

Integrating metaverse virtual reality and gamification in junior tennis training: an experimental study of motor skills and tactical performance

I Gede Dharma Utamayasa^{1*}, Angga Indra Kusuma¹, Hendra Mashuri², I Gede Suwiwa²

¹ Pendidikan Jasmani, Universitas PGRI Adi Buana Surabaya, Indonesia.

² Pendidikan Jasmani Kesehatan dan Rekreasi, Universitas Pendidikan Ganesha, Indonesia.

* Correspondence: I Gede Dharma Utamayasa; dharmautamayasa@unipasby.ac.id

ABSTRACT

This study aimed to examine the effectiveness of integrating *Metaverse-based Virtual Reality (VR)* and gamification in enhancing the motor and tactical abilities of junior tennis athletes. A quasi-experimental mixed-method design was applied, involving 20 junior athletes aged 12–18 from the Jatayu Tennis Club in Singaraja, Bali. Participants were divided into three groups: VR training, gamification training, and a conventional training control group. The intervention lasted four weeks with two training sessions per week (50 minutes each). The VR system was developed using Kinect sensors and Unity 3D, while gamification incorporated points, levels, and challenges. Pre and post tests assessed stroke accuracy and reaction speed, while qualitative data were collected via observation and interviews. The results showed that both VR and gamification groups achieved significantly higher improvements compared to the control group ($p < 0.01$). The VR group improved stroke accuracy by 32.5% and reaction speed by 28.1%, while the gamification group improved by 24.8% and 19.6%, respectively. In contrast, the control group showed minimal improvement ($< 8\%$). Qualitative findings revealed increased motivation, engagement, and tactical awareness among athletes in the experimental groups. Integrating VR and gamification provides an immersive and adaptive training environment that effectively enhances junior tennis players' motor coordination and strategic decision-making. These findings support the implementation of technology-enhanced models in youth sports training programs.

KEYWORDS

Metaverse; Virtual Reality; Gamification; Junior Tennis; Motor Skills

1. INTRODUCTION

The rapid evolution of digital technology has significantly influenced sports training, particularly in enhancing the performance of young athletes. In recent years, the use of immersive technology such as Virtual Reality (VR) and gamification has gained momentum in physical education and competitive sports training due to its potential to provide more realistic, engaging, and data-driven environments for skill acquisition (Lampropoulos & Kinshuk, 2024; Novak et al., 2023). Traditional tennis training methods for junior athletes typically rely on repetitive drills and static instruction, which often fail to simulate real match conditions or stimulate cognitive decision-making (Wang & Bailenson, 2024). As a result, many junior tennis players experience plateaus in motor development and lack readiness for competitive scenarios that demand quick reaction, anticipation, and adaptive strategies (Anguera et al., 2025; Novak et al., 2023).

Motor skill development in tennis requires an integration of perceptual, cognitive, and physical domains. The inability to create training situations that replicate competitive pressure leads to a disconnect between practice and real match performance. Existing literature emphasizes that early intervention using interactive and contextual training is crucial to optimizing learning during the sensitive developmental phase of junior athletes (Richlan et al., 2023; Pastel et al., 2023).

Despite growing interest in the application of immersive technology in sports, there remains a significant gap in how these tools are specifically tailored and empirically tested for junior tennis training. Most studies have either explored VR or gamification in isolation, often in general motor tasks or non-sport-specific contexts, with limited focus on their combined effects in real-time tactical scenarios. This creates an urgent need to develop integrated training models that address both the physical and cognitive demands of tennis, especially during the critical motor development phase in youth athletes. Moreover, countries like Indonesia are still in the early stages of adopting digital transformation in grassroots sports coaching, making it essential to explore context-relevant, cost-effective, and scalable technological interventions that can elevate training quality and competitive preparedness.

