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# Enhancing Mathematical Modeling and Ethnomathematics Learning Through Virtual Reality: A Case Study in Higher Education

**Satya Santika[1*], Depi Ardian Nugraha[2], Mega Nur Prabawati[3]**

**Mathematics Education, Universitas Siliwangi**
**Jalan Siliwangi 24 Kota Tasikmlaya, Jawa Barat, Indonesia**
[1*]satyasantika@unsil.ac.id; [2]depi@unsil.ac.id; [3]meganurprabawati@unsil.ac.id

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## Abstrak
Penelitian ini menjawab kebutuhan inovasi dalam pembelajaran matematika dengan mengintegrasikan Virtual Reality (VR) pada mata kuliah Pemodelan Matematika dan Etnomatematika, sebuah terobosan yang membedakannya dari studi sejenis yang terbatas pada geometri. Berlandaskan teori konstruktivisme, pendekatan ini dirancang untuk menciptakan pengalaman belajar aktif yang meningkatkan keterlibatan, pemahaman konseptual, dan motivasi mahasiswa. Metode pengembangan 4D (Define, Design, Develop, Disseminate) digunakan dengan evaluasi melalui tes, survei (reliabilitas $\alpha$=0,85), dan observasi. Hasil uji coba awal membuktikan efektivitas model ini, ditunjukkan oleh peningkatan signifikan dalam ketiga aspek tersebut. Konten VR yang dikembangkan telah memperoleh sertifikat HaKI, menjamin orisinalitasnya. Temuan penelitian ini tidak hanya menawarkan model integrasi teknologi imersif yang dapat diadopsi perguruan tinggi, tetapi juga merekomendasikan penelitian lanjutan dengan desain eksperimental dan evaluasi retensi pengetahuan jangka panjang untuk mendukung implementasi Kurikulum Merdeka Belajar secara lebih luas dan efektif.
Kata Kunci: Virtual Reality; Pemodelan Matematika; Etnomatematika; Pengalaman Belajar yang Ditingkatkan; Teknologi Pendidikan

## Abstract
This study addresses the need for innovation in mathematics learning by integrating Virtual Reality (VR) into the Mathematical Modelling and Ethnomathematics courses, a breakthrough that distinguishes it from similar studies limited to geometry. Based on constructivist theory, this approach is designed to create an active learning experience that increases student engagement, conceptual understanding, and motivation. The 4D (Define, Design, Develop, Disseminate) development method was used with evaluation through tests, surveys (reliability $\alpha$=0.85), and observations. Initial trial results proved the effectiveness of this model, as shown by significant improvements in all three aspects. The developed VR content has obtained an intellectual property rights certificate, guaranteeing its originality. The findings of this study not only offer an immersive technology integration model that universities can adopt but also recommend further research with experimental designs and long-term knowledge retention evaluations to support the broader and more effective implementation of the Merdeka Belajar Curriculum.
Keywords: Virtual Reality; Mathematics Modelling; Ethnomathematics; Enhanced Learning Experience; Educational Technology

## I. INTRODUCTION

Innovative technologies such as Virtual Reality (VR) fundamentally change the paradigm of classroom learning by providing an immersive and interactive learning experience (Shihab, Sultana, & Samad, 2023; Pramanik, 2024). From a constructivist learning theory perspective, VR provides opportunities for students to construct knowledge through direct interaction and real experiences in a virtual environment. The learning environment created by VR allows students to actively engage with content, strengthening their understanding and memory of the material being studied (Pintado et al., 2023; Young, Stehle, Walsh, & Tiri, 2020). In addition, experiential learning features in VR, such as simulations and virtual field trips, open up opportunities for students to experience various situations that would be impossible in a traditional classroom, making learning more interesting and meaningful (Gar Chi & Idris, 2021; Liao, 2023). The use of gamification in VR has also been shown to increase student motivation and engagement, in line with constructivist principles that emphasize interactivity and enjoyment in learning (Predescu, Caramihai, & Moisescu, 2023). From the perspective of cognitive load theory, VR helps reduce unnecessary cognitive load by providing visual and interactive representations of complex concepts, making it easier for students to understand and process information (Liu, Liu, & Ma, 2022). Through the multimodal learning experience provided by Virtual Reality (VR), cognitive load can be optimally distributed across various sensory channels, so that in the context of mathematical modeling and ethnomathematics, abstract concepts can be transformed into something more tangible and easier to understand by allowing students to visualize and manipulate models in three-dimensional space (Young et al., 2020). Thus, the integration of VR in mathematics education not only supports the latest learning theories but also provides concrete solutions to the challenges of understanding abstract concepts in the classroom.

