

Enhancing vocational education through augmented reality: Android-based learning media for CNC TU-2A instruction in technical and vocational high schools

Rezky Azhari Salim*, Syahril and Nelvi Erizon

Department of Mechanical Engineering, Faculty of Engineering, Universitas Negeri Padang, Indonesia

*Corresponding Author: rezkyazhari24@gmail.com

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Abstract: The rapid evolution of digital technologies has opened new opportunities for transforming vocational education, particularly in CNC (Computer Numerical Control) machining. Despite its vital role in preparing skilled workers, CNC instruction in Indonesian vocational schools remains constrained by teacher-cantered methods, static materials, and limited access to costly machines, resulting in low engagement and achievement. This study aimed to design, implement, and evaluate Android-based Augmented Reality (AR) learning media for CNC TU-2A machines to enhance students' cognitive performance, psychomotor skills, and classroom participation. Using a Classroom Action Research (CAR) model across two cycles, the research involved 31 eleventh-grade Mechanical Engineering students at SMK Negeri 5 Padang. Data were collected through cognitive tests, student activity observations, and surveys. Results showed significant improvements: average cognitive scores rose from 75.91 to 82.47, classical mastery increased from 54.83% to 100%, and psychomotor scores improved by 3.24 points. Student learning activities also climbed from 72.2% to 80.4%, with discussion and collaboration showing the highest gain (17%). While barriers such as device limitations and technical issues arose, they were addressed through device sharing, offline content, and teacher mentoring. Findings confirm AR as an effective, scalable tool for modernizing CNC instruction, fostering engagement, and preparing vocational students for Industry 4.0 learning demands.

Keywords: augmented reality; CNC TU-2A; Android learning media; vocational education; student engagement; psychomotor skills

1. Introduction

Vocational education plays a critical role in preparing a skilled workforce that can meet the demands of today's rapidly evolving industries ([McGrath & Yamada, 2023](#); [Prasetya et al., 2025](#)). Technical and Vocational High Schools (*Sekolah Menengah Kejuruan/SMK*) in Indonesia are tasked with equipping students with the competencies needed to enter the job market immediately after graduation. Among the essential competencies is CNC (Computer Numerical Control) machining, a cornerstone of modern manufacturing that requires both theoretical understanding and practical mastery of machines such as CNC lathes and milling units ([Kumar et al., 2023](#); [Obe et al., 2022](#); [Yao et al., 2024](#)).

Despite its importance, CNC instruction in SMKs continues to face persistent challenges ([Wahyu et al., 2024](#)). Learning remains heavily dependent on teacher-centered lectures, static job sheets, and limited access to expensive machine tools ([Muskhir et al., 2024](#); [Prasetya et al., 2023, 2024](#)). These constraints lead to low engagement and poor retention of complex technical concepts, as evidenced by the mid-semester exam at SMK Negeri 5 Padang, where only 28.12% of students in the XI Mechanical Engineering class met the Minimum Mastery Criteria (KKM) of 75, with an average class score of 68.88% ([Fadillah et al., 2024](#); [Permana et al., 2024](#)). This gap underscores the urgent need for more interactive and accessible

instructional strategies to support both theory and practice.

The emergence of Augmented Reality (AR) offers a transformative opportunity to address these challenges. AR overlays digital 3D objects into real-world environments in real-time, enabling learners to interact with virtual models as if they were tangible ([Dargan et al., 2023](#); [Papanastasiou et al., 2019](#)). In technical education, AR has proven to improve engagement, comprehension, and cost efficiency, particularly in scenarios where physical tools are limited. Studies by ([Samala & Amanda, 2023](#)) and ([Prasetya et al., 2024](#)) demonstrated that AR-based CNC applications not only reduced training costs but also enhanced students' visualization of machine operations and programming.

Additionally, despite its promise, the use of AR in Indonesian vocational education especially for CNC TU-2A instruction remains underexplored. Previous studies have focused on general AR applications or CNC milling, leaving a research gap in AR-assisted teaching for CNC lathes at the secondary vocational level ([Ibarra Kwick et al., 2024](#); [Morales Méndez & del Cerro Velázquez, 2024](#)). This study addresses that gap by developing and implementing an Android-based AR learning media tailored for the CNC TU-2A machine, aiming to improve both cognitive learning outcomes and classroom engagement.

