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Augmented reality in vocational mechanical engineering education: a systematic literature review

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ABSTRACT

The integration of Augmented Reality (AR) in vocational and mechanical engineering education has become increasingly important in the era of Industry 4.0, where digital competence and practical skills are essential. This systematic literature review aims to identify research trends, methodologies, learning contexts, and challenges related to the use of AR in vocational mechanical engineering education. Guided by the PRISMA framework, a total of 13 empirical studies published between 2020 and 2025 were collected from Scopus and ScienceDirect databases and analysed based on research design, learning topics, and educational outcomes. The findings reveal that most studies employed quasi-experimental and R&D approaches, integrating AR into subjects such as mechanical systems, thermodynamics, structural analysis, CNC machining, and engineering drawing. Across these studies, AR consistently improved learning achievement, spatial reasoning, motivation, and engagement. However, common challenges included hardware limitations, model precision issues, usability constraints, and a lack of teacher readiness. These results highlight AR's strong potential to enhance technical learning experiences and bridge the gap between theoretical and practical understanding in vocational engineering education.

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Introduction

The rapid advancement of digital technology has profoundly transformed the landscape of education at all levels, from elementary schools to higher education institutions. This transformation has not only changed the way knowledge is delivered and accessed but also encouraged the integration of innovative tools and digital platforms to enhance learning effectiveness and engagement (Grodotzki et al., 2018). Along with the rapid development of Industry 4.0, vocational education faces new demands to produce graduates with high technical competence, digital literacy, and the ability to operate complex technology systems (Mojidra et al., 2025a). The trend of using digital resources in education stems from their ability to encourage active and independent learning, which in turn increases student engagement and understanding of the material (Rebello et al., 2024). In education, technology functions to coordinate people, ideas, procedures, and results so that the entire learning process runs in a directed manner and educational goals can be achieved effectively (Refdinal et al., 2023).

Technology has been shown to create immersive and contextual learning experiences across a variety of educational settings (Billinghurst, 2021; Marques et al., 2024; Motejlek & Alpay, 2021), making it a great potential in vocational education, especially in the field of mechanical engineering, which requires a high level of spatial and practical understanding. In the industrial sector, integrating technology to accelerate the transition towards the 4.0 industrial revolution is crucial, as we know that AR is one of the nine pillars of technological advancement in achieving Industry 4.0 (Wahab et al., 2023). AR can visualize internal machine components, provide visual workpieces when drawing visually, demonstrate assembly and maintenance processes, and simulate machining operations. (Ibáñez & Delgado-Kloos, 2018).

Based on previous studies, AR systems increase student motivation and help replicate remote laboratory experiences (Amouzgar & Mousavi, 2025). These advantages make AR particularly suitable for vocational students, who often learn through experiential and visual-spatial activities. Furthermore, AR can increase student motivation, engagement, and conceptual understanding by combining real-world practices with interactive virtual content (Hendriyani et al., 2019). AR can also serve as an effective tool for workshop supervision, allowing instructors or operators to monitor student activities in real time, verify adherence to safety procedures, and offer individualized guidance or assistance whenever necessary (Damgrave et al., 2024a). In this context, AR functions as an innovative pedagogical medium that enhances the teaching and learning process. At the same time, it serves as an introduction for engineering students to emerging industrial technologies, allowing them to explore and understand the potential applications of AR in future industry settings (Alawyah et al., 2024; Scaravetti & Doroszewski, 2019). This study also provides practical implications, as evidence showing that AR enhances students' academic self-efficacy highlights its positive potential for classroom implementation. Such findings may motivate more educators to adopt AR as part of their teaching practices (O'Connor & Mahony, 2023).

Mobile devices have become the primary tool for accessing information in various formats and, together with AR technology, have successfully formed a combination that facilitates learning and ensures the educational (Vásquez-Carbonell, 2022), The advent of advanced smart mobile devices and powerful software platforms has made AR more accessible to the general public, thereby enabling its effective integration into educational applications (Zhou et al., 2024). Several empirical studies have demonstrated the potential of AR in supporting vocational and technical education. For example, Ibáñez & Delgado-Kloos (2018) found that AR improves students' spatial reasoning and procedural knowledge in manufacturing tasks. Additionally, in AR training, AR technology can enhance learning effectiveness in terms of motivation, independent learning, and learning performance. Additionally, this method reduces the time and costs spent on training new employees, thereby facilitating (Chiang et al., 2022). Similarly, Suryanto et al. (2018) reported that AR-based lathe simulations increased students' motivation and skill performance in machining practices. However, despite these promising findings, the integration of AR into mechanical engineering and vocational education remains fragmented and lacks a comprehensive synthesis of evidence (Akçayır & Akçayır, 2017; Rebello et al., 2024) and according to constructivist learning theory, students construct knowledge through active learning, interacting with objects and elements in the environment (Jarutkamolpong & Kwangmuang, 2025). Garzón (2021) argue that the combination of these factors has highlighted AR technology, attracting the attention of developers around the world to create educational AR applications.

