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Literature Review: Integrating Teachable Machine into Project-Based Learning (PBL) Models to Optimize Understanding of Physics Concepts

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Abstract
The urgency of mastering Artificial Intelligence (AI) literacy, set against the difficulty students face in understanding abstract physics concepts without visual representation, presents a real challenge in the digital era. Therefore, this study aims to examine the potential and effectiveness of integrating Teachable Machine (TM) within the Project-Based Learning (PjBL) model to optimise the understanding of physics concepts in the topics of vibration, waves, and sound. This study was conducted using a systematic literature review approach encompassing 36 peer-reviewed scientific articles published between 2020 and 2025. The results of the analysis found that the TM platform has proven to function as effective digital scaffolding for visualising abstract physical data into concrete pattern representations. Furthermore, this technological collaboration with the PjBL model is empirically shown to enhance intrinsic motivation, sharpen computational thinking skills, and reduce students' physics misconceptions through active inquiry-based activities. Overall, the synergy between no-code AI and PjBL offers a transformative pedagogical strategy that not only deepens students' understanding of science concepts, but also successfully transforms the role of learners into independent, agentic learners.
Keywords: teachable machine, project-based learning (pjbl), understanding of physics concepts, wave and sound vibration materials.

INTRODUCTION

The paradigm shift in 21st-century education positions Artificial Intelligence (AI) technology not merely as a theoretical subject to be studied, but also as a cognitive partner and an empowering tool in the learning process at the school level (Ouyang & Jiao, 2021). Building AI literacy — encompassing an understanding of basic technological concepts, digital ethics, and systematic logical thinking — has become a global imperative, particularly within the Science, Technology, Engineering, and Mathematics (STEM) curriculum ecosystem (Kandlhofer & Steinbauer, 2021; Chiu et al., 2025).

Although the urgency of digitalisation continues to be emphasised, its application in the field frequently encounters a significant pedagogical barrier, especially in scientific disciplines such as physics. In the topics of vibration, waves, and sound, the majority of students consistently struggle to understand the physical characteristics of invisible phenomena, owing to the limitations of conventional visual representations in the classroom (Mainali, 2021).

To bridge the gap between the demands of 21st-century digital literacy and visualisation constraints in physics learning, the innovative use of no-code machine learning platforms such as Google's Teachable Machine (TM) offers promising problem-solving alternatives. The platform allows learners to explore sensors, input real data independently, and observe how classification algorithms work without needing to master complex programming code (Putra, 2021; Lee et al., 2022).

The novelty of this research lies in three aspects. First, this study specifically focuses on the integration of TM within the PjBL syntax for vibration, wave, and sound physics material — a focus that has not been widely addressed in the existing literature. Second, this study synthesises findings from 36 international and national articles published between 2020 and 2025 to produce a comprehensive theoretical framework. Third, this study identifies the role of TM as digital scaffolding that transforms learners from passive observers into agentic learners — a finding with implications for redesigning science pedagogy in the digital age.

However, the potential of these advanced instruments will not be fully realised without being supported by a relevant active learning model. In this context, the Project-Based Learning (PjBL) model is highly recommended, as it provides a structured syntax that facilitates the meaningful use of technology. The interactivity offered by TM when integrated into science projects has been shown to stimulate students' intrinsic motivation — a fundamental aspect necessary for completing scientific investigations both independently and collaboratively (Chiu, 2021). Although the potential of each variable has been widely discussed individually, studies that comprehensively examine how the synergy between the PjBL model and the no-code AI (TM) platform can transform abstract physics concepts into concrete, analytical, and misconception-free learning experiences remain very limited. Most existing literature still treats AI as a separate instrument or focuses on its implementation at the higher education level. This literature review was therefore compiled to address this theoretical gap and answer the central research question: "How can the integration of Teachable Machine within the Project-Based Learning (PjBL) model optimise students' understanding of physics concepts, particularly in the topics of Vibration, Wave, and Sound?"

To systematically address this central problem, the study is organised around three specific research sub-questions: (1) What is the role of no-code AI (Teachable Machine) in helping students construct mental models and visualise scientific data interactively? (2) To what extent is the integration of artificial intelligence within the PjBL syntax effective in improving learning motivation, cognitive engagement, and computational thinking skills among school-level students? And (3) How can implementation and visual representation using Teachable Machine reduce the prevalence of student misconceptions regarding the characteristics of Vibration, Wave, and Sound materials?