This research sets out with two primary objectives: (1) to design and implement AR-based instructional media for CNC TU-2A, and (2) to evaluate its impact on students' understanding and participation in the learning process. The study's novelty lies in its integration of mobile AR technology with CNC vocational training in Indonesia, creating a scalable, cost-effective, and immersive learning solution. By merging advanced visualization with hands-on interaction, this research contributes to the modernization of technical education, offering insights for educators and policymakers seeking to bridge the gap between conventional teaching and Industry 4.0 learning demands.

2. Methods

2.1 Research design

This study employed Classroom Action Research (CAR), a research approach designed to address real classroom situations and systematically solve instructional problems through cycles of intervention ([Bleicher, 2014](#); [Ceylan & Comoglu, 2024](#)). CAR provides a structured framework for improving teaching practices by implementing iterative phases of planning, action, observation, and reflection ([Kitchen & Stevens, 2008](#)). The model adopted for this study followed John Elliot's CAR framework, which emphasizes the teacher's role as an active researcher in designing, implementing, evaluating, and refining instructional strategies.

The research was conducted in two cycles, with each cycle encompassing four core stages: (1) Planning, (2) Action, (3) Observation, and (4) Reflection as illustrated in Figure 1. During the planning stage, lesson plans, jobsheets, and assessment instruments were designed to align with the CNC TU-2A learning objectives. In the action stage, an Android-based Augmented Reality (AR) learning media was implemented to support the teaching process. The observation stage involved systematic monitoring of student engagement, documentation of learning outcomes, and recording student responses during lessons ([Ahmadi, Golchehreh, Mohammadi et al., 2023](#); [Ahshan, 2021](#)). Finally, in the reflection stage, researchers and teachers collaboratively analyzed findings from each cycle to identify successes, challenges, and opportunities for improvement, which then informed revisions for the next cycle.

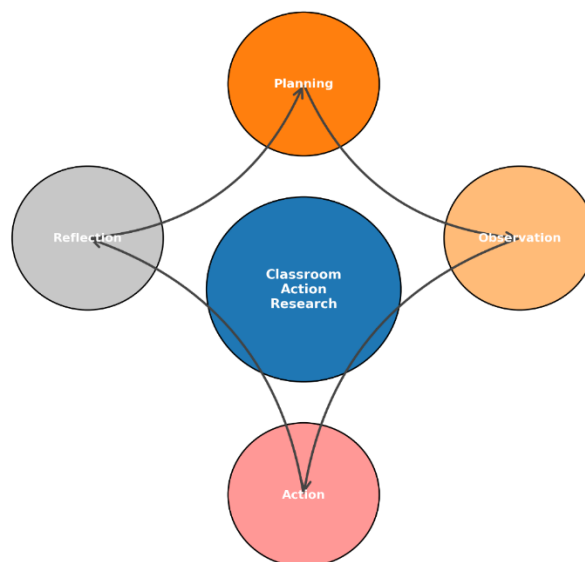


Figure 1. Classroom action research cycle

2.2 Research subjects and sampling

A total sampling technique was applied, whereby all students in the target class were included as participants. The study involved 31 eleventh-grade Mechanical Engineering students from SMK Negeri 5 Padang, ensuring that the data captured represented the entire class population.

2.3 Research flow and procedure

The research procedure was structured into two Classroom Action Research (CAR) cycles conducted over a four-week period. Each week had a specific focus, starting from the preparation of instructional materials to the implementation, observation, and evaluation of AR-based learning interventions. This staged approach allowed for iterative improvement, ensuring that each cycle was built on the findings and reflections of the previous one. The detailed timeline of activities for each week is outlined in Table 1.