AR allows us to consider the evolution towards "augmented operators." This technology is currently still rarely used in higher education, especially for mechanical engineers (Achachagua & Chinchay, 2022). Publications discussing the use AR in education remain relatively scarce within the domain of mechanical engineering, as most existing studies are concentrated in the medical field. Nevertheless, the application of AR is expected to grow significantly in the future, extending its impact to various educational disciplines, including mechanical engineering education (Maier et al., 2022a). Furthermore, studies have noted that education in general currently faces several challenges, including maintaining student attention and engagement in the classroom and motivating students to learn independently; AR is one option for addressing this situation (Urbina Coronado et al., 2022). In some cases, there are still areas of study that are not suitable for using AR technology. The use of only 3D concepts as AR content does not provide a detailed explanation of these concepts. An example is mathematics, which is more important to calculate than to understand through images. There are many considerations for AR development, such as cost-effectiveness, maximum potential, and making it suitable for all ages, especially students (Blankenberg et al., 2022). However, very little research has been conducted on the application of AR in VET and its impact on the diverse special educational needs of students, such as learning difficulties (Liu et al., 2024). Therefore, a gap remains in understanding how AR has been specifically and effectively applied in the vocational environment of mechanical engineering.

In addition, previous studies varied greatly in terms of research design, type of AR technology (marker-based vs markerless), learning objectives, and outcome measures. Some studies focused on cognitive outcomes (knowledge and understanding), while others assessed affective and behavioural outcomes such as motivation, engagement, and skill performance (Mohamad et al., 2024; Vásquez-Carbonell, 2022). A systematic synthesis of these dimensions is needed to identify patterns, strengths, and limitations in the existing literature. Such a synthesis can provide evidence-based insights to educators, policymakers, and researchers on how AR contributes to vocational mechanical learning and where future research should be directed (Bacca et al., 2014; Marques et al., 2024). As other studies in various fields have noted, students are often unable to apply their theoretical knowledge practically, even though the materials used for AR appear identical to regular images/books at first glance (Kaur et al., 2020). The world of education must be able to adapt to current developments in science and technology, such as the use of AR technology in learning (Pradana et al., 2020).

The advancement of Industry 4.0 has increased the urgency for vocational mechanical engineering education to strengthen students' digital competence, spatial reasoning, and practical understanding of complex mechanical systems. Although Augmented Reality (AR) has shown promise in visualising internal machine components, supporting technical drawing, and simulating machining or assembly processes, research findings remain fragmented across varied contexts, AR types, and learning outcomes. As a result, the field still lacks a clear synthesis of how AR contributes to vocational mechanical competencies and under what conditions it is most effective, especially since many studies focus on non-vocational or higher engineering domains rather than mechanical vocational training.

In the era of Industry 4.0, which emphasizes the integration of advanced technologies within manufacturing systems and production facilities, Augmented Reality (AR) has emerged as a vital component in the engineering field. Industries have adopted AR for multiple purposes, such as developing maintenance and manufacturing programs, conducting training sessions, and visualizing complex assembly processes (Reljić et al., 2021; Santi et al., 2021; Takrouri et al., 2022). This paper explores how conducting a systematic literature review in mechanical engineering education enhances the understanding of AR's role in supporting learning within this field. It also outlines a technology that promotes future innovation in vocational education, aligning with the evolving needs of Industry 4.0 and future technological advancements.

Method

This study employs a Systematic Literature Review (SLR) approach, adhering to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. The review process consists of four main stages: Identification, Screening, and Eligibility to ensure a transparent and replicable selection of relevant studies. The primary objective is to identify, analyse, and synthesise research related to the implementation of Augmented Reality (AR) in vocational mechanical engineering education, encompassing both vocational high school and higher education contexts. The literature search covered publications from 2020 to 2025, accessed through two major databases: Scopus and ScienceDirect, as of September 30, 2025.

Table 1. Systematic Literature Review Search String

Database	Search String
Scopus	TITLE-ABS-KEY ((augmented reality) AND (mechanical engineering) AND (vocational education))
ScienDirecrt	((augmented reality) AND (mechanical engineering))

Source: September 2025 (Scopus and ScienDirect)

During the Identification stage, a comprehensive search using predefined keywords and Boolean operators (e.g., Table 1) yielded 309 records (155 from Scopus and 154 from ScienceDirect). After automated screening to remove irrelevant document types, 200 records remained for further review. In the Screening phase, titles and abstracts were evaluated, resulting in the exclusion of 129 records that were unrelated to AR or mechanical engineering fields, leaving 71 reports for retrieval. Of these, 34 were excluded due to the unavailability of complete texts, and 37 proceeded to the Eligibility assessment.