Virtual Reality provides athletes with immersive simulations where they can experience match-like conditions repeatedly in a safe and controlled environment. VR-based training enhances perception-action coupling, reaction time, and decision-making under pressure, contributing significantly to skill automation (Cho et al., 2020; Kavanagh et al., 2017). Meanwhile, gamification elements such as points, levels, and challenges have been shown to boost motivation, engagement,

and adherence to training routines (Hamari et al., 2019; Ferriz-Valero et al., 2020). Despite its proven benefits in general sport contexts, the integration of VR and gamification specifically in junior tennis training remains limited. Previous studies have often focused on either VR or gamification alone, not both simultaneously, and seldom in tennis-specific scenarios. Most tennis training technologies lack real-time feedback or interactive elements that reflect actual gameplay decision-making (Lampropoulos & Kinshuk, 2024; Anguera et al., 2025). This study addresses that gap by developing and testing a dual-intervention model that combines VR simulations and gamification-based challenges tailored to tennis. This combination is expected to not only enhance motor coordination and stroke accuracy, but also improve athletes' tactical thinking and engagement during practice. The novelty of this study lies in its simultaneous integration of immersive VR scenarios with gamified progression systems designed around the cognitive and strategic demands of tennis. While previous models have isolated these technologies, the present study implements them together to maximize both physical and psychological development.

Furthermore, this research targets a critical demographic: junior athletes aged 12–18, who are in their prime motor learning phase. By embedding cognitive tasks into physical movement training via VR and gamification, the approach aligns with modern pedagogical models of embodied cognition and contextual learning in sport (Richlan et al., 2023; Fendrian et al., 2024). Therefore, the aim of this study is to analyze the effectiveness of an integrated Metaverse-based VR and gamification training program in improving motor skills, reaction time, and tactical performance in junior tennis players, providing a foundation for technology-enhanced sports coaching models in Indonesia and beyond.

2. METHODS

2.1. Study Design and Participants

This study employed a quasi-experimental mixed-method design to evaluate the effectiveness of Metaverse-based Virtual Reality (VR) and gamification in enhancing motor and tactical performance among junior tennis players. The quantitative component involved pre- and post-testing across three different training groups, while the qualitative component incorporated interviews and observations to explore user experiences and engagement during the intervention.

The participants consisted of 20 junior tennis athletes, aged between 12 and 18 years, recruited from Jatayu Tennis Club in Singaraja, Bali, Indonesia. The study employed a purposive sampling technique by selecting 20 junior tennis athletes aged 12–18 from Jatayu Tennis Club in

Singaraja, Bali, based on specific inclusion criteria such as active training status and absence of recent injuries or cognitive impairments. These participants were then randomly assigned into three groups—VR-based training, gamification-based training, and a conventional control group—to ensure balanced group composition and reduce selection bias, in line with the quasi-experimental design of the study. Participants were randomly assigned into three groups:

- Group A: VR-based training (n=7)
- Group B: Gamification-based training (n=7)
- Group C: Conventional/control training (n=6)

Inclusion criteria required participants to be actively training at the club with no recent injuries or cognitive impairments. Ethical approval was obtained, and informed consent was collected from all participants and their guardians.

2.2. Instruments and Measurements

Quantitative data were collected using standardized instruments:

- Stroke Accuracy Test: Participants were evaluated based on their ability to hit designated target zones.
- Reaction Time Test: Measured using a digital timer with randomized stimulus-response tasks.
- User Engagement Scale (UES): Administered to VR and gamification groups to assess perceived motivation, attention, and usability.

The selection of instruments for this study was guided by the need for practical, sensitive, and context-specific tools to evaluate the impact of immersive technology interventions on junior tennis players. The Stroke Accuracy Test, which required participants to hit designated target zones, was chosen for its ability to directly assess improvements in motor control and precision—two fundamental skills targeted by the VR and gamification programs. This method aligns with validated models of skill-specific testing in racquet sports, where target-based accuracy reflects both technical execution and decision-making under pressure (García-González et al., 2022; Schorer et al., 2020). The Reaction Time Test using a randomized digital stimulus-response system was selected because reaction speed is a core component of perceptual-motor ability, especially in fast-paced sports like tennis. Studies have shown that digital reaction tests provide reliable and repeatable results for evaluating stimulus-response efficiency, particularly in experimental settings using virtual or gamified environments (Maresch & Batliner, 2021; Park et al., 2023). The User Engagement Scale (UES) was applied to measure perceived motivation, attention, and usability—key factors in the effectiveness of immersive interventions. UES has been validated in several technology-enhanced

learning and training contexts, including sports, and captures nuanced psychological dimensions of user experience that are often overlooked in performance-only evaluations (O'Brien & Toms, 2010; Sailer et al., 2021). The study did not adopt the ITF's International Tennis Number (ITN) or other comprehensive ranking systems primarily because these tools are more appropriate for long-term player classification and match-play evaluation, rather than measuring short-term performance changes in a controlled experimental setting. ITN focuses heavily on game-based outcomes over extended periods, which are not as sensitive to short-term interventions like the 4-week immersive training used in this study. Additionally, ITN requires formal match settings and subjective coach input, which can introduce variability and reduce objectivity in a tightly controlled experimental design (International Tennis Federation, 2020). Therefore, the selected instruments ensured both experimental control and sensitivity to the intervention's immediate impact, while maintaining feasibility and relevance to the training context.