Table 1. Classroom Action Research (CAR) implementation timeline and activities

Week	Activities
Week 1	Designing lesson plans (RPP) & job sheets, Introduction to CNC TU-2A AR Media, Administering assessment instruments
Week 2	Using AR Media, Student Observation, Evaluation of obtained results, Analysis of results and Learning Revision
Week 3	Adjustment of Material and Additional Content
Week 4	Using AR Media, CNC TU-2A Practice, Final Evaluation, Comparing Improvement Results of Cycle 1 and Cycle 2

2.4 Research instruments

The primary instrument used in this study was a multiple-choice cognitive test designed to measure students' understanding of CNC TU-2A operations. The instrument comprised 22 items, carefully constructed to evaluate both theoretical knowledge and applied technical skills essential for CNC machining learning outcomes. The test was based on the core competencies outlined in the curriculum for the CNC Lathe Machine subject and aligned with the research objective of assessing how Augmented Reality (AR) media improved students' cognitive achievements.

To ensure comprehensive content coverage, the test blueprint included four major sub-indicators: (1) CNC lathe machine components, (2) functions of CNC machine parts, (3) identification of CNC machine parts, and (4) CNC programming codes. A larger proportion of items (10 out of 22) focused on CNC lathe machine components, reflecting the foundational importance of this competency. The remaining items were distributed across related sub-indicators to assess functional knowledge, identification skills, and basic programming literacy. A test blueprint table was created to clearly map the relationship between each sub-indicator and the number of items allocated. This blueprint ensured that the instrument was balanced, targeted, and representative of the learning objectives, providing an accurate measure of student progress, as shown in Table 2.

Table 2. Blueprint of cognitive test instrument

Sub-indicator	Topic	Number of items
CNC lathe machine components	Structure & parts of CNC lathe	10
Functions of CNC machine parts	Operational functions of components	2
Identification of CNC machine parts	Recognizing and labeling parts	6
CNC programming codes	G-code & M-code basics	4
Total		22

2.5 Validity and reliability testing

To ensure the accuracy and quality of the research instrument, validity and reliability testing were conducted prior to its use in the study. Validity testing aimed to measure the extent to which the test items accurately represented the learning objectives and content being assessed (Matthews et al., 2022), while reliability testing evaluated the consistency of the instrument in producing stable results across applications. Validity testing was performed by comparing the calculated r_{value} (r_{count}) of each test item with the critical r_{table} value (t_{table}). With $n = 24$ and a significance level of $\alpha = 0.05$, the critical value was determined to be 0.388. Items with a $r_{\text{count}} \geq r_{\text{table}}$ were deemed valid, while those falling below this threshold were considered invalid. The analysis revealed that the majority of the 22 items met the validity criterion, demonstrating that they effectively measured the intended knowledge and competencies. However, three items, specifically Questions 2, 4, and 23 did not meet the required r_{value} threshold and were subsequently excluded from the final instrument to maintain the integrity of the test.

Reliability testing was conducted using Cronbach's Alpha via SPSS 25.0 software. This analysis produced a coefficient of $\alpha = 0.831$, which falls within the "Very High" category. A Cronbach's Alpha value above 0.80 indicates strong internal consistency, meaning the items collectively measure the same construct and generate dependable data. This high reliability score confirms that the final version of the instrument was appropriate for use in evaluating students' cognitive learning outcomes, as the likelihood of measurement errors was minimal.

Table 3. Summary of validity and reliability testing

Test type	Method / Tool	Results	Interpretation
Validity test	Correlation analysis comparing r_{count} to r_{table} ($n = 24$, $\alpha = 0.05$, $r_{\text{table}} = 0.388$)	19 valid items, 3 invalid items (Q2, Q4, Q23 removed)	Majority of items valid; 3 excluded for accuracy
Reliability test	Cronbach's Alpha (SPSS 25.0)	$\alpha = 0.831$	Very High instrument reliability consistent and suitable

By conducting both validity and reliability tests, the research instrument was refined to ensure it accurately measured the desired learning objectives and maintained consistent performance. The removal of the three invalid items improved the overall validity, while the very high reliability score ($\alpha = 0.831$) confirmed the instrument's robustness and appropriateness for data collection throughout the study.