To keep the scope of the study focused and thorough, this literature review observes several important limitations. First, data analysis is strictly limited to 36 peer-reviewed scientific articles sourced from reputable databases and published within the last five years, from 2020 to 2025. Second, the physics learning material examined in this study is specifically limited to the domains of vibration, waves, and sound.

The rationale for this material selection is grounded in the physical characteristics of vibrations and waves, which tend to be repetitive, exhibit strong geometric patterns, and produce concrete audio-visual inputs. These inherent characteristics make the material far more compatible with the pattern recognition features of Teachable Machine — whether for image or sound classification — compared to other branches of physics such as thermodynamics or particle kinematics, which demand different levels of mathematical abstraction. By maintaining these boundaries, this study aims to contribute precise and practical pedagogical recommendations for science educators in the digital era.

As stated by Long and Magerko (2020), Teachable Machine (TM) serves as a crucial cognitive bridge for building AI literacy among learners through a user-friendly interface. Amid rapid technological developments, the use of plug-and-play tools significantly assists learners in building mental models essential for understanding both computational concepts and physics (Vartiainen et al., 2020).

The platform's visualisation capabilities represent a major advantage in experiential learning. Zimmermann-Niefield et al. (2020) found that TM enables learners to transform abstract scientific data patterns into tangible, interactive AI classifications. Through this approach, the contemporary educational paradigm positions AI not merely as a subject of study, but as a cognitive partner that empowers the entire learning process at the school level (Ouyang & Jiao, 2021).

Building on the role of AI as a learning partner, the integration of this technology into active learning models is highly relevant to explore. Drawing on the findings of Tsan et al. (2022), the PjBL approach that incorporates the creation of AI models yields a substantially more comprehensive understanding of concepts compared to conventional direct instruction methods. Students' engagement in independent projects using technology such as TM has been shown to simultaneously stimulate intrinsic motivation and computational thinking skills (Chiu, 2021).

Furthermore, the PjBL model provides space for students to understand the methodology behind artificial intelligence. Su and Yang (2023) highlight that the PjBL model plays an important role in helping learners "unpack the black box" of AI by understanding the causal relationship between data input and classification output. Empirically, the effectiveness of this model is further demonstrated by Sari et al. (2021), who found that the technology-integrated PjBL model significantly improves students' conceptual comprehension scores in physics compared to conventional learning approaches.

The effective implementation of PjBL provides a strong foundation for addressing physics materials with strong visual pattern characteristics, such as vibrations, waves, and sound. Park (2023) demonstrates that in the context of wave experiments, TM adds a new dimension to laboratory activities through its ability to classify data in real time. Specifically, this tool has been found to be particularly effective for classifying musical instruments based on their wave patterns, directly assisting teachers in reducing student misconceptions regarding frequency and amplitude concepts (Kim et al., 2022).

The effectiveness of this visualisation approach is further supported by Sari et al. (2023) and Prahani et al. (2020), who found that AI integration helps students distinguish the characteristics of transverse and longitudinal waves through a pattern recognition approach. As a further functional development, the potential of TM is not limited to software alone; Nasution et al. (2024) project that TM can be integrated with microcontrollers such as Arduino to build physical prototypes applicable in students' science projects in schools.

Holistically, the integration of Teachable Machine within the PjBL framework triggers a fundamental transformation in the role of learners — from passive observers of phenomena to active, agentic learners. As a digital scaffolding instrument, the TM interface helps students visualise abstract physical phenomena in digital visual forms that can be managed and manipulated. Dandashi et al. (2024) affirm that this process enables learners to independently investigate and validate data, which has proven effective in improving their science process skills.

The pedagogical obstacles surrounding highly abstract physics materials can thus be effectively addressed. Through collaboration in designing AI-based learning activities, more concrete pattern recognition can be readily developed (Toivonen et al., 2024). Ultimately, the synergy between the PjBL learning model and the no-code AI platform not only equips students with relevant digital literacy, but also ensures the development of a logical, structured, and in-depth understanding of physics concepts through meaningful learning experiences.