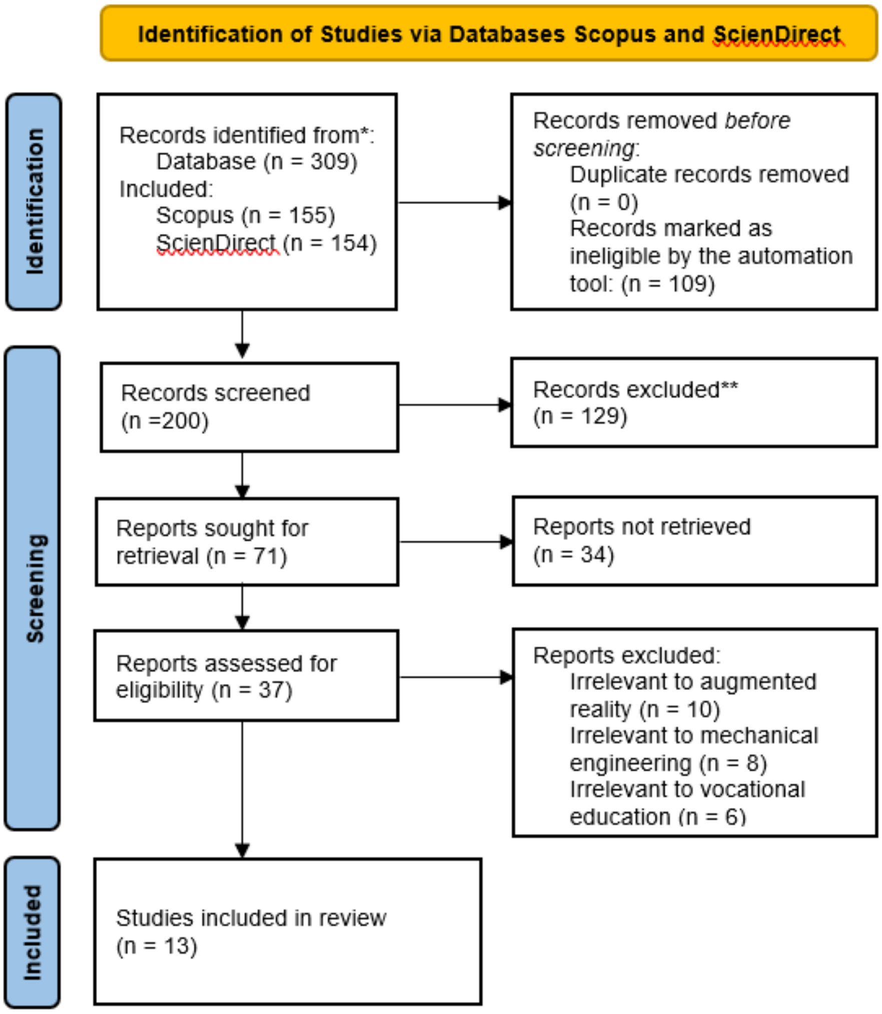

Figure 1. PRISMA flow diagram

At the Eligibility stage, inclusion and exclusion criteria (e.g. Table 2) were applied to ensure relevance and quality. Articles were excluded if they did not focus on AR, mechanical engineering, or vocational education, resulting in 13 studies meeting the eligibility standards. Finally, in the Inclusion stage, 13 studies were selected for synthesis and in-depth analysis. These studies provide empirical evidence on the integration of AR to enhance learning outcomes, engagement, and skill development in vocational mechanical engineering education. The complete process of article selection is presented in Fig. 1.

Table 2. Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Articles published between 2020 and 2025.	Articles published before 2020 or after 2025.
Studies that specifically implement Augmented Reality (AR) in teaching or training.	Studies focusing on Virtual Reality (VR), Mixed Reality (MR), or Extended Reality (XR) without a specific AR application.
Conducted in the context of vocational mechanical engineering education, including vocational high schools and higher vocational institutions.	Conducted in industrial or professional training contexts, or in non-vocational education settings.
Empirical papers, including journal articles, literature reviews, or conference proceedings, that report AR implementation and its effects on students' learning or performance.	Non-empirical papers, such as conceptual works, editorials, book chapters, conference abstracts, or studies without implementation data.
Articles that provide sufficient methodological information, including subject details, learning environment, and student feedback.	Articles lacking essential methodological details (e.g., no learning context or measured outcomes).

Results and Discussions

Research Distribution and Characteristics

The systematic review analysed 13 selected studies published between 2020 to 2025, focusing on the implementation of AR in vocational and higher education contexts related to mechanical engineering.

Table 3. Distribution of Reviewed Articles Based on Country and Research Method

Author	Country	Method
Scaravetti & Doroszewski (2019)	Prancis	Quasi-experiments
Achachagua & Chinchay (2022)	Peru	Quasi-experiments
Camilleri (2025)	Malta	Structural Equation Modelling (SEM)
Waskito et al. (2024)	Indonesia	R&D (Research & Development)
Mojidra et al. (2025a)	Amerika Serikat	Quasi-experiments
Park (2025a)	Korea Selatan	Literature Review
Suhail et al. (2024a)	Uni Emirat Arab	Systematic Review (PRISMA)
Weis et al. (2024a)	Slovakia	Quasi-experiments
Ghobrial et al. (2024)	Francis	Quantitative comparative experiment
Qu, Ma, et al. (2022)	China	Quasi-experiments
Marinakis et al. (2021a)	Yunani	R&D (Research & Development)
Maier et al. (2022a)	Jerman	R&D (Research & Development)
Damgrave et al. (2024a)	Belanda	Case Study

Based on Table 3, most of the studies originate from several continents. Among the entire list of countries, there are four from Asia, six from Europe, and two from America. Methodologically, the reviewed studies employed a variety of research approaches to investigate the use of AR in education. Most studies adopted quasi-experimental designs and mixed-method approaches to examine the effectiveness of AR in learning contexts. Several studies have applied R&D models to design, develop, and validate AR-based learning media. Additionally, quantitative techniques such as SEM were employed to analyse the factors influencing behavioural intentions toward AR adoption. Several studies also implemented systematic and literature reviews to synthesise existing findings. In contrast, others employed case study and comparative experimental methods to explore the integration of AR within technical and vocational education settings.