3. Results and discussion

3.1 Improvement of students' learning outcomes

The implementation of the Augmented Reality (AR)-based learning media for CNC TU-2A produced a significant positive impact on students' academic performance. Students' learning outcomes were assessed using cognitive tests and practical skill evaluations within the NC/CNC and CAM subjects. The average score increased from 75.91 in Cycle 1 to 82.47 in Cycle 2, with classical mastery rising dramatically from 54.83% to 100%. Moreover, the number of students who met the minimum mastery criteria increased from 17 to all 31 students. This improvement indicates that AR media contributed meaningfully to students' achievement, particularly in understanding the structure, functions, and operational mechanisms of CNC machine components. The summary of student performance across both cycles is presented in Figure 2.

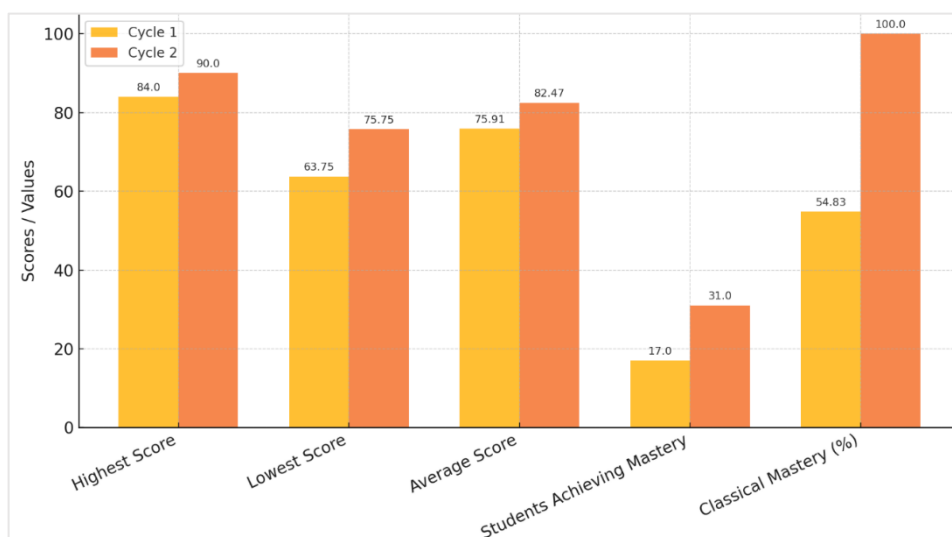


Figure 2. Learning Outcomes Comparison: Cycle 1 vs Cycle 2

This outcome aligns with ([Fernández-Enríquez & Delgado-Martín, 2020](#)), who emphasized that AR strengthens conceptual understanding in technical subjects by providing interactive 3D visualizations. Similarly, ([Alkhabra et al., 2023](#)) found that AR enhances students' knowledge retention in technical learning by offering concrete and direct visualization of complex objects.

3.2 Enhancement of psychomotor skills

The implementation of Augmented Reality (AR) learning media demonstrated a notable improvement in students' psychomotor skills, which refers to the ability to perform technical tasks requiring coordination between cognitive understanding and physical execution. Data analysis revealed an increase in the average psychomotor score from 81.57 in Cycle 1 to 84.81 in Cycle 2, reflecting a gain of 3.24 points. This upward trend signifies that AR media not only strengthened conceptual understanding but also translated into improved technical performance as depicted in Figure 3.