Mathematical modeling and ethnomathematics are two disciplines that require a deep understanding of mathematical concepts and their applications in various cultural contexts and real life (Rosa & Orey, 2023). Ethnomathematics itself connects mathematical concepts with cultural practices, making learning more meaningful and relevant to students (Musliana et al. 2024; Devita, Puspitasari, & Afriansyah, 2025). For example, the Turonggo Yakso batik motif from Trenggalek and traditional crafts such as Pandai Sikek songket and the folk game "Lore" contain mathematical principles such as symmetry, congruence, and geometry, which can be used as media for mathematics learning in the classroom (Cesaria, Fitri, & Rahmat, 2022; Frisda Eldiana, Kusumaningrum, Sukma, & Dewi, 2023). Mathematical modeling and the ethnomodel approach not only help transform real-world problems into mathematical forms and find solutions, but also encourage students to think critically and solve problems in their cultural context (Desai et al., 2022; Arzu Ari & Demir, 2022). Virtual laboratories provide interactive and visual learning experiences that help bridge students' conceptual understanding gaps, but they still have limitations because they cannot replace the real experience of hands-on practice in the field (Asare et al., 2023; Kehi & Naimnule, 2023).

Recent research shows that Virtual Reality (VR) is an innovative technology that allows students to interact with a three-dimensional environment that closely resembles real-life situations. Through VR, students can gain unique learning experiences by exploring virtual worlds that resemble reality, enabling them to manipulate objects and explore environments that are difficult to present in conventional classrooms (Hite, 2022; Melinda & Widjaja, 2022). This immersive experience is crucial in understanding complex and abstract mathematical concepts, such as spatial relationships and Cartesian coordinate-based geometric principles, as students can observe and interact with virtual objects from various perspectives (Melinda & Widjaja, 2022). Furthermore, the integration of VR in mathematics education bridges theory with practical application through simulations of real phenomena, allowing students to apply theoretical knowledge in relevant and interactive contexts (Lai & Cheong, 2022; Melinda & Widjaja, 2022). The experiential learning approach offered by VR is in line with constructivism theory, which emphasizes the importance of active engagement and direct problem solving to make abstract concepts more tangible and easier to understand (Gar Chi & Idris, 2021; Pintado et al., 2023). VR enables culturally relevant mathematics learning by creating virtual environments that reflect cultural diversity, allowing students from different backgrounds to understand the application of mathematics in different cultural contexts and increase their appreciation of the global value of mathematics (Melinda & Widjaja, 2022).

Over the past year, the Faculty of Teacher Training and Education at Siliwangi University has established a Smartclassroom Laboratory equipped with VR learning tools, prompting researchers to explore the integration of VR into mathematics modeling and ethnomathematics lectures. The Smartclassroom at Siliwangi University is an ideal location for this research due to its comprehensive VR support facilities, such as state-of-the-art VR devices, stable internet connection, and adequate classroom capacity, enabling the optimal application of this technology. Through this research, it is hoped that Virtual Reality (VR) can become a medium that enriches the context and application of teaching materials in various disciplines. The use of VR as a learning medium has expanded to various fields, ranging from medical education, flight training, to schools and universities. In medical education, VR is used to provide realistic simulations of surgical procedures and interactions with patients, allowing students to improve their procedural knowledge and confidence without the risks of real-world practice (Akinola, Agbonifo, & Sarumi, 2020; Y. Chen, 2023). In aviation, VR is used for pilot training, safety information delivery, and maintenance procedures, allowing trainees to experience various flight scenarios and emergency situations in a safe and controlled environment (Akinola et al., 2020; Lekea, Stamatelos, & Raptis, 2021). VR integration is also becoming increasingly common in schools and colleges, where this technology helps create a dynamic learning environment and supports various educational approaches such as constructivism and experiential learning, thereby improving students' understanding of complex material (Pintado et al., 2023; Predescu et al., 2023). Not only that, VR is also used in professional training to simulate real work situations, which is particularly useful in fields where physical practice is limited or high-risk (Ferreira, Xavier, & Ancioto, 2021; T. C. Huang, Limniou, & Wu, 2023). The advantage of VR lies in its ability to create immersive learning experiences, increase motivation and learning outcomes, and provide a safe environment for practicing dangerous or complex tasks (Y. Huang, Richter, Kleickmann, & Richter, 2023; Liu et al., 2022). Thus, VR has great potential to revolutionize the learning process in various fields of education and training.