Learning Contexts and Learning Outcomes

AR applications are integrated into various mechanical engineering topics; the following explanation is provided in Table 4.

Table 4. Distribution of Reviewed Studies by Integrated Materials and Learning Outcomes

Author	Integrated Materials	Outcome
Scaravetti & Doroszewski (2019)	Mechanical systems of electric door actuators, aircraft turbines, and automobile gearboxes)	Learning achievement; Engagement
Achachagua & Chinchay (2022)	Engineering drawing (representation of threaded joints, welded joints, and piping systems)	Learning achievement; Engagement
Camilleri (2025)	Technical drawing using the Zappar platform (Zapworks)	Learning achievement; Engagement
Waskito et al. (2024)	Learning engineering mechanics	Engagement
Mojidra et al. (2025a)	Learning Structural Analysis	Learning Achievement; Engagement
Park (2025a)	Thermodynamics	Learning Achievement; Engagement
Suhail et al. (2024a)	The use of AR in engineering education	Learning Achievement; Skill Performance; Engagement
Weis et al. (2024a)	Gearbox mechanism	Learning Achievement; Engagement
Ghobrial et al. (2024)	CNC machining centre	Learning Achievement; Engagement
Qu, Ma, et al. (2022)	Engineering Drawing	Learning Achievement; Engagement
Marinakis et al. (2021a)	Engineering Drawing	Learning Achievement; Engagement
Maier et al. (2022a)	Learning the structure and function of a lathe	Learning Achievement; Skill Performance; Engagement
Damgrave et al. (2024a)	Machine operation and occupational safety training	Learning Achievement; Skill Performance; Engagement

The reviewed studies integrated AR technology into various engineering learning materials, reflecting diverse application areas across technical education. The integrated materials ranged from mechanical systems such as electric door actuators, turbines, and gearboxes, to engineering drawings, thermodynamics, structural analysis, and machine operation training. Methodologically, these implementations primarily targeted learning outcomes related to learning achievement, engagement, and skill performance.

These contexts demonstrate AR's flexibility in bridging abstract conceptual learning and practical visualisation, particularly where limited workshop tools or physical equipment hinder real-world practice. Across the reviewed studies, several learning outcomes were consistently reported: (1) Knowledge and academic achievement: AR enhanced conceptual understanding of mechanical mechanisms (Scaravetti & Doroszewski, 2019); (2) Skill performance and cognitive processing: Students demonstrated improved spatial reasoning and problem-solving (Achachagua & Chinchay, 2022); (3) Motivation and engagement: AR's interactivity increased learner enthusiasm and time-on-task engagement (Waskito et al., 2024); (4) Retention and attitude: Sustained memory retention and positive attitudes toward technology were observed, though rarely measured longitudinally. Overall, AR was found to significantly improve learning achievement and motivation, aligning with constructivist learning principles emphasising active and situated learning.

Effectiveness and Student Engagement

The results of a review of several papers, a summary of learning outcomes and aspects of engagement identified from various studies that integrate AR in the context of vocational and technical education can be described in Table 5.

Table 5. Effectiveness and Engagement Outcomes of AR in Vocational and Engineering Education

Author	Effectiveness	Students Engagement
Scaravetti & Doroszewski (2019)	AR use improved understanding of complex mechanical systems; AR users scored 22.6% higher than the control group.	Increased motivation, interactivity, and enjoyment; 93.3% satisfied, 84.4% found AR helpful, 91.1% reported time efficiency.
Achachagua & Chinchay (2022)	Significant improvement in spatial ability and technical drawing comprehension; 64% of the AR group reached the "expected" level vs. 8% in the control.	AR enhanced focus, interactivity, and learning enthusiasm.
Camilleri (2025)	Behavioural intention is influenced by Performance Expectancy, Effort Expectancy, Hedonic Motivation, and Cognitive Presence.	Hedonic motivation significantly boosted engagement and reflective, collaborative learning.
Waskito et al. (2024)	AR media enhanced conceptual understanding and supported self-learning, providing a clear visualisation of abstract concepts.	Increased interest and motivation through animation, audio, and 3D simulations; supported self-paced and interactive learning.
Mojidra et al. (2025a)	Effective in improving consistency and reducing score variation ($p < 0.05$).	High engagement and enjoyment (mean = 4.4–4.7/5); students found AR helpful for visualising abstract concepts.
Park (2025a)	Although not experimentally measured, thermal feedback improved realism and immersion.	Multisensory feedback enhanced the sense of presence, engagement, and user comfort in AR/VR simulations.
Suhail et al. (2024a)	Highly effective in improving conceptual understanding, visualisation, and collaboration.	Increased motivation, 3D visualisation engagement, and problem-based learning participation.
Weis et al. (2024a)	Very effective; AR and 3D improved visualisation, self-exploration, and experience-based learning.	94% found the app engaging, 71% wanted to continue learning, and 100% recommended AR; students felt more confident and industry-ready.
Ghobrial et al. (2024)	High effectiveness; improved task completion efficiency, depending on headset adaptation.	AR is perceived as engaging but initially challenging; videos are easier to use for autonomy.
Qu, Ma, et al. (2022)	Very effective; AR improved visual comprehension, learning efficiency, and active exploration.	85% reported being "very satisfied" or "satisfied"; motivation and interest increased sharply.
Marinakis et al. (2021a)	Highly effective in visualising CAD-CAM concepts; improved time efficiency.	Students found AR "interesting and interactive" for complex geometry.
Maier et al. (2022a)	Effective, MR-aided visualisation of complex mechatronic systems safely and realistically.	Participants described the experience as "immersive," "interesting," and "effective" (mean score 5.89/7).
Damgrave et al. (2024a)	Practical AR-based training was more precise and more consistent than manuals; it improved efficiency and safety.	Students were more engaged and motivated; instructors noted that praise features increased motivation.