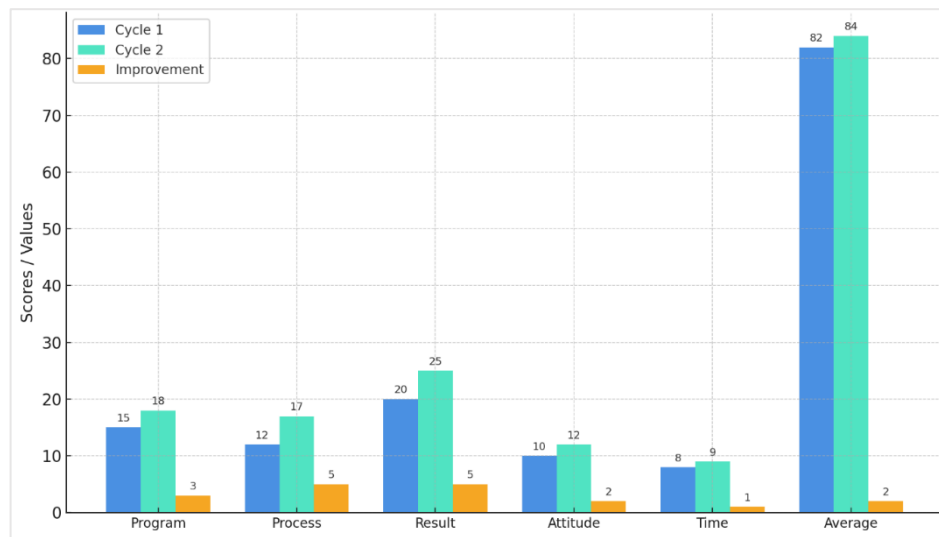


Figure 3. Skill learning outcomes comparison

Through AR technology, students could independently explore 3D models of CNC TU-2A machine components, including the chuck, tailstock, revolver, and step motor before engaging in real workshop practice. This pre-practice visualization enabled learners to mentally simulate the assembly, disassembly, and operation of CNC components, which significantly reduced hesitation and errors during hands-on sessions. By bridging theory and practice, AR fostered a more seamless transition from cognitive learning to technical application.

These findings reinforce prior studies emphasizing the immersive benefits of AR in skill-based training. Like the conclusions of ([Samala & Amanda, 2023](#)), AR facilitates a safe, repeatable, and interactive learning space, allowing students to experiment and gain familiarity with technical tools without the pressure of immediate real-world consequences. As a result, AR media created a more confident and competent cohort of learners, with improved precision and dexterity in performing CNC operations.

3.3 Improvement of student learning activities

The integration of Augmented Reality (AR) learning media did not only enhance students' cognitive performance and psychomotor skills it also had a measurable impact on students' overall learning activity levels. As presented in Table 5 and visually summarized in Figure 4, observations across the two action research cycles revealed a steady and meaningful rise in student engagement. The average level of learning activity increased from 72.2% in Cycle 1 to 80.4% in Cycle 2, representing an overall gain of 8.2%. The most substantial growth was seen in the Discussion and Collaboration category, which rose dramatically from 57% to 74% (a 17% increase). This improvement indicates that AR media stimulated peer-to-peer interaction, fostered a more collaborative learning environment, and encouraged students to engage in meaningful dialogue rather than passively absorbing content. Similarly, Digital Interaction also recorded a significant increase (from 68% to 81%, +13%), suggesting that students became more comfortable using AR tools to explore CNC machine concepts and functions independently.

Even though gains in some indicators were smaller, such as Visual (from 88% to 92%, +4%) and Emotional & Attitudinal (from 76% to 77%, +1%), these figures reflect a high baseline performance rather than a lack of impact. Visual engagement was already strong in Cycle 1 and remained consistently high, while the slight uptick in emotional and attitudinal engagement suggests that students felt more confident and positive about their learning experience as AR became a regular part of classroom activities.

Table 4. Student learning activity observation summary

Learning activity indicator	Cycle 1 (%)	Cycle 2 (%)	Increase (%)
Visual	88	92	4
Digital Interaction	68	81	13
Cognitive	72	78	6
Discussion & Collaboration	57	74	17
Emotional and Attitudinal	76	77	1
Average	72.2	80.4	8.2

These findings in Table 4 support the argument that AR-based learning goes beyond knowledge acquisition; it shapes how students interact, think, and feel about learning. By leveraging 3D visualization, students were able to see and manipulate CNC machine components virtually, which triggered curiosity, fostered hands-on exploration, and encouraged active participation in group discussions. This aligns with (Hsu & Liu, 2023), who emphasized that AR technologies enhance socially mediated learning experiences by prompting collaboration and co-construction of knowledge.