Mathematical modeling is a bridge between mathematical concepts and the real world through the creation of models that represent real-life phenomena (Khusna & Ulfah, 2021). With the advent of Virtual Reality (VR) technology, the mathematical modeling process has become more interactive and intuitive, as students can explore and manipulate these models directly in an immersive virtual environment. This approach allows students to visualize complex mathematical concepts, strengthen their understanding, and improve their retention of the mathematical principles they are learning (Çakıroğlu, Güler, Dündar, & Coşkun, 2024; Y. Chen, 2023). In addition, the application of VR in geometry learning has been shown to facilitate spatial reasoning and reduce cognitive load through dynamic and interactive features that guide the student learning process (Price, Yiannoutsou, & Vezzoli, 2020). Meanwhile, ethnomathematics, which examines the relationship between mathematics and culture, also benefits from the integration of VR, as this technology can simulate real-life culture-based mathematical experiences. Students can gain a broader and deeper perspective on the application of mathematics in various social and cultural contexts, such as traditional games or local crafts that are rich in geometry, calculation, and probability (Anisa, Siregar, & Hafiz, 2023; Gunawan, Jamna, Solfema, Oktariza, & Erita, 2022). The integration of VR and ethnomathematics not only enriches the learning experience, but also proves its effectiveness in increasing student engagement and learning outcomes through media that is more culturally and contextually relevant (Rahmawati, Buchori, & Ghoffar, 2022). By utilizing multimedia and immersive 3D environments, VR is able to transport students as if they were in the midst of real-life situations, making mathematics learning more meaningful and enjoyable.

VR research in mathematics increases motivation, engagement, and learning outcomes. Careful attention is needed in the design, pedagogical and technological evaluation, and adaptation to the needs of Siliwangi University students. This study aims to improve conceptual understanding, problem-solving skills, and appreciation of mathematical culture using VR in mathematical modeling and ethnomathematics learning. Specifically, this research seeks to answer the following sub-questions: (1) How can VR be used to improve students' understanding of mathematical concepts in mathematical modeling and ethnomathematics? (2) How does VR affect student motivation and engagement in case study-based mathematics learning? (3) What challenges are encountered in integrating VR into mathematics modeling and ethnomathematics courses, and how can they be overcome?

This research is important to determine the potential, limitations, and recommendations for implementing VR in higher education. It is in this context that the study "Integration of Virtual Reality Technology in Case Studies in Mathematics Modeling and Ethnomathematics Lectures" at Siliwangi University in Tasikmalaya was conducted. This research is strategic in the development of modern and relevant mathematics education in Indonesia and in honing the potential of VR technology.

The approach taken includes the development of VR content tailored to the mathematics and ethnomathematics modeling curriculum, assessment of its effectiveness in teaching, and application of case-based teaching methods. This approach involves multidisciplinary collaboration between mathematicians, educators, and VR developers.

To date, Virtual Reality (VR) has proven effective in enhancing immersive learning experiences, particularly in facilitating the understanding of abstract concepts through three-dimensional visualization. In mathematics education, the implementation of VR-based learning with an ethnomathematics approach in high school students can significantly improve learning outcomes and student motivation when compared to conventional methods, as demonstrated by better mastery of mathematical concepts in the experimental class (Rahmawati et al., 2022). In addition, VR applications have also been developed to strengthen learning motivation by providing interactive learning experiences, which are particularly useful in vocational education where the practical application of theoretical knowledge is essential (Ramansyah, Aini, Maulana, & Purnomo, 2021). In geometry learning, immersive VR technology can help students understand geometric principles in a more concrete and interesting way, thereby increasing their motivation and learning outcomes (Su, Cheng, & Lai, 2022). In the field of robotics engineering, platform-based VR laboratories such as Millealab allow students to experiment and interact directly with robotic systems in a virtual environment, thereby honing their practical skills and understanding of complex engineering concepts more optimally (Lai & Cheong, 2022). The use of 3D visualization through VR in STEM fields, including robotics, has also been shown to improve students' spatial and visualization abilities, especially for those with low spatial abilities, making the learning experience more inclusive and meaningful (Safadel & White, 2020).

Several studies have explored the application of VR in scientific simulation, medical training, and distance learning, where users can experience a fully controlled learning environment and receive real-time feedback. However, this study adds novelty by simultaneously integrating VR into the fields of mathematical modeling and ethnomathematics in higher education, particularly in the local context of Indonesia.