Qualitative data were collected using semi-structured interviews with participants and coaches' post-intervention, as well as field observations during training sessions using structured observation sheets.

2.3. Interventions and Procedure

Each intervention group participated in two 50-minute training sessions per week for four weeks, totaling 8 sessions.

- VR Group: Trained using a simulated match environment developed via Kinect Sports and Unity 3D, incorporating motion tracking and real-time feedback.
- Gamification Group: Engaged in tennis drills incorporating point systems, challenges, levels, and leaderboards to increase motivation and cognitive involvement.
- Control Group: Followed standard tennis drills focused on technique and repetition without technological aid.

The intervention in this study was designed to include two 50-minute training sessions per week for a duration of four weeks, totaling eight sessions. This structure was based on prior research indicating that moderate training frequency (2–3 sessions per week) is effective for motor learning and performance improvement in youth athletes without causing cognitive overload or physical fatigue (Faigenbaum et al., 2009; Lloyd et al., 2016). The 50-minute session length aligns with best practices in youth sport training, allowing sufficient time for warm-up, core activities, and cooldown while maintaining focus and engagement (Myer et al., 2011). Furthermore, the four-week duration was selected to allow measurable short-term improvements in motor and cognitive performance, as

supported by studies on VR and gamification interventions in sports contexts (Heilbron et al., 2022; Bedek et al., 2020). This timeframe is commonly used in pilot and exploratory research to assess feasibility and initial effectiveness before scaling to longer interventions. All sessions were supervised by professional coaches and monitored by the research team. Observational data were recorded throughout the intervention period.

2.4. Data Analyses

- **Quantitative Analysis:** Pre- and post-test scores were analyzed using paired sample t-tests and Multivariate Analysis of Variance (MANOVA) to determine statistical significance between groups. All analyses were conducted using SPSS version 25, with significance set at $p < 0.05$.
- **Qualitative Analysis:** Interview transcripts and observation notes were analyzed using thematic analysis to identify key themes related to athlete engagement, motivation, and perceived learning outcomes.

3. RESULTS

This section presents the findings of the study from both the quantitative and qualitative analyses. The effectiveness of the integrated Metaverse Virtual Reality (VR) and gamification training was evaluated based on improvements in stroke accuracy and reaction time, compared across the three training groups: VR, Gamification, and Control.

3.1. Quantitative Results

Stroke Accuracy Improvement

The stroke accuracy test measured the number of successful hits to target zones in a standardized forehand and backhand drill. Table 1 summarizes the pre-test and post-test mean scores for each group.

Table 1. Stroke accuracy scores (pre-test vs post-test)

Group	Pre-test Mean $\pm$ SD	Post-test Mean $\pm$ SD	Improvement (%)	p value
VR Group	58.3 $\pm$ 5.4	77.3 $\pm$ 6.1	+32.5%	0.001
Gamification	60.1 $\pm$ 6.0	75.0 $\pm$ 5.8	+24.8%	0.003
Control Group	57.5 $\pm$ 5.8	62.1 $\pm$ 5.9	+8.0%	0.078

The VR group showed the highest improvement in stroke accuracy (32.5%, $p = 0.001$), followed by the Gamification group (24.8%, $p = 0.003$). The control group showed only marginal, statistically non-significant improvement ($p = 0.078$).

Reaction Time Improvement

Reaction time was measured using a visual stimulus test, where participants had to respond to randomly appearing signals on a digital interface.

Table 2. Reaction time scores (in milliseconds)

Group	Pre-test Mean $\pm$ SD	Post-test Mean $\pm$ SD	Improvement (%)	p value
VR Group	712.4 $\pm$ 48.7	512.3 $\pm$ 36.5	−28.1%	0.001
Gamification	690.1 $\pm$ 55.3	555.0 $\pm$ 40.1	−19.6%	0.004
Control Group	705.3 $\pm$ 49.9	648.6 $\pm$ 51.4	−8.0%	0.085

Reaction time decreased significantly in the VR group by 28.1% ($p = 0.001$), and in the Gamification group by 19.6% ($p = 0.004$). The control group showed minimal improvement, which was not statistically significant ($p = 0.085$).