Overall, the reviewed studies consistently demonstrate that AR enhances learning effectiveness, particularly in visualising complex mechanical and technical concepts, improving spatial understanding, and supporting self-directed learning. Moreover, AR integration significantly increases student engagement, motivation, and satisfaction, making it a promising pedagogical tool for engineering and vocational education.

AR Implementation Challenges

Table 6. Implementation Challenges Encountered

Author	Challenges	Description
Scaravetti & Doroszewski (2019)	3D Model Precision & Device Limitations	Limited accuracy of 3D models, hardware constraints of the HoloLens, and difficulties in managing occlusions.
Achachagua & Chinchay (2022)	Hardware & Accessibility Constraints	Requires high-performance mobile devices for stable AR display; unequal access to advanced Technology; institutional resource limitations.
Camilleri (2025)	Lack of User Experience & Support	Most users (87%) are AR beginners due to insufficient technical support and training.
Waskito et al. (2024)	Application Stability	AR applications must remain responsive; marker-based tracking is often affected by lighting and physical marker conditions.
Mojidra et al. (2025a)	Design & Scalability Limitations	Restricted to single-floor or short-term use; adaptation needed due to marker and ground-plane detection issues.
Park (2025a)	Technical & Design Constraints	Low energy efficiency, heavy hardware, limited thermal sensitivity, and difficulty scaling actuators for large areas.
Suhail et al. (2024a)	Infrastructure & Pedagogical Barriers	Limited technological infrastructure, lack of teacher training, device compatibility problems, high cognitive load, and absence of standard evaluation frameworks.
Weis et al. (2024a)	Sample & Contextual Limitations	Technical issues on some devices (12%); small sample sizes; limited local university context.
Ghobrial et al. (2024)	Usability & Ergonomic Challenges	Heavy headsets, focus and lighting difficulties, unstable hand tracking; users need time to adapt to gestures.
Qu, Ma, et al. (2022)	Digital Resource Constraints	Limited 3D model variations and insufficient digital resources in applications.
Marinakis et al. (2021a)	User Interface Sensitivity	Model rotation is too sensitive; users request additional features, such as the ability to import external models.
Maier et al. (2022a)	Spatial Alignment Difficulties	Misalignment between holograms and real-world objects requires training with HoloLens 2.
Damgrave et al. (2024a)	Cost & Technological Dependency	High device cost, complex system integration, and dependence on advanced technologies.

Overall, the primary challenges of implementing AR in engineering and vocational education include technical limitations (such as system stability, model precision, and hardware), infrastructural and resource constraints, and pedagogical difficulties, including teacher training and user adaptation. However, the findings highlight the importance of comprehensive teacher training and pedagogical integration to ensure the sustainable adoption of AR in engineering and vocational education (Camilleri, 2025; Suhail et al., 2024). Future studies are encouraged to explore large-scale implementations and the integration of real-time sensor data through digital twin systems to enhance interactivity and authenticity in learning environments (Maier et al., 2022; Weis et al., 2024).

Additionally, developing lightweight AR software that can run efficiently across various devices is essential to promote accessibility and inclusivity among all learners, regardless of their hardware limitations (Ghobrial et al., 2024; Marinakis et al., 2021). These constraints underscore the need for cross-disciplinary collaboration between educators, engineers, and software developers to produce scalable and pedagogically sound AR solutions (Achachagua & Chinchay, 2022).

The findings of this review collectively highlight the pedagogical effectiveness and challenges of integrating AR within the context of vocational and mechanical engineering education. AR has consistently demonstrated its capacity to enhance conceptual understanding, spatial visualisation, learner engagement, and skill performance, aligning with constructivist and experiential learning principles (Achachagua & Chinchay, 2022; Scaravetti & Doroszewski, 2019; Suhail et al., 2024).

Across multiple studies, AR proved effective in improving learners' cognitive comprehension of complex mechanical systems and abstract technical representations. For instance, Scaravetti & Doroszewski (2019) demonstrated that AR-based simulations increased students' understanding of mechanical actuators and gear systems, while Achachagua & Chinchay (2022) reported significant improvements in spatial reasoning and technical drawing performance through interactive 3D visualisations. These outcomes corroborate the argument that AR enables situated cognition, allowing learners to visualise mechanisms that are otherwise difficult to observe in real-world workshops. Similarly, studies by Camilleri (2025) and Mojidra et al. (2025) confirmed that AR-based learning environments facilitate cognitive presence, self-regulated learning, and reflective thinking, driven by hedonic motivation and visual immersion. The integration of AR within mechanical engineering modules, such as thermodynamics (Park, 2025), CNC machining (Ghobrial et al., 2024), and structural mechanics (Maier et al., 2022) reinforces its role in transforming abstract theoretical content into experiential learning environments. This aligns with experiential learning theory, which emphasises the transition from passive knowledge acquisition to active, discovery-oriented learning.