## II. METHOD

This research procedure is based on the 4D framework (Thiagarajan, Semmel, & Semmel, 1974), which includes Define-Design-Develop-Disseminate. The application of this framework helps to create a structured process that focuses on the development of effective materials that can be adapted to educational needs, so that the research results are accountable and have the potential to have a real impact on educational practice.

In the Define stage, the research team identified problems, reviewed the literature extensively, and formulated research objectives and questions. This process began with gathering the latest information on the application of VR in mathematical modeling and ethnomathematics, analyzing previous studies, and identifying research gaps that would be filled by this study. This research has obtained ethical approval from the Siliwangi University Research Ethics Committee, which ensures that the research procedures meet applicable research ethics standards.

In the Design stage, researchers developed a data collection strategy, measurement tools, and testing procedures. The research design was non-experimental. The team designed a VR case study, determined how VR would be integrated, and designed evaluation tools to measure the engagement, motivation, responses, and satisfaction of lecturers and students. The validity and reliability of the survey instruments and questionnaires were tested, with the reliability test results using Cronbach's alpha showing a value of 0.85, indicating that the reliability of the instruments was high and suitable for use in this study.

In the Develop stage, the research involved the creation and initial testing of VR content from case studies on mathematical modeling and ethnomathematics. The research team developed VR learning modules, conducted pilot testing with a small sample to obtain initial feedback, and refined the materials based on the results. This process included technical and pedagogical adjustments to the VR materials to ensure quality in the learning context. Interview data were analyzed thematically (thematic analysis) following the steps developed by Braun and Clarke (2006), including interview transcription, identification of main themes, data coding, and systematic interpretation to find patterns and insights into users' perceptions of VR use in the context of this study.

In the Disseminate stage, researchers focus on disseminating research results and VR materials developed to a wider audience. This involves publishing research findings in scientific journals and sharing them with mathematics educators (lecturers/teachers). This process may include documenting VR in certain media, conducting workshops for educators, and holding VR demonstration sessions.

The expected outcome of this research is a functional and engaging VR prototype that can enhance the learning experience of students. Feedback from pilot testing will be used to refine the VR, ensuring that the content and user experience meet educational standards and learning objectives. Furthermore, the VR materials will be ready for testing on a larger scale in subsequent research.

The targeted achievement indicators include clarity, feasibility, and potential effectiveness, which measure the completeness and functionality of the VR prototype, the positivity and usefulness of feedback from the pilot testing session, and iterative improvements to the VR based on evaluation. Other indicators include the ability of the VR module to facilitate the learning objectives identified in the mathematics modeling and ethnomathematics courses.

## III. RESULT AND DISCUSSION

The Define stage successfully identified that the main gap in related research is the lack of integration of VR technology in ethnomathematics teaching and mathematics modeling based on local culture. Based on a literature review, VR has the potential to bridge this gap by providing a more interactive, immersive, and relevant learning experience.

The application of Virtual Reality (VR) technology in education shows a major trend in the field of problem solving, with a percentage of 40%. This reflects the potential of VR in helping students develop analytical skills and conceptual understanding in complex and contextual situations. Meanwhile, 30% of its application is recorded in general mathematics education, which indicates the role of VR in strengthening basic learning and mathematical abstraction visually. The STEM field also accounts for 30% of VR usage, indicating the integration of this technology to support an interdisciplinary approach that combines science, technology, engineering, and mathematics in a more immersive and applicable learning process.

In the Design Stage, researchers successfully designed a VR-based case study relevant to mathematical modeling and ethnomathematics, focusing on local cultural elements visualized in a VR environment. Evaluation tools were designed to measure various important aspects of VR-based learning, such as student engagement, motivation, response, and satisfaction. The pilot test results showed that the use of VR increased student engagement and motivation, and elicited positive responses to this new learning method.

The integration of Virtual Reality (VR) in mathematics learning can be seen through two case studies that demonstrate the use of 3D simulation elements to support students' conceptual understanding. In the tree height estimation study, students were invited to explore trigonometric modeling through 3D simulations that represented tree objects and distances to them, enabling interactive measurement and visualization of the relationship between steps and object height. Meanwhile, in the engklek game, VR elements enable direct interaction with the geometric shapes of the typical Indonesian engklek image. This approach encourages students to gain a deeper understanding of traditional architectural design through spatial exploration and visual analysis.

During the development stage, the VR module was successfully tested and received positive feedback from students. Technical and pedagogical adjustments based on pilot testing improved the quality of the content and the overall learning experience.