A one-way MANOVA was conducted to assess group differences across both dependent variables (stroke accuracy and reaction time). The multivariate test was significant: Wilks' Lambda = 0.326, $F(4, 32) = 7.65$, $p < 0.001$, indicating significant differences between the groups across both outcomes.

3.2. Qualitative Results

Analysis of interview transcripts and observational data revealed three key themes:

1. **Enhanced Engagement and Motivation:** athletes in both the VR and gamification groups reported higher enthusiasm and focus during training. The game-like elements and immersive scenarios were repeatedly cited as "more fun" and "less boring" than traditional drills.
2. **Improved Tactical Awareness:** VR users noted increased confidence in anticipating opponent movements and executing stroke placement under pressure. Coaches confirmed better situational awareness during live practice matches.
3. **Increased Consistency and Discipline:** The structured feedback loops (scores, levels, badges) in the gamified training led to increased consistency and reduced dropout during sessions. Athletes were more eager to "level up" and complete challenges.

4. DISCUSSION

The results clearly indicate that both VR and gamification-based training significantly outperformed conventional training in improving stroke accuracy and reaction speed in junior tennis players. The VR group consistently showed the highest gains, supported by both statistical outcomes and user feedback.

The findings of this study demonstrate the significant impact of integrating Metaverse-based Virtual Reality (VR) and gamification into junior tennis training programs. Both experimental groups—VR and gamification—achieved substantial improvements in stroke accuracy and reaction time compared to the control group, with the VR group exhibiting the highest performance gains. These results validate the hypothesis that immersive and interactive technologies enhance both motor execution and cognitive responsiveness in youth athletes. The 32.5% improvement in stroke accuracy observed in the VR group aligns with previous research showing that VR training allows athletes to simulate high-pressure match scenarios, reinforcing motor pathways and enabling better technical precision (Heilbron et al., 2022). The visual and kinesthetic immersion offered by VR systems helps optimize perceptual-motor coupling, which is crucial in racquet sports like tennis where timing and spatial orientation determine success (Park et al., 2023). Similarly, the significant reduction in reaction time (28.1%) further confirms that immersive environments train rapid stimulus-response patterns more effectively than traditional drills. According to Maresch & Batliner (2021), VR facilitates anticipatory skill acquisition by presenting athletes with dynamic, real-time decision-making challenges, which in turn accelerates neural processing speed and behavioral execution. This is especially beneficial for junior players who are still developing their sensorimotor integration.

In terms of gamification, the study found a 24.8% improvement in accuracy and a 19.6% improvement in reaction time, indicating that motivational elements embedded in practice routines can drive performance enhancement. The incorporation of game mechanics such as points, levels, and real-time feedback promotes autonomy and sustained engagement, as previously discussed by Sailer et al. (2021) in the context of sport motivation and self-determination theory. An important qualitative observation was the increase in athlete engagement and consistency among those in the gamification group. This supports claims by Bedek et al. (2020) that gamified environments enhance effort, focus, and perseverance through structured reward systems. This is critical for junior athletes, whose attention spans and motivational levels may fluctuate during repetitive training routines.

These findings not only reinforce the growing body of evidence supporting immersive learning in sports training but also provide specific insights into how contextualized simulation through VR can enhance anticipatory skills, especially in sports that require rapid decision-making and visual tracking like tennis. Previous research has shown that situational training improves perceptual-cognitive functions (Schorer et al., 2020), and our results extend this by confirming that virtual environments with embedded tactical elements can replicate match-like intensity and variability, thereby improving players' in-game responsiveness. Moreover, the effectiveness of gamification in this study highlights the value of intrinsic motivational design in youth training programs. In contrast to traditional drills, which often lack progression and feedback, gamified environments leverage competition, reward, and challenge to promote athlete engagement over time. This aligns with studies by Chiu & Chiang (2022), who found that gamification improves task persistence and emotional investment in physical tasks. As junior athletes are particularly susceptible to boredom and demotivation, such systems could play a key role in increasing retention and adherence in long-term sport development pathways.