A recurring theme across the reviewed studies is AR's capacity to increase engagement and motivation, both affective and behavioural. Students expressed greater enthusiasm and persistence when interacting with AR applications, citing their visual realism and interactivity as significant motivating factors (Waskito et al., 2024; Weis et al., 2024). The use of gamified elements and 3D visualisation tools has been shown to elevate learning enjoyment and time-on-task, supporting earlier claims by Camilleri (2025) that hedonic motivation plays a crucial role in technology adoption within education. Furthermore, studies such as those by Suhail et al. (2024) and Qu et al. (2022) have revealed that AR promotes collaborative and inquiry-based learning, allowing students to co-construct understanding through shared exploration. This aligns with the socio-constructivist approach, where interaction and communication in augmented environments facilitate deeper conceptualisation. However, as Ghobrial et al. (2024) noted, user comfort and ergonomic design remain significant factors influencing engagement, as heavy or complex hardware may reduce sustained participation.

In addition to cognitive and affective outcomes, AR significantly contributes to the acquisition of psychomotor and technical skills. Studies integrating AR in CNC machining Ghobrial et al. (2024), safety training (Damgrave et al., 2024) and mechanical assembly (Marinakis et al., 2021) have found that AR enhances learners' hands-on readiness by simulating real industrial scenarios in safe and cost-efficient environments. Maier et al. (2022) further demonstrated that AR and MR platforms support procedural learning and mechanical troubleshooting by allowing repeated practice without the risk of equipment damage or safety hazards.

Despite its promise, several technical and pedagogical barriers hinder the large-scale adoption of AR. Many studies identified issues related to hardware dependence, 3D model precision, and application stability (Mojidra et al., 2025; Scaravetti & Doroszewski, 2019; Waskito et al., 2024). Marker-based tracking, lighting sensitivity, and spatial alignment errors (Maier et al., 2022) often affect learning continuity and user immersion. Moreover, cost and accessibility barriers remain prevalent, especially in developing contexts where high-end devices and stable internet connectivity are not universally available (Achachagua & Chinchay, 2022; Damgrave et al., 2024).

The studies reviewed indicate that AR can improve conceptual understanding, spatial reasoning, and certain technical skills in vocational mechanical engineering, yet these benefits appear inconsistent due to variations in research design, learner readiness, and AR technology used. While several studies report strong gains in comprehension and engagement, others show only moderate improvements when students have low prior skills or when hardware limitations such as unstable tracking, poor ergonomics, and alignment errors disrupt learning. Motivation and engagement also prove sensitive to instructional quality, as inadequate scaffolding often weakens AR's impact. Moreover, many studies employ short interventions, small samples, or lack control groups, limiting the reliability of their findings. Issues of teacher preparedness and uneven AR content design further constrain pedagogical effectiveness. Collectively, the evidence suggests that AR's success depends heavily on technological stability, instructional design, and contextual alignment, signalling the need for more rigorous and sustained research to determine how AR can be integrated optimally into vocational mechanical curricula.

The cumulative evidence suggests that future AR research and practice in vocational mechanical education should shift from pilot experimentation to the integration of a systemic curriculum. This entails embedding AR into competency-based learning frameworks, linking it to industry 4.0 technologies such as digital twins, IoT, and simulation-based manufacturing systems (Maier et al., 2022; Weis et al., 2024). To ensure sustainability, future studies should prioritise the development of lightweight, cross-platform AR applications that can operate on low-spec devices while maintaining pedagogical quality (Ghobrial et al., 2024; Marinakis et al., 2021).

Conclusions

AR has demonstrated robust potential as an instructional innovation that enhances learning outcomes in vocational mechanical education. It enables immersive, student-centred, and competency-based learning experiences that align with the demands of Industry 4.0. Nevertheless, realising its full educational value requires addressing technological, pedagogical, and infrastructural challenges through collaborative design, teacher empowerment, and standardised evaluation approaches. Future research should therefore focus on developing adaptive, scalable AR ecosystems that integrate seamlessly into mechanical engineering curricula and industrial training environments.

Furthermore, establishing evaluation frameworks that measure AR's impact across cognitive, affective, and psychomotor domains will be crucial. Such frameworks should align with vocational learning standards to comprehensively assess learners' readiness for industrial practice. Institutional strategies should also promote teacher collaboration, co-design, and ongoing digital literacy training to strengthen implementation capacity.

