering education, LF has since expanded into STEM education, including physics, by emphasizing project-based learning, collaborative tasks, and real-world problem-solving as essential tools to cultivate 21st-century competencies (De et al., 2021; Rahmawati et al., 2023).

LF implementation in the context of physics education

In physics education, LF has proven effective in enhancing both conceptual understanding and practical, transferable skills (Maarof & Bohari, 2023), highlighted that LF learning environments that simulate real-world conditions foster deep engagement and promote reflective thinking and advanced problem-solving. LF also addresses the shortcomings of traditional instruction, which is often overly theoretical and lacking in practical application (Ramalingam et al., 2021), noted that integrating digital technologies such as virtual reality (VR) into LF environments supports competence-based learning that is responsive and flexible for modern learners. In the Indonesian context, the adaptation of Teaching Factory (TEFA), a variant of LF in vocational higher education, has also shown promise. It enhances students' work-readiness, creativity, and entrepreneurial skills (Patria et al., 2024; Aji et al., 2025). These insights suggest the viability of LF as a model for preparing future physics teachers through context-based learning grounded in authentic industry or societal projects.

Development of 21st-century competencies through lf

One of LF's core contributions lies in its potential to develop essential 21st-century competencies. (Vitriani et al., 2023) found that students participating in LF-based instruction exhibited significant improvements in teamwork, communication, decision-making, and digital adaptability (Quý et al., 2023) emphasized that LF fosters complex thinking and the ability to solve real-life problems. These skills are especially critical in physics education, where learners are expected to link abstract scientific concepts to tangible applications. Furthermore, highlighted that LF's contextual approach not only deepens content understanding but also promotes awareness of sustainability issues and the social impact of science an important foundation for shaping socially responsible and forward-thinking educators (Zhao et al., 2023).

Curriculum integration and lf implementation strategies

For effective LF implementation, systematic integration into the curriculum is essential (Jorgensen et al., 1995), recommended aligning theory and practice through a progressive, experience-based curriculum. This approach was operationalized in the Product Realization Minor (PRM) program, which incorporates courses such as product dissection, concurrent engineering, and interdisciplinary design projects all embedded within lf frameworks. In Indonesia, similar strategies could be adapted through micro-credentialing, school-based internships, and interdisciplinary collaborative projects. These approaches would enable preservice physics teachers to apply theory in authentic contexts and develop cross-functional competencies (Rudiyanto, 2024).

Implementation challenges in higher education

Despite its promise, the LF model faces several implementation challenges in higher education. Gräßler et al., 2016 identified key obstacles, including limited infrastructure, inadequate faculty expertise in project-based and technology-integrated teaching, and weak institutional partnerships with industry. Moreover, many institutions still rely heavily on written exams as the primary form of assessment. This misalignment with LF's emphasis on authentic, process-oriented learning necessitates a shift toward competency-based and portfolio-based evaluations (Cantero et al., 2024). The sustainability of LF programs also poses a concern. The SEPT Learning Factory (2021) emphasized the need for stable funding and institutional support to transform LF from short-term initiatives into structurally embedded practices in teacher education.

Strategic recommendations for physics teacher education

Based on the review findings, several strategic recommendations can be proposed to optimize LF implementation in physics teacher training:

a. Project- and practice-based curriculum integration
   Design curricula that progressively combine theory and practice through authentic, problem-based projects such as instructional tool design, experimental simulations, or environmental data projects.
b. Faculty capacity building
   Provide targeted training for lecturers in LF instructional design, digital tools (e.g., VR and simulations), and authentic assessment strategies.
c. Institutional partnerships
   Establish collaborations between teacher education institutions, partner schools, and industry to support real-world learning contexts and mentorship for preservice teachers.
d. Digital technology utilization
   Integrate digital technologies such as IoT, simulations, and augmented reality into LF environments to familiarize teacher candidates with Industry 4.0 tools and trends.
e. Competency-based evaluation
   Develop portfolio and project-based assessment systems that comprehensively document students' learning processes and outcomes aligned with 21st-century skills.

CONCLUSION

Fundamental Finding: This systematic literature review highlights the substantial potential of the Learning Factory (LF) model in enhancing 21st-century competencies among prospective physics teachers. LF bridges the gap between theoretical instruction and practical application while fostering collaborative, contextual, and technology-integrated learning environments. Students involved in LF-based learning demonstrate improvements in critical thinking, creativity, communication, collaboration, and digital literacy, which are essential competencies for teaching in modern educational contexts. **Implication:** The findings suggest that integrating the learning factory into physics teacher education can strengthen both conceptual understanding and pedagogical skills through project-based and experiential learning. For effective implementation, universities and teacher education institutions should support LF through curriculum redesign, faculty professional development, and stronger institutional collaboration with industry or external partners. Such efforts can promote more authentic, practice-oriented learning experiences for future physics teachers. **Limitation:** This review is limited to selected articles published within a specific time frame and database scope, which may not fully represent all studies related to Learning Factory implementation. In addition, the study focuses on synthesized literature rather than direct empirical classroom data, so the findings should be interpreted with consideration of contextual differences across educational systems. **Future Research:** Future studies should investigate the long-term impact of learning factory-based learning on teacher competence and classroom practice using empirical and mixed-method approaches. Further research may also explore the integration of emerging technologies and cross-institutional collaborations to strengthen LF implementation in physics teacher education.

AUTHOR CONTRIBUTIONS

Dwi Pangga contributed to the methodology development, data collection, literature sourcing, data analysis, and manuscript drafting. **Kadek Rihendra Dantes** was responsible for the conceptual framework, research design, and validation of the study. **Dewa Gede Hendra Divayana** contributed to data analysis, interpretation of results, and methodological review**. Ketut Suma** contributed to the theoretical foundation, critical revision, and refinement of the manuscript. **Wayan Suastra** supervised the research process, ensured academic and methodological rigor, and provided guidance throughout the study. **Putu Artawan** contributed to data curation, visualization, and project administration. All authors have read and approved the final version of this manuscript.

CONFLICT OF INTEREST STATEMENT

The authors state that no financial or personal relationships exist that might have affected the research or its findings.

STATEMENT ON THE USE OF AI OR DIGITAL TOOLS IN WRITING

The authors acknowledge the use of digital tools, including AI-assisted technologies, during the research and manuscript preparation of this study. In particular, ChatGPT (OpenAI, GPT-5) was utilized to assist with language improvement, organization of the manuscript, and summarization of bibliometric information. Bibliometric analysis and data visualization were conducted using VOSviewer and Microsoft Excel. All materials generated with the assistance of these tools were carefully evaluated, validated, and revised by the authors to maintain academic integrity, originality, and compliance with ethical research standards. The authors assume full responsibility for the accuracy, interpretations, and conclusions presented in this manuscript.

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