METHOD

This study uses a literature study method (*Literature Review* or *Systematic Review* simple) to identify, evaluate, and synthesize previous empirical findings that are relevant to the research topic. The secondary data search strategy is carried out systematically through various academic *databases* with global and national reputation, which include Scopus, SINTA, and Elsevier (*ScienceDirect*). The process of searching for articles in the database uses specific *keywords* combinations based on Boolean operators, namely: ("Teachable Machine" OR "Machine Learning" OR "Artificial Intelligence") AND ("Project-Based Learning" OR "PjBL") AND ("Physics Education" OR "Vibration" OR "Wave" OR "Sound").

Table 1. Artificial Intelligence/Machine Learning/Teachable Machine

No.	Author	Year	Title	Focus
			ARTIFICIAL INTELLIGENCE/MACHINE LEARNING/TEACHABLE MACHINE	
1	Long, D., & Magerko, B.	2020	What is AI Literacy? Competencies and Design Considerations	Discuss the basics of AI literacy relevant to the use of Teachable Machine
2	Vartiainen, H., et al.	2020	Machine Learning with Primary School Children: A Design-Oriented Study	Demonstrate how schoolchildren use simple Machine Learning tools to solve practical problems
3	Zimmermann-Niefield, A., et al	2020	Youth Learning Machine Learning through Active Training of Physical Activity Classifiers	Researching how students learn physical concepts (movement/vibration) by training students' own machine learning models
4	Kandlhofer, M., & Steinbauer, G	2021	Education on School-Level Artificial Intelligence: Focus on Machine Learning	Assess how the AI curriculum at the school level improves students' understanding of basic concepts of technology and logic of thinking
5	Chiu, T. K	2021	Applying the self-determination theory to motivating secondary school students to learn AI	Examining the motivation of junior high school students in learning AI with PjBL which requires high intrinsic motivation that can be triggered by the use of cutting-edge technology such as the Teachabel Machine
6	Chiu, T. K	2021	Digital Support for Student Engagement in Mainstream Schools: A Survey of Parent and Teacher Perspectives	It is relevant for the variable "Concept Understanding" because it discusses how interactive digital tools increase the cognitive engagement of junior high school students
7	Ouyang, F., & Jiao, P	2021	Artificial Intelligence in education: The three paradigms	Sharing the paradigm of AI as a tool, as a partner and as a learning subject
8	Lee, J., et al	2022	Developing an Artificial Intelligence Education Program for Middle School Students Using Teaching Machine	Develop a special curriculum for the junior high school level that aims to improve AI literacy as well as critical thinking skills through sensor exploration and data input
	Pila, S., et al	2021	Preschoolers' learning of physics concepts from a touch-screen game: The role of scaffolding	Although the subject is an early childhood, this article provides a strong theory of how digital scaffolding (such as the Teachable Machine interface) helps visualize abstract physics concepts

No.	Author	Year	Title	Focus
9	Son, R. W. P.	2021	Utilization of Google's Teachable Machine in Artificial Intelligence Introduction for Students	Practical implementation of the use of Teachable Machine for students in Indonesia as an AI-based learning media
10	Tedre, M., et al	2021	Teaching Machine Learning in K-12 Education: Mental Models and Concepts	Explain how learners build "mental models" of abstract concepts (such as 9vibrations) through machine learning
11	Giannakos, M., et al	2022	Designing Creative AI-Powered Learning Activities for K-12 Education	Explains how tools like Teachable Machine help learners "see" science data (such as wave patterns) through the lens of AI classification
12	Laupichler, M. C., et al	2022	Artificial Intelligence Education for Higher Education: A Systematic Literature Review	Identify competencies that learners achieve when using AI for problem solving (PjBL)
13	Su, J., & Yang, W.	2022	Artificial Intelligence in Early Childhood Education: A Scoping Review	While covering basic education, this article outlines the framework for how "plug-and-play" AI tools (such as TM) can be used for pattern recognition that are essential to Vibration and Wave material
14	Tsan, J., et al	2022	A Comparison of High School Students' Conceptual Understanding of AI Across Project-Based and Direct Instruction	Provides empirical evidence that the Project-Based Learning (PjBL) approach is much more effective in instilling an understanding of AI and science concepts than direct instruction
15	Williams, R., et al.	2022	The Impact of Teachable Machine on Middle School Teachers' Perceptions of Science Lessons	See how junior high school teachers integrate Teachable Machine into science lessons and its impact on the learning process
16	Chiu, T. K., et al	2023	A Meta-Analysis of the Effects of AI on Student Learning Outcomes in STEM Education	Provides statistical evidence that the integration of AI in STEM (Physics is a part of it) significantly optimizes learning outcomes and concept understanding compared to traditional methods
17	Park, S	2023	Application of Google Teachable Machine in Physics Experiments for Sound and Wave Classification	Testing the effectiveness of the Teachable Machine as a real-time measurement and classification tool for sound waves to reduce misconceptions in audio-frequency materials