References

Achachagua, Y. H. Y., & Chinchay, H. E. G. (2022). Augmented reality and its effect on the spatial ability of mechanical engineering students. Revista de Educación a Distancia, 22(70). https://doi.org/10.6018/red.509931

Akçayır, M., & Akçayır, G. (2017). Advantages and challenges associated with augmented reality for education: A systematic review of the literature. Educational Research Review, 20, 1–11. https://doi.org/10.1016/j.edurev.2016.11.002

Alawyah, K., Giatman, Rizal, F., & Irfan, D. (2024). Needs Analysis of Augmented Reality (AR) Based Learning Media Development in Road and Bridge Construction Subjects. Jurnal Penelitian Pendidikan IPA, 10(9), 6993–6700. https://doi.org/10.29303/jppipa.v10i9.8475

Amouzgar, K., & Mousavi, M. (2025). Holomech: an extended reality tool for supporting student motivation and perceived spatial reasoning in structural mechanics. Virtual Reality, 29(3), 121. https://doi.org/10.1007/s10055-025-01183-4

Bacca, J., Baldiris, S., Fabregat, R., & Graf, S. (2014). Augmented Reality Trends in Education: A Systematic Review of Research and Applications. In Educational Technology & Society (Vol. 17, Issue 4).

Billinghurst, M. (2021). Grand Challenges for Augmented Reality. Frontiers in Virtual Reality, 2. https://doi.org/10.3389/frvir.2021.578080

Blankenberg, C., Gebel-Sauer, B., & Schubert, P. (2022). Using a graph database for the ontology-based information integration of business objects from heterogenous Business Information Systems.

Procedia Computer Science, 196, 314–323. https://doi.org/10.1016/j.procs.2021.12.019

Camilleri, C. (2025). Investigating the Factors Influencing Augmented Reality Adoption in Blended Learning Environments for Mechanical Engineering Degree Students at the University of Malta. International Journal of Information and Education Technology, 15(5), 912–921. https://doi.org/10.18178/ijiet.2025.15.5.2297

Chiang, F. K., Shang, X., & Qiao, L. (2022). Augmented reality in vocational training: A systematic review of research and applications. Computers in Human Behavior, 129. https://doi.org/10.1016/j.chb.2021.107125

Damgrave, R. G. J., Knollema, S. L., & Lutters, E. (2024). Engineering workshop education and supervision: AR for machine operation guidance and safety instructions. Procedia CIRP, 128, 430–435. https://doi.org/10.1016/j.procir.2024.03.023

Garzón, J. (2021). An Overview of Twenty-Five Years of Augmented Reality in Education. Multimodal Technologies and Interaction, 5(7), 37. https://doi.org/10.3390/mti5070037

Ghobrial, M., Seitier, P., Lagarrigue, P., Galaup, M., & Gilles, P. (2024). Effectiveness of machining equipment user guides: A comparative study of augmented reality and traditional media. Materials Research Proceedings, 41, 2320–2328. https://doi.org/10.21741/9781644903131-255

Grodotzki, J., Ortelt, T. R., & Tekkaya, A. E. (2018). Remote and Virtual Labs for Engineering Education 4.0. 26, 1349–1360. https://doi.org/10.1016/j.promfg.2018.07.126

Hendriyani, Y., Effendi, H., Novaliendry, D., & Effendi, H. (2019). Augmented Reality Sebagai Media Pembelajaran Inovatif Di Era Revolusi Industri 4.0. Jurnal Teknologi Informasi Dan Pendidikan, 12(2), 63–68. https://doi.org/10.24036/tip.v12i2.244

Ibáñez, M.-B., & Delgado-Kloos, C. (2018). Augmented reality for STEM learning: A systematic review. Computers & Education, 123, 109–123. https://doi.org/10.1016/j.compedu.2018.05.002

Jarutkamolpong, S., & Kwangmuang, P. (2025). Enhancing undergraduate creative thinking through a constructivist mobile learning application: Design, development, and evaluation. Thinking Skills and Creativity, 57, 101866. https://doi.org/10.1016/j.tsc.2025.101866

Kaur, D. P., Mantri, A., & Horan, B. (2020). Enhancing Student Motivation with use of Augmented Reality for Interactive Learning in Engineering Education. Procedia Computer Science, 172, 881–885. https://doi.org/10.1016/j.procs.2020.05.127

Liu, Y., Zhan, Q., & Zhao, W. (2024). A systematic review of VR/AR applications in vocational education: models, affects, and performances. Interactive Learning Environments, 32(10), 6375–6392. https://doi.org/10.1080/10494820.2023.2263043

Maier, W., Rothmund, J., Möhring, H. C., Dang, P. D., Hoffarth, E., Zinn, B., & Wyrwal, M. (2022). Experiencing the structure and features of a machine tool with mixed reality. Procedia CIRP, 106, 244–249. https://doi.org/10.1016/j.procir.2022.02.186

Marinakis, A., Mania, K., & Antoniadis, A. (2021). Augmented reality for cad-cam training featuring 3d interactive geometric transformations. Computer-Aided Design and Applications, 18(3), 561–570. https://doi.org/10.14733/cadaps.2021.561-570

Marques, B., Santos, B. S., & Dias, P. (2024). Ten years of immersive education: Overview of a Virtual and Augmented Reality course at postgraduate level. Computers & Graphics, 124, 104088. https://doi.org/10.1016/j.cag.2024.104088