Based on feedback from pilot testing, several technical and pedagogical adjustments were made to refine the VR module. In response to student input, several adjustments were made to improve the effectiveness of VR simulations in learning. In terms of visual quality, visualizations that were initially considered too complex were simplified by increasing resolution and improving the interface, allowing important elements in the simulation to be seen more clearly. In terms of interactivity, students can now interact more actively through object manipulation features, manual measurements, and automatic explanations added to each element. To overcome difficulties in understanding the material, especially in the context of comparison, the VR simulation is now equipped with interactive guides and explicit examples that facilitate a more focused and intuitive learning process.

Findings in various studies fully support the adjustments made in the development of this VR module. Improvements in visual quality and simplification of visualization have been shown to increase clarity and facilitate focus on important elements, as revealed by T. Chen et al. (2021) and Salehi et al. (2022) in simulations of complex learning environments. The interface improvements are also in line with the findings of Karam et al. (2022), which show that more straightforward navigation can reduce cognitive load and improve the learning experience. The addition of interactive features, such as object manipulation and manual measurement, is in line with experiential learning theory, which emphasizes the importance of learning through direct interaction, as reported by Pintado et al. (2023) and proven effective in various fields such as surgical training and pilot education (T. Chen et al., 2021; Hight, Fussell, Kurkchubasche, & Hummell, 2022). The integration of interactive guides and explicit examples has been proven to facilitate the understanding of complex concepts, helping students connect theoretical knowledge with practical applications, as demonstrated by Philip, Ali, Duggal, Daas, & Nazzal (2023) and Guzmán, Tapia, & Rendón (2021). Thus, the adjustments made in the development of the VR module are consistent with and strongly supported by the findings and recommendations of previous research.

This study found that 30 minutes of Virtual Reality (VR) use in case study interactions is the optimal amount of time to achieve the best results. Preliminary test results showed a high success rate, as

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evidenced by the high level of engagement, motivation, favorable responses, and participant satisfaction during the learning process. These findings align with previous research results, which demonstrate that the use of VR can significantly enhance user engagement and satisfaction, both in the context of education and other fields, such as health (Louis, Cagigas, Brant-Zawadzki, & Ricks, 2020; Rafiq, Triyono, & Djatmiko, 2022). Studies in vocational education, for example, prove that VR environments can increase the intensity of student engagement and motivation. In addition, the application of 30-minute VR sessions is also supported by research conducted on elderly and disabled groups, where sessions of similar duration have been proven effective in improving participants' cognitive and physical functions (Chau et al., 2021). Positive user experiences and high levels of satisfaction with VR-based learning have also been reported in various other studies in both academic and non-academic fields (Guldager et al., 2023; Phelan et al., 2021; Predescu et al., 2023). Thus, the results of this study are supported by relevant literature, both in terms of duration of use and the positive impact of VR on engagement, motivation, and satisfaction.

Testing results on the use of Virtual Reality (VR) show a positive impact on student learning experiences. A total of 85% of students reported feeling more engaged with the learning material, indicating an increase in active participation during the learning process. Motivation levels also showed similar results, with 85% of students admitting that they were more motivated to learn after the VR session. Support for conceptual understanding was reinforced by positive responses from 90% of respondents who stated that VR helped them understand the material better. Overall satisfaction also reflects the effectiveness of this approach, with 90% of students feeling very satisfied with the integration of VR in mathematics learning. At the dissemination stage, researchers presented the research results to lecturers from other mathematics education study programs, with the hope of broadening their understanding of the use of VR media in the courses they teach.

The theoretical framework in education suggests that VR should enhance learning by providing immersive and interactive experiences, making abstract concepts more tangible and easier to understand. According to constructivist learning theory, students learn better when they are actively engaged and apply knowledge in realistic contexts. The findings of this study are consistent with this theory, particularly in terms of increasing engagement and understanding of complex concepts through VR.

Although the positive results are in line with several previous studies that show the benefits of VR in increasing student engagement and understanding (Kenedi et al., 2023; Rahmawati et al., 2022), this study found additional challenges related to the comfort of using VR and the initial learning curve, which have not been widely discussed in previous studies.

However, there are some gaps compared to theoretical expectations, particularly in terms of cognitive overload and difficulties in applying knowledge to real-world situations. Students' perceptions of VR vary: positive feedback on visualization and motivation, but also challenges related to the learning curve.