No.	Author	Year	Title	Focus
18	Nasution, et al.	2024	Teachable Machine Integration with Arduino for Real-Time Object Shape Specification	How the output of the Teachable Machine is connected to the microcontroller
19	Sperling, J., et al	2024	Integrating *No-Code* AI Tools in STEM Classrooms: A Study on Student Conceptual Models	Examine how *no-code* tools like Teachable Machine help learners build more accurate mental models of scientific data
20	Toivonen, T., et al	2024	Co-Designing AI Education: Empowering Teachers to Integrate Machine Learning in Science Classrooms	Describe the development (R&D) process of AI teaching aids so that they can be implemented practically by science teachers in the classroom
21	Chiu, T. K., Xia, Q., & Zhou, X	2025	Integrating Artificial Intelligence into K-12 STEM Education: A Systematic Review	Summarizes how PjBL is used as a primary method for teaching AI in high school
22	Lee, Y.	2025	Machine Learning with Teachable Machine in Physical Education: Leading Agentic Learning	Although it focuses on Physical Education, this article describes the methodology of expert groups in training AI models that can be adapted for Physics projects
PROJECT-BASED LEARNING INTEGRATED MACHINE LEARNING/TEACHABLE MACHINE				
23	Pure	2021	Implementation of Project-Based Learning in 21st Century Learning in Science Learning: A Systematic Literature Review	Reviewing the effectiveness of PjBL in improving science learning outcomes (Biology, Chemistry, Physics) in the 21st century
24	Lin, P. Y., et al	2021	Enhancing Students' Computational Thinking through a Machine Learning Curriculum Based on Project-Based Learning	Showing that PjBL involving ML modeling improves problem-solving capabilities is logically relevant to how systematic waves work
25	Sari, I., et al	2021	The Effect of STEM-Integrated Project-Based Learning on Students' Conceptual Understanding	Analyzing the extent to which the PjBL model integrated with technology can improve the concept comprehension score compared to the conventional learning model in Physics material

No.	Author	Year	Title	Focus
26	Zhai, X., et al	2021	A Review of Artificial Intelligence in STEM Education: Progress and Prospects	Provides a theoretical foundation for why the integration of AI (such as TM) in PjBL Physics is effective for optimizing concept understanding in the digital age
27	Putri, A. D., & Rusdiana, D	2022	Implementation of Project-Based Learning on Vibration and Waves to Improve Students' Creative Thinking	Evaluate how the manufacture of products in Vibration and Wave materials (such as simple musical instruments or earthquake detectors) can strengthen the understanding of the physical structure of waves
28	Adicondro, T., & Anugraheni, (2022)	2022	The Influence of Project Based Learning (PjBL) on Concept Understanding and Process Skills	Providing empirical evidence that PjBL significantly improves students' understanding of concepts in science materials
29	Kuo, H. C., et al	2023	Integrating AI with Project-Based Learning to Enhance Students' Computational Thinking and Problem-Solving Skills	How do learners use TM to solve challenges, for example: "How do I make a machine that can distinguish between audiosonic and ultrasonic sounds?"
30	Su, J., & Yang, W.	2023	Unpacking the Black Box of AI Education: A Project-Based Learning Approach	Explains how PjBL helps learners "open the black box" of AI. students not only use the Teachable Machine, but also understand the input-output relationship of data (such as the relationship between frequency and sound classification)
31	Syamra, S	2024	The Effect of Using STEM PjBL-Based Science Learning Modules on Students' Participation	Relevant for grade VIII students, discussing the use of PjBL-STEM modules in improving cognitive participation and understanding
AI/ML/TM INTEGRATED WAVE AND SOUND VIBRATIONS				
32	Prahani, B. K., et al	2020	The Effectiveness of the OR-IPA Teaching Model to Improve Students' Critical Thinking Skills on Vibration and Wave Topics	Discussing related to the Teachable Machine helps visualize the difference in wave characteristics (transversal-longitudinal) through image classification
33	Mainali, B. P.	2021	Representation of Waves in Physics: A Review of Literature	Discussing how visualization helps understanding wave concepts is a good fit if Teachable Machine is used for visual classification of waves