Mohamad, S. A., Zaharudin, R., Ariffin, H. F., & Abdullah, S. (2024). A SYSTEMATIC REVIEW EXPLORING THE IMPACT OF AUGMENTED REALITY ON TEACHING MODULES IN VOCATIONAL EDUCATION. Journal of Contemporary Social Science and Education Studies, 4(3), 177–189. https://doi.org/10.5281/zenodo.14064593

Mojidra, R., Li, J., Crane, A., & Taher, S. A. (2025). Immersive learning for structural analysis through mobile augmented reality and the MOLA structural kit. Computers and Education: X Reality, 7. https://doi.org/10.1016/j.cexr.2025.100100

Motejlek, J., & Alpay, E. (2021). Taxonomy of Virtual and Augmented Reality Applications in Education. IEEE Transactions on Learning Technologies, 14(3), 415–429. https://doi.org/10.1109/TLT.2021.3092964

O'Connor, Y., & Mahony, C. (2023). Exploring the impact of augmented reality on student academic self-efficacy in higher education. Computers in Human Behavior, 149, 107963. https://doi.org/10.1016/j.chb.2023.107963

Park, M. (2025). Recent Advances in Wearable Thermal Devices for Virtual and Augmented Reality. In Micromachines (Vol. 16, Issue 4). Multidisciplinary Digital Publishing Institute (MDPI).

https://doi.org/10.3390/mi16040383

Pradana, Y. J., Syahri, B., Primawati, P., & Waskito, W. (2020). Use Augmented Reality Interactive Learning Media on Basic Mechanical Engineering Work Subjects at SMK Negeri 1 Batipuh. Jurnal Vokasi Mekanika (VoMek), 2(4), 129–134. https://doi.org/10.24036/vomek.v2i4.162

Qu, J., Ma, B., Zheng, L., & Kang, Y. (2022). Design and Implementation of Teaching Assistant System for Mechanical Course based on Mobile AR Technology. International Journal of Advanced Computer Science and Applications, 13(4). https://doi.org/10.14569/IJACSA.2022.0130410

Rebello, C. M., Deiró, G. F., Knuutila, H. K., Moreira, L. C. de S., & Nogueira, I. B. R. (2024). Augmented reality for chemical engineering education. Education for Chemical Engineers, 47, 30–44. https://doi.org/10.1016/j.ece.2024.04.001

Refdinal, R., Adri, J., Prasetya, F., Tasrif, E., & Anwar, M. (2023). Effectiveness of Using Virtual Reality Media for Students' Knowledge and Practice Skills in Practical Learning. JOIV : International Journal on Informatics Visualization, 7(3), 688–694. https://doi.org/10.30630/joiv.7.3.2060

Scaravetti, D., & Doroszewski, D. (2019). Augmented Reality experiment in higher education, for complex system appropriation in mechanical design. Procedia CIRP, 84, 197–202. https://doi.org/10.1016/j.procir.2019.04.284

Suhail, N., Bahroun, Z., & Ahmed, V. (2024). Augmented reality in engineering education: enhancing learning and application. In Frontiers in Virtual Reality (Vol. 5). Frontiers Media SA. https://doi.org/10.3389/frvir.2024.1461145

Suryanto, A., Kusumawati, D. A., & Sanhoury, I. M. H. (2018). Development of Augmented Reality Technology Based Learning Media of Lathe Machines. Jurnal Pendidikan Teknologi Dan Kejuruan, 24(1), 32–38. https://doi.org/10.21831/jptk.v24i1.18245

Urbina Coronado, P. D., Demeneghi, J. A. A., Ahuett-Garza, H., Orta Castañon, P., & Martínez, M. M. (2022). Representation of machines and mechanisms in augmented reality for educative use. International Journal on Interactive Design and Manufacturing (IJIDeM), 16(2), 643–656. https://doi.org/10.1007/s12008-022-00852-x

Vásquez-Carbonell, M. (2022). A Systematic Literature Review of Augmented Reality in Engineering Education: Hardware, Software, Student Motivation & Development Recommendations. Digital Education Review, 41, 249–267.

Wahab, R. M., Taharudin, A. I., Hemdi, A. R., Noor, N. M. M., Zubair, A. F., & Azmi, N. N. (2023). Interactive Visualization to Enhance Learning Experienced on Machining Process of EDM Wire Cut Through Augmented Reality (AR). 2023 IEEE 12th International Conference on Engineering Education (ICEED), 1–6. https://doi.org/10.1109/ICEED59801.2023.10264037

Waskito, Fortuna, A., Prasetya, F., Wulansari, R. E., Nabawi, R. A., & Luthfi, A. (2024). Integration of Mobile Augmented Reality Applications for Engineering Mechanics Learning with Interacting 3D Objects in Engineering Education. International Journal of Information and Education Technology, 14(3), 354–361. https://doi.org/10.18178/ijiet.2024.14.3.2057

Weis, P., Smetanka, L., Hrček, S., & Vereš, M. (2024). Interactive Application as a Teaching Aid in Mechanical Engineering. Computers, 13(7). https://doi.org/10.3390/computers13070170

Zhou, Z., Oveissi, F., & Langrish, T. (2024). Applications of augmented reality (AR) in chemical engineering education: Virtual laboratory work demonstration to digital twin development. Computers & Chemical Engineering, 188, 108784. https://doi.org/10.1016/j.compchemeng.2024.108784