Specifically, the learning curve challenges and discomfort with VR use reported by participants indicate that although VR promises an immersive learning experience, ergonomic factors and technical adaptation must be carefully considered to optimize learning effectiveness.

From a pedagogical perspective, the use of VR in this study fulfilled many of its theoretical promises, but also revealed the need for carefully structured learning activities in the VR environment. The design must be pedagogically sound, ensuring that the VR experience is aligned with learning outcomes and does not overwhelm students with excessive stimuli.

The integration of VR in education, as evidenced by this study, demonstrates that VR is a powerful tool for enhancing student engagement and understanding of complex material, such as mathematical modeling and ethnomathematics. However, its success depends on careful implementation, ongoing research, and adequate support for students and educators.

The small and unrepresentative research sample is a significant limitation in this study, which restricts the ability to generalize the results to a broader student population. This condition underscores the importance of replication using a larger and more diverse sample to validate the consistency of findings across different educational contexts.

Participants' prior experience with VR technology varied, creating differences in the learning curve that were difficult to control. The VR content used focused on specific aspects so that the findings may be limited to those specific applications.

The lack of longitudinal data on knowledge retention in this study is also a limitation, making it impossible to conclude whether the increase in student understanding and engagement will be sustained in the long term. Further research, including long-term measurements, is highly recommended to gain a more comprehensive understanding of the impact of VR on knowledge retention.

The controlled research environment may not accurately represent actual classroom conditions, which could limit the generalizability of the findings to real educational contexts. This study also did not measure other educational aspects such as problem-solving skills, collaborative learning, or creativity. The non-experimental design, lacking a comparison group, also limits definitive cause-and-effect interpretations.

Technical problems with VR equipment during the study, such as occasional glitches and interface difficulties, add to the complexity of interpreting the results, indicating the need for special attention to technical readiness in the implementation of VR in real educational settings.

These findings suggest that, although the study's results demonstrate the significant potential of VR, awareness of the fundamental challenges related to technical, ergonomic, and pedagogical aspects is necessary when applying this technology in a broad educational context. Future research should explicitly address these challenges and seek solutions to enable VR to be used more effectively in everyday educational practice.

## IV. Conclusion

Based on research findings, Virtual Reality (VR) can be effectively integrated into the presentation of case studies in mathematical modeling and ethnomathematics by providing an immersive and interactive environment where students can engage with abstract concepts through contextual simulations relevant to the real world. VR enhances student engagement, facilitates a deeper understanding of complex mathematical principles, and provides a unique platform for visualizing ethnomathematical patterns in culturally relevant contexts. However, successful integration requires careful design, tiered learning experiences, and adequate training for educators and students to ensure optimal use without cognitive overload. Overall, VR has great potential to transform the mathematics learning experience. However, its application must be carefully managed to overcome challenges such as technical difficulties and individual differences in familiarity with the technology. As a concrete next step, it is recommended that further research be conducted using experimental designs involving control groups to compare the effectiveness of VR with traditional methods, as well as to measure long-term knowledge retention. In addition, this VR integration aligns with Indonesia's education reform agenda through the Merdeka Belajar (Freedom of Learning) program, which emphasizes innovation, project-based learning, and enhancing technological literacy among students. Therefore, the implementation of VR in mathematics modeling and ethnomathematics courses can strategically support national goals in creating an adaptive, creative learning environment that is relevant to the needs of Industry 4.0.

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## AUTHOR'S BIOGRAPHY

**Satya Santika, S.Pd., M.Pd.**

Born in Tasikmalaya, November 27, 1986. Lecturer at Siliwangi University. Bachelor's degree in Mathematics Education from Siliwangi University, Tasikmalaya City, graduated in 2009; and Master's degree in Mathematics Education from Pasundan University, Bandung City, graduated in 2013.

**Depi Ardian Nugraha, S.Pd., M.Pd.**

Born in Tasikmalaya, February 7, 1989. Lecturer at Siliwangi University. Bachelor's degree in Mathematics Education from Siliwangi University, Tasikmalaya City, graduated in 2011; and Master's degree in Mathematics Education from Pasundan University, Bandung City, graduated in 2014.

**Dr. Mega Nur Prabawati, S.Pd., M.Pd.**

Born in Tasikmalaya City, January 24, 1988. Lecturer at Siliwangi University. Bachelor's degree in Mathematics Education from Siliwangi University, graduated in 2009; Master's degree in Mathematics Education from the Graduate School of UPI, graduated in 2011; and Doctorate in Mathematics Education from the Graduate School of UPI, graduated in 2021.