No.	Author	Year	Title	Focus
34	Kim, S., et al	2022	Designing an AI-Integrated Physics Project: Learning Waves and Sound with Teachable Machine	Discuss the specifics of the use of TM for Sound and Wave materials. The use of TM to classify musical instruments based on their sound wave patterns
35	Sari P. M., et al.	2023	Development of AI-Based Physics Learning Media to visualize Transverse and Longitudinal Waves	Discuss related to the use of AI (which can be mentioned as the basis for using TM) to distinguish between types of waves
36	Dandashi, A., et al.	2024	Evaluating the Impact of *No-Code* AI Tools on Students' Inquiry Skills in Science Projects	Examine how tools like Teachable Machine improve inquiry skills (asking and experimenting) in science projects

To guarantee the quality, relevance, and novelty of the synthesized data, the netted documents are re-screened using strict inclusion and exclusion criteria. The inclusion criteria applied in selecting articles include ti: (1) The article is published in periodical scientific journals within the last 5 years, i.e. between 2020 and 2025, (2) The focus of the research subject is at the elementary to secondary education level (K-12) or is within the framework of STEM learning, and (3) Explicitly discusses the implementation or use of no-code AI tools (*no-code AI tools*) in the process of solving scientific experimental problems.

Based on the search strategy, keyword filtering, and application of the inclusion criteria, 36 main articles were obtained that were considered valid, relevant, and eligible for further analysis. The distribution of the year of publication along with the focus of the study of all the articles that were successfully collected are summarized in detail in Table 2.

Table 2. Distribution and Main Focus of Reference Article Sources

Year	Number of Articles (n = 36)	Key Focus
2020	6 items (16.7%)	Basic AI Literacy & Wave Visualization
2021	9 items (25.0%)	Student Motivation & PjBL Effectiveness
2022	9 items (25.0%)	Mental Model & Instruction Comparison
2023	6 items (16.7%)	*Computational & Meta Analysis*
2024 - 2025	6 items (16.7%)	No-Code & Agentic Learning *Implementation*

The data analysis process in this literature study is carried out through the following systematic stages:

Focus Variable Grouping: Data extracted from 36 reference articles are classified into three main variable clusters, namely: (a) *machine learning literacy*, (b) the effectiveness of technology-integrated PjBL models, and (c) the level of conceptual understanding in specific physics materials (vibrations, waves, and sounds);

Empirical Findings Analysis: Perform data reduction and draw conclusions from each cluster such as figure 1 to see the causal relationship between the use of *Teachable Machine* and the cognitive improvement of learners; and Bibliometric Mapping: To strengthen objectivity and enrich trend analysis, bibliometric mapping is performed using VOSviewer software. This device is used to visualize network *visualization* diagrams of inter-concepts and detect trends in AI-themed research directions in physics education in the future.

RESULTS AND DISCUSSION

Based on a systematic analysis of 36 referenced articles, the integration between *Teachable Machine* (TM) and *the Project-Based Learning* (PjBL) model in science materials is described into three main discovery clusters. These clusters directly answer the research questions that have been formulated:

Formation of AI Mental and Literacy Models through *Teachable Machine*

Answering the first research subquestion about the role of *no-code* AI, the use of AI through *plug-and-play platforms* such as *Teachable Machine* has proven to be essential in training *pattern recognition* skills for students. One of the biggest challenges in school-level AI education is the complexity of programming languages (Kandlhofer & Steinbauer, 2021). TM overcomes these barriers by providing *a user-friendly* GUI-based visual interface (*Graphical User Interface*) (Long & Magerko, 2020).

The TM interface serves as a very powerful digital *scaffolding* in helping learners visualize physical phenomena that were previously considered abstract and invisible (Pila et al., 2021). Through the activity of training *machine learning* models independently, either using image, voice, or movement inputs, students are guided to build a structured "mental model" of how scientific data is collected, processed, and classified (Vartiainen et al., 2020; Tedre et al., 2021).