In addition, the observed improvements reflect a shift toward student-centered learning practices. Rather than being passive recipients of teacher explanations, students took on active roles as explorers and collaborators, consistent with contemporary pedagogical approaches that value constructivist learning environments. Ultimately, the data from Table 5 and Figure 4 demonstrate that AR media can be a powerful catalyst for affective and social dimensions of learning, making the classroom not only more interactive but also more dynamic and inclusive.

3.4 Barriers and solutions in implementation

The implementation of Augmented Reality (AR) media in CNC TU-2A instruction at SMK Negeri 5 Padang brought remarkable improvements in students' cognitive, psychomotor, and affective learning outcomes; however, the process was not without challenges. Several barriers emerged throughout the two Classroom Action Research (CAR) cycles, which required immediate and strategic solutions to ensure the project's success and sustainability (Ceylan & Comoglu, 2024). One of the most notable barriers was the limited access to compatible Android devices among students. Not all learners owned smartphones capable of running the AR application, which initially created an imbalance in participation and limited the hands-on interaction that the AR tool was designed to facilitate (Cheng et al., 2024; Iqbal et al., 2022; Takroui et al., 2022). To address this, the school provided shared devices and implemented paired or small-group learning sessions, ensuring every student could still experience the AR content. Interestingly, this solution not only resolved the device gap but also encouraged peer collaboration, aligning well with the cooperative learning goals of the research.

Another barrier involved initial technical difficulties with the AR application itself. In the early stages of Cycle 1, students and even instructors encountered scanning errors, calibration issues, and occasional lag when loading 3D models. These disruptions slowed down the teaching process and risked frustrating both teachers and learners. To overcome this, the teaching team conducted short technical training and troubleshooting workshops before Cycle 2, familiarizing users with marker scanning, model navigation, and basic troubleshooting steps. This significantly reduced downtime and created a smoother, more confident user experience.

The transition from traditional teacher-centered instruction to AR-driven pedagogy also posed a challenge. Some teachers were initially hesitant to move away from conventional lectures and job sheets, limiting the full integration of AR during the first cycle. Through collaborative planning sessions and mentoring, teachers received support in aligning AR use with their lesson objectives and were gradually empowered to use the technology as a facilitative tool rather than a supplementary gimmick (Mystakidis et al., 2021). By the second cycle, instructors

displayed greater confidence, allowing the AR media to drive more interactive, student-centered learning experiences. Additional hurdles included occasional connectivity and resource constraints. Although the AR app worked mostly offline after installation, certain updates and demonstrations required internet access, which was inconsistent in some areas of the school. The research team mitigated this by preparing offline AR content packages and preloading all necessary assets onto devices, eliminating dependency on live connectivity during lessons.

Finally, some students initially experienced a learning curve when adapting to AR-based interaction, with a few hesitant to explore 3D models independently due to unfamiliarity with mobile learning tools. Teachers addressed this by pairing tech-savvy students with those less confident in navigating AR features, fostering peer mentoring and creating a supportive learning environment. This approach not only eased the adoption of the technology but also reinforced the discussion and collaboration component, which showed the highest improvement among all learning activity indicators.

In summary, while the integration of AR media into CNC TU-2A instruction faced technological, pedagogical, and logistical barriers, the iterative CAR framework enabled the research team to identify and address these issues in real-time. Solutions such as device sharing, technical orientation, teacher mentoring, offline resource preparation, and peer support proved highly effective. These actions not only resolved immediate obstacles but also strengthened the overall implementation, demonstrating that AR media can be successfully adopted in vocational education settings when paired with adaptive strategies and collaborative problem-solving.

3.5 Connection to previous studies

The findings of this study align closely with and extend the growing body of literature demonstrating the transformative potential of Augmented Reality (AR) in vocational and technical education. Similar to the results reported by ([Zulfiqar et al., 2023](#)), this research confirmed that AR-based instructional media significantly improves students' conceptual understanding by enabling them to visualize CNC machine operations in 3D, making abstract technical concepts more concrete and accessible. Prior research has consistently highlighted AR's ability to enhance cognitive engagement and technical comprehension in fields requiring spatial reasoning and procedural mastery, and this study further validates those conclusions within the context of CNC TU-2A instruction at the vocational secondary level.