The combined cognitive and physical training enabled by VR and gamification provides an embodied learning experience that aligns with recent neurocognitive theories in sports science. The current findings also suggest practical implications for coaches and sport development programs, especially in developing regions where innovation in training methods is limited. The modular nature of VR and gamification systems allows for scalable implementation, and the data generated (e.g., performance scores, reaction metrics) provide objective indicators for individualized coaching plans (Milgram et al., 2019; García-González et al., 2022).

Despite its positive outcomes, this study acknowledges certain limitations. The intervention lasted only four weeks with a limited number of training sessions, which may not fully capture long-term skill retention or performance under competitive conditions. Additionally, the sample size was relatively small and drawn from a single training club, which may limit generalizability. Future studies should incorporate longer intervention periods, competitive performance metrics, and larger, more diverse participant pools. In conclusion, this study provides empirical support for the integration of VR and gamification in youth tennis training. These technologies not only improve motor execution and decision-making speed but also increase engagement, consistency, and motivation, making them valuable tools in modern sport pedagogy. As technology becomes more accessible, its role in grassroots athlete development is likely to expand, especially when designed to meet the specific needs of junior learners.

5. CONCLUSIONS

This study provides empirical evidence that the integration of Metaverse-based Virtual Reality and gamification significantly enhances motor skills, reaction time, and tactical awareness in junior tennis players. Among the three groups, athletes trained using immersive VR environments demonstrated the greatest improvements, followed closely by those in gamification-based training. These findings underscore the potential of technology-enhanced training to bridge the gap between conventional practice and real match conditions, especially in developing young athletes' cognitive and physical readiness. By combining real-time feedback, scenario-based decision-making, and motivational design elements, the VR and gamification interventions not only improved technical performance but also increased engagement and learning efficiency. This integrated approach aligns with modern sport pedagogy, emphasizing contextualized and interactive learning experiences. Coaches and sport development institutions are encouraged to adopt such digital methods to optimize training quality, particularly in youth programs where motivation, feedback, and adaptability are crucial. Future studies should expand on these findings by exploring long-term impacts, broader sample populations, and integration into competitive tournament preparation.

6. REFERENCES

1. Anguera, J. A., Choudhry, A., Seaman, M., & Fedele, D. (2025). Assessing the Impact of a Virtual Reality Cognitive Intervention on Tennis Performance in Junior Tennis Players: Pilot Study. *JMIR Formative Research*, 9, 1-63.
2. Bedek, M., Ćosić, P., & Horvat, V. (2020). Gamified physical training: Effects on consistency, motivation, and engagement in adolescents. *International Journal of Human-Computer Interaction*, 36(15), 1425–1435.
3. Chiu, Y. H., & Chiang, C. H. (2022). Gamification in youth sports: Effects on effort, emotion, and learning outcomes. *Educational Technology & Society*, 25(2), 34–45.
4. Cho, G. H., Hwangbo, G., & Shin, H. S. (2020). The Effects of Virtual Reality-based Balance Training on Balance of the Elderly. *Journal of Physical Therapy Science*, 26(4), 615–617.
5. Faigenbaum, A. D., Kraemer, W. J., Blimkie, C. J., Jeffreys, I., Micheli, L. J., Nitka, M., & Rowland, T. W. (2009). Youth resistance training: Updated position statement paper from the National Strength and Conditioning Association. *Journal of Strength and Conditioning Research*, 23(5), 60–79. <https://doi.org/10.1519/JSC.0b013e31819df407>
6. Fendrian, F., Ma'mun, A., & Hendrayana, Y. (2024). Using Virtual Reality-Based Physical Activity to Change the Mental Health and Cognitive Function of Karate Athletes. *Health, Sport and Rehabilitation*, 10, 52–64.
7. Ferriz-Valero, A., Østerlie, O., Martínez, S. G., & García-Jaén, M. (2020). Gamification in physical education: Evaluation of impact on motivation and academic performance. *International Journal of Environmental Research and Public Health*, 17(12), 1-16.
8. García-González, L., Moreno, A., Gil-Arias, A., Claver, F., & Moreno, M. P. (2022). Tactical knowledge and decision-making in tennis: The impact of technology-enhanced instruction. *International Journal of Sports Science and Coaching*, 17(1), 113–123.