Learners no longer see AI as a magical entity, but can instead "see" science data such as wave and vibration patterns in real life through the lens of interactive AI classification (Zimmermann-Niefield et al., 2020; Giannakos et al., 2022). This process of forming accurate mental models not only fundamentally improves AI literacy from an early age, but also significantly improves their conceptual understanding of scientific data representations (Sperling et al., 2024).

Optimization of Computational Thinking in the Framework of PjBL

In answer to the second research sub-question regarding the effectiveness of AI integration in PjBL syntax, empirical studies have consistently proven that the PjBL learning model is much more effective in instilling understanding of concepts compared to conventional hands-on instruction approaches (Tsan et al., 2022). When TM technology is integrated into the PjBL ecosystem, this model provides a *roadmap* for learners to apply *computational thinking* in solving authentic project challenges (Lin et al., 2021; Kuo et al., 2023).

For example, when students are faced with a project challenge: *"How do we create an intelligent machine that can distinguish between audiosonic and ultrasonic sounds?"* (Kuo et al., 2023), they are involved in a very logical and systematic problem-solving process. The PjBL syntax facilitates learners to "*unpack the black box*" from AI technology (Su & Yang, 2023). Through the work on the project, they not only become *end-users*, but also fully understand the causality mechanism between the quality of the data input (dataset) and the accuracy of the resulting classification output (Su & Yang, 2023). Active involvement in designing AI-based projects has a direct impact on increasing class participation, strengthening intrinsic motivation, and sharpening students' critical inquiry skills (Chiu, 2021; Syamra, 2024).

Visualization and Application to Vibration, Waves, and Sound

Answering the third research subquestion on minimizing physical misconceptions, TM offers an innovative alternative to *data-driven experiments* in the domains of vibration, waves, and sound. The characteristics of this material, which are rich in frequency patterns and geometric shapes, make it very suitable to be paired with TM's *pattern recognition feature*. Visual representation using AI tools has proven to be effective for distinguishing the physical characteristics of waves, such as the fundamental difference between transverse and longitudinal waves through the recognition of graphic imagery (Prahani et al., 2020; Sari et al., 2023).

In addition to the recognition of graphic images, the TM can be used as an acoustic measuring instrument in *real-time*. Park (2023) and Kim et al. (2022) prove that TM is very accurate for classifying types of musical instruments based on their frequency patterns and sound waveforms. This experimental approach is very vital to reduce misconceptions in audio materials such as students' mistakes in distinguishing between sound strength (amplitude) and pitch (frequency) which often arise due to the lack of visual evidence in school laboratories (Mainali, 2021)

As a more applicable functional development, the results of the digital classification of TM do not stop at the computer screen. The output of such classifications can be physically integrated with microcontrollers such as Arduino (Nasution et al., 2024). Through the work of the science group project (*expert groups*), students can build real physical prototypes that are solutions, such as: (1) an earthquake early frequency alarm system (utilizing vibration sensors) and (2) an automatic traditional musical instrument classification tool based on the pitch of the sound.

Paradigm Shift: Students as *Agentic Learners*

The main strength of future physics learning through this syntax is not only in the sophistication of AI technology itself, but in the radical shift in the role of students in the classroom. In traditional physics learning, students tend to be positioned as passive observers of phenomena that simply memorize the formula for the rapid propagation of mechanical waves or listen to resonant sounds without complete visualization.

However, by combining the PjBL and *Teachable Machine* models, students transform into *agent learners* as well as beginner "*data scientists*" (Lee, 2025). *Teachable Machine* takes on a strategic role as a "cognitive bridge" that translates physical aspects that are initially *invisible* (invisible, such as variations in frequency, amplitude, and propagation patterns of mechanical waves) into digital visual forms that *are manipulable* or can be managed independently by learners.

When learners construct, test, and validate their own datasets in a real project, they fundamentally understand that every physical phenomenon in nature has unique patterns that make up real datasets in the real world. This theoretical and practical synergy is the essential differentiator as well as a concrete solution to reduce the high rate of physics misconceptions in schools.