Moreover, the observed improvement in psychomotor skills resonates with the findings of ([Asoodar et al., 2024](#); [Marques et al., 2024](#)), who emphasized that AR provides a safe, repeatable, and immersive environment for students to experiment with technical tools before engaging in real-world practice. By allowing learners to mentally rehearse assembly and operational tasks, AR bridges the gap between theory and hands-on application, resulting in greater precision and confidence in performing CNC-related skills. This study also supports the conclusions of ([Scavarelli et al., 2021](#)), who noted that AR not only enriches content delivery but also fosters collaborative and socially mediated learning. The significant gains in discussion and collaboration activities found here reflect that AR can cultivate a more interactive, student-centered learning environment an outcome in line with constructivist pedagogical principles and complementary to earlier studies in engineering and technical training.

What distinguishes this research from earlier works is its specific focus on CNC TU-2A machines in an Indonesian vocational school context a topic previously underexplored in AR literature. While prior studies have concentrated on AR for general technical education or CNC milling, this study addresses a key gap by demonstrating AR's impact on CNC lathe instruction, revealing measurable gains in cognitive performance, psychomotor execution, and classroom engagement. In doing so, it not only reaffirms existing evidence on AR's pedagogical value but also expands the discourse by providing a localized, scalable model for AR integration in

vocational education that responds to Industry 4.0 learning demands and the realities of resource-limited schools.

4. Conclusion

This research confirms the powerful potential of Augmented Reality (AR) as a transformative instructional tool in vocational education, particularly for CNC TU-2A instruction. The implementation of Android-based AR media significantly enhanced students' learning outcomes, as reflected in the substantial rise in average cognitive scores, psychomotor performance, and overall classroom engagement. Students moved beyond passive learning, becoming active explorers and collaborators, supported by immersive 3D visualizations that made complex machine concepts tangible and accessible. The study also identified and addressed key barriers, including limited access to compatible devices, initial technical challenges, and the need for pedagogical adjustments through practical, collaborative solutions such as device sharing, offline content preparation, troubleshooting workshops, and teacher mentoring. These adaptive strategies not only resolved implementation hurdles but also strengthened the AR integration process, making it sustainable and replicable. Ultimately, this study contributes a localized, scalable model for AR integration in Indonesian vocational schools, bridging the gap between traditional teaching and Industry 4.0 learning needs. By merging advanced visualization with hands-on learning, AR media has proven to be an effective, engaging, and affordable solution for modernizing technical education. Future research could expand its application to other competencies and explore long-term impacts on employability, ensuring vocational graduates are better prepared for the demands of today's and tomorrow's industries.

Author's Declaration

Author contribution

Rezky Azhari Salim: Conceptualization, methodology, software development, investigation, writing – original draft, data analysis, visualization. **Syahril:** Conceptualization, supervision, project administration, resources, writing – review & editing. **Nelvi Erizon:** Methodology, data analysis, writing – review & editing, and validation.

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Competing interest

The authors declare that there are no conflicts of interest regarding the research, authorship, or publication of this article.

Ethical clearance

This study involved human participants (students). All participants were informed about the research objectives, procedures, and their rights, and participation was entirely voluntary. Informed consent was obtained from all participants prior to the study. All collected data were kept confidential and anonymized to ensure privacy and ethical compliance. Ethical approval

for this research was obtained from the West Sumatra Education Office (Approval No. 000.9/2655/SEK/DISDIK-2025)

Data availability

The raw research data are not publicly available due to the involvement of human subjects and concerns regarding confidentiality and privacy.

AI statement

No generative AI tools were used for the creation of the study's core content, analysis, or conclusions. Any AI assistance was limited to language refinement and formatting, with full responsibility for the research integrity remaining with the authors.

Publisher's and Journal's Note

Researcher and Lecturer Society as the publisher, and the editor of Journal of Engineering Researcher and Lecturer state that there is no conflict of interest towards this article publication.

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