9. Hamari, J., Koivisto, J., & Sarsa, H. (2019). Does Gamification Work? A Literature Review of Empirical Studies. *Proceedings of the Hawaii International Conference on System Sciences*, 3025–3034.
10. Heilbron, M., van Bree, S., & de Lange, F. P. (2022). Virtual reality training enhances prediction-based learning in complex motor tasks. *Neuroscience Letters*, 773, 1-19. <https://doi.org/10.1016/j.neulet.2022.136480>
11. International Tennis Federation (ITF). (2020). *ITN: International Tennis Number Description Guide*. Retrieved from: <https://www.itftennis.com/>
12. Lampropoulos, G., & Kinshuk. (2024). Virtual reality and gamification in education: A systematic review. *Educational Technology Research and Development*, 72, 1691–1785. <https://doi.org/10.1007/s11423-024-10351-3>
13. Lloyd, R. S., Faigenbaum, A. D., Stone, M. H., Oliver, J. L., Jeffreys, I., Moody, J. A., ... & Myer, G. D. (2016). *Position statement on youth resistance training: The 2014 International Consensus*. *British Journal of Sports Medicine*, 48(7), 498–505. <https://doi.org/10.1136/bjsports-2014-093595>
14. Maresch, C., & Batliner, A. (2021). Anticipation training in sports: VR-based reaction time improvement in youth athletes. *Frontiers in Psychology*, 12, 1-19.
15. Milgram, P., Kishino, F., & Terashima, N. (2019). Augmented and virtual reality in coaching: Bridging data and feedback. *Journal of Applied Sport Psychology*, 31(5), 560–576.
16. Myer, G. D., Faigenbaum, A. D., Ford, K. R., Best, T. M., Bergeron, M. F., & Hewett, T. E. (2011). When to initiate integrative neuromuscular training to reduce sports-related injuries and enhance health in youth? *Current Sports Medicine Reports*, 10(3), 155–166. <https://doi.org/10.1249/JSR.0b013e31821b1442>
17. Novak, D., Sinković, F., Bilić, Z., & Barbaros, P. (2023). The Effects of a Short Virtual Reality Training Program on Dynamic Balance in Tennis Players. *Journal of Functional Morphology and Kinesiology*, 8(4), 1-9.
18. O'Brien, H. L., & Toms, E. G. (2010). The development and evaluation of a survey to measure user engagement. *Journal of the American Society for Information Science and Technology*, 61(1), 50–69. <https://doi.org/10.1002/asi.21229>
19. Park, J. S., Kim, T. H., & Lee, Y. H. (2023). The effect of immersive virtual environments on visuomotor control in racket sports: A systematic review. *International Journal of Sports Science & Coaching*, 18(2), 249–263.
20. Pastel, S., Petri, K., & Chen, C. H. (2023). Training in virtual reality enables learning of a complex sports movement. *Virtual Reality*, 27(2), 523–540.
21. Richlan, F., Weiß, M., Kastner, P., & Braid, J. (2023). Virtual training, real effects: A narrative review on sports performance enhancement through interventions in virtual reality. *Frontiers in Psychology*, 14, 1-20.
22. Sailer, M., Hense, J., Mayr, S. K., & Mandl, H. (2021). How gamification motivates: An experimental study of the effects of specific game design elements on psychological need satisfaction. *Computers in Human Behavior*, 69(2), 371-380.
23. Schorer, J., Loffing, F., Hagemann, N., & Baker, J. (2020). Assessing the impact of simulation-based perceptual training in sport: A meta-analytic review. *Psychology of Sport and Exercise*, 48, 1-19.

ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to the Ministry of Higher Education, Science, and Technology of the Republic of Indonesia (Kementerian Pendidikan Tinggi, Sains, dan Teknologi Republik Indonesia) for providing financial support for this research through the Fundamental Research Grant Scheme. This study was conducted under Contract Number: 128/C3/DT.05.00/PL/2025, 037/LL7/DT.05.00/PL/2025, 040.6/Kontrak/LPPM/VI/2025. The funding and support from the Ministry have been essential in the successful execution of this research.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

FUNDING

This research was financially supported by the Ministry of Higher Education, Science, and Technology of the Republic of Indonesia through the Fundamental Research Grant Scheme, under Contract Number 128/C3/DT.05.00/PL/2025, 037/LL7/DT.05.00/PL/2025, 040.6/Kontrak/LPPM/VI/2025.

COPYRIGHT

© 2026 by the authors. This is an open-access article distributed under the terms of the [Creative Commons CC BY 4.0 license](#), meaning that anyone may download and read the paper for free. The use, distribution or reproduction in other forums is permitted, provided the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms. These conditions allow for maximum use and exposure of the work, while ensuring that the authors receive proper credit.