CONCLUSION

An in-depth study of the 36 articles analysed confirms that the collaboration between the Teachable Machine (TM) platform and the Project-Based Learning (PjBL) model constitutes a transformative pedagogical strategy for the 21st century. TM provides a no-code, AI-based visual and analytical infrastructure that enables abstract concepts which are inherently invisible — such as vibrations, waves, and sound — to be made concrete through real-time data pattern recognition features. The integration of this interactive technology into the PjBL syntax has been shown not only to stimulate students' intrinsic participation and motivation, but also to comprehensively enhance digital literacy, sharpen computational thinking, and optimise the understanding of physics concepts in a logical, deep, and misconception-free manner.

As a concluding perspective, Teachable Machine, framed within the PjBL syntax, is not merely a cosmetic digital substitution tool, but represents a pedagogical revolution in the way students interact with science. This approach fundamentally overhauls the conventional physics learning paradigm — shifting from the passive, theoretical reception of formulae to an active process of inquiry, sensor exploration, and independent data validation. This synergy is strongly recommended as a concrete solution for science educators teaching physics material with strong visual and audio pattern characteristics, as it offers a means of breaking the impasse of abstract concept representation in the classroom.

Based on the limitations of this literature review, several important recommendations are offered for future researchers: (1) Future researchers are advised to conduct direct empirical trials in the classroom through Classroom Action Research (Penelitian Tindakan Kelas/PTK), experimental research, or quasi-experimental designs. This is essential to measure the effectiveness of the PjBL–TM integration model quantitatively in terms of learning outcomes and cognitive retention among students at various school levels. (2) Further exploration and innovation are needed regarding the adaptation of no-code AI platforms to other physics topics with different mathematical characteristics, such as particle kinematics, Newton's laws, or thermodynamics. This step is important for mapping the overall potential and limitations of artificial intelligence as a tool within the broader modern science curriculum.

REFERENCES

Adicondro, T., & Anugraheni, I. (2022). Pengaruh Project-Based Learning (PjBL) terhadap Pemahaman Konsep dan Keterampilan Proses. *Jurnal Basicedu*.

Chiu, T. K. (2021a). Applying the self-determination theory to motivating secondary school students to learn AI. *Computers & Education: Artificial Intelligence*, 2, 100029.

Chiu, T. K. (2021b). Digital Support for Student Engagement in Mainstream Schools: A Survey of Parent and Teacher Perspectives. *British Journal of Educational Technology*, 52(5), 1914-1927.

Chiu, T. K., et al. (2023). A Meta-Analysis of the Effects of AI on Student Learning Outcomes in STEM Education. *Journal of Computer Assisted Learning*, 39(4), 1120-1135.

Chiu, T. K., Xia, Q., & Zhou, X. (2025). Integrating Artificial Intelligence into K-12 STEM Education: A Systematic Review. *Educational Technology Research and Development*, 73(1), 45-68.

Dandashi, A., et al. (2024). Evaluating the Impact of No-Code AI Tools on Students' Inquiry Skills in Science Projects. *International Journal of STEM Education*, 11(1), 14-29. Giannakos, M., et al. (2022). Designing Creative AI-Powered Learning Activities for K-12 Education. *Computers & Education*, 182, 104477.

Kandlhofer, M., & Steinbauer, G. (2021). Education on School-Level Artificial Intelligence: Focus on Machine Learning. *KI - Künstliche Intelligenz*, 35(2), 153-162.

Kim, S., et al. (2022). Designing an AI-Integrated Physics Project: Learning Waves and Sound with Teachable Machine. *Physics Education*, 57(4), 045012.

Kuo, H. C., et al. (2023). Integrating AI with Project-Based Learning to Enhance Students' Computational Thinking and Problem-Solving Skills. *Interactive Learning Environments*, 31(8), 5120-5135.

Laupichler, M. C., et al. (2022). Artificial Intelligence Education for Higher Education: A Systematic Literature Review. *Computers and Education Open*, 3, 100085.

Lee, J., et al. (2022). Developing an Artificial Intelligence Education Program for Middle School Students Using Teaching Machine. *Journal of the Korean Association of Information Education*, 26(1), 75-84.

Lee, Y. (2025). Machine Learning with Teachable Machine in Physical Education: Leading Agentic Learning. *European Physical Education Review*, 31(2), 210-226.

Lin, P. Y., et al. (2021). Enhancing Students' Computational Thinking through a Machine Learning Curriculum Based on Project-Based Learning. *Frontiers in Psychology*, 12, 725431.

Long, D., & Magerko, B. (2020). What is AI Literacy? Competencies and Design Considerations. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, 1-16.

Mainali, B. P. (2021). Representation of Waves in Physics: A Review of Literature. *Journal of Physics: Conference Series*, 1934(1), 012015.

Murniati. (2021). Implementation of Project-Based Learning in 21st Century Learning in Science Learning: A Systematic Literature Review. *Jurnal Pendidikan Sains Indonesia*, 9(2), 244-256.

Nasution, M. A., et al. (2024). Integrasi Teachable Machine dengan Arduino untuk Pengklasifikasian Bentuk Objek secara Real-Time. *Jurnal Teknik Elektro dan Komputer*, 13(1), 89-98.

Ouyang, F., & Jiao, P. (2021). Artificial Intelligence in education: The three paradigms. *International Journal of Educational Technology in Higher Education*, 18(1), 20.

Park, S. (2023). Application of Google Teachable Machine in Physics Experiments for Sound and Wave Classification. *Journal of Baltic Science Education*, 22(3), 472-485.

Pila, S., et al. (2021). Preschoolers' learning of physics concepts from a touch-screen game: The role of scaffolding. *Early Childhood Research Quarterly*, 55, 172-184.

Prahani, B. K., et al. (2020). The Effectiveness of the OR-IPA Teaching Model to Improve Students' Critical Thinking Skills on Vibration and Wave Topics. *Journal of Baltic Science Education*, 19(1), 112-125.

Putra, R. W. P. (2021). Pemanfaatan Teachable Machine Google dalam Pengenalan Kecerdasan Buatan bagi Peserta Didik. *Jurnal Teknologi Pendidikan*, 10(2), 143-152.

Putri, A. D., & Rusdiana, D. (2022). Implementation of Project-Based Learning on Vibration and Waves to Improve Students' Creative Thinking. *Journal of Science Education Research*, 6(1), 34-42.

Sari, I., et al. (2021). The Effect of STEM-Integrated Project-Based Learning on Students' Conceptual Understanding. *Journal of Physics: Conference Series*, 1806(1), 012024.

Sari, P. M., et al. (2023). Pengembangan media pembelajaran fisika berbasis AI untuk memvisualisasikan gelombang transversal dan longitudinal. *Jurnal Inovasi Pendidikan Fisika*, 12(2), 155-164.

Sperling, J., et al. (2024). Integrating No-Code AI Tools in STEM Classrooms: A Study on Student Conceptual Models. *Journal of Research on Technology in Education*, 56(2), 189-204.

Su, J., & Yang, W. (2022). Artificial Intelligence in Early Childhood Education: A Scoping Review. *Computers & Education: Artificial Intelligence*, 3, 100049.

Su, J., & Yang, W. (2023). Unpacking the Black Box of AI Education: A Project-Based Learning Approach. *Computers & Education*, 200, 104800.

Syamra, S. (2024). The Effect of Using STEM PjBL-Based Science Learning Modules on Students' Participation. *Jurnal Penelitian Pendidikan IPA*, 10(2), 612-619.

Tedre, M., et al. (2021). Teaching Machine Learning in K-12 Education: Mental Models and Concepts. *Proceedings of the 52nd ACM Technical Symposium on Computer Science Education*, 590-596.

Toivonen, T., et al. (2024). Co-Designing AI Education: Empowering Teachers to Integrate Machine Learning in Science Classrooms. *Research in Science & Technological Education*, 42(3), 345-364.

Tsan, J., et al. (2022). A Comparison of High School Students' Conceptual Understanding of AI Across Project-Based and Direct Instruction. *Computer Science Education*, 32(4), 412-435.

Vartiainen, H., et al. (2020). Machine Learning with Primary School Children: A Design-Oriented Study. *International Journal of Child-Computer Interaction*, 25, 100186.

Williams, R., et al. (2022). The Impact of Teachable Machine on Middle School Teachers' Perceptions of Science Lessons. *Journal of Science Education and Technology*, 31(5), 589-602.

Zhai, X., et al. (2021). A Review of Artificial Intelligence in STEM Education: Progress and Prospects. *Educational Society & Technology*, 24(4), 115-132.

Zimmermann-Niefield, A., et al. (2020). Youth Learning Machine Learning through Active Training of Physical Activity Classifiers. *Proceedings of the 2020 Interaction Design and Children Conference*, 125-136