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Toward a Metaverse-Ready Language Learning Ecosystem: A Mobile-Assisted Language Learning Platform Based on Trigatra Principles

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Abstract: This study aims to integrate Trigatra language principles into 21st-century language education through the development of a mobile-assisted learning application that supports multiliteracy competence, cultural awareness, and student-centered learning. In multilingual educational contexts such as Indonesia, the implementation of Indonesian, regional, and foreign languages remains fragmented despite the increasing demand for digital literacy, intercultural communication, and technology-enhanced learning. Therefore, this study addresses the need for an innovative educational approach capable of integrating linguistic diversity, national identity, and mobile learning within a unified pedagogical framework. This research employed the Design Science Research (DSR) methodology to design, develop, and evaluate the Trigatra mobile learning application. The application was developed using educational technology principles, multiliteracy pedagogy, and user-centered design approaches. The evaluation involved 30 respondents and utilized the User Experience Questionnaire (UEQ) to measure attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty. User testing was also conducted to assess students' learning engagement and understanding of Trigatra language principles. The findings revealed that the application achieved positive user experience results, with attractiveness and efficiency categorized as "excellent," while perspicuity, dependability, stimulation, and novelty were categorized as "good." Students demonstrated strong positive perceptions regarding the application's implementation in learning, with scores ranging from 86% to 93%. Rather than being conceptualized as a metaverse application itself, the proposed Trigatra platform is designed as a mobile-assisted language learning application that establishes the pedagogical and technological foundation for the future development of metaverse-ready language education ecosystems. The present study empirically evaluates only the mobile platform, while the metaverse dimension is proposed as a future direction for educational innovation. The findings indicate that this architecture provides an initial pathway toward the development of metaverse-ready language education ecosystems capable of supporting immersive, culturally responsive, and technology-enhanced multilingual learning.

Keywords: Trigatra language; Mobile-assisted learning; Smart learning environment; Education 5.0; 21st-century language education; Metaverse-based education

1. Introduction

Language plays a fundamental role in education, not only as a communication tool but also as a medium for knowledge construction, cultural transmission, identity formation, and social integration. In multilingual societies such as Indonesia, language education carries broader responsibilities in maintaining national unity

while simultaneously preparing students to participate in global communication and multicultural interactions [1]. Within this context, Indonesia recognizes three interconnected language dimensions known as Trigatra Bahasa, consisting of the Indonesian language, regional languages, and foreign languages. These three language components function as complementary pillars in strengthening national identity, preserving local wisdom, and enhancing international competitiveness [2].

Conceptually, the three pillars of Trigatra language principles are not intended to function as separate domains of language learning but as an integrated multilingual educational framework. Indonesian serves as the primary language for national identity, social cohesion, and formal communication; regional languages preserve local wisdom, cultural heritage, and community identity; while foreign languages enable learners to participate in global communication, intercultural dialogue, and international knowledge exchange. Rather than competing with one another, these three language dimensions are mutually reinforcing, allowing learners to develop balanced linguistic competence that simultaneously strengthens cultural rootedness and global engagement. Accordingly, the Trigatra framework promotes multilingualism as an interconnected educational process in which local, national, and global language competencies collectively support lifelong learning, intercultural understanding, and 21st-century citizenship.

The ongoing digital transformation has fundamentally reshaped educational systems worldwide, creating new opportunities for technology-enhanced learning and knowledge acquisition. Emerging educational paradigms such as Education 5.0 emphasize the integration of advanced digital technologies, human-centered learning, creativity, innovation, and sustainable development within educational environments. Consequently, mobile learning ecosystems, AI-enhanced education, smart learning environments, and virtual learning environments are increasingly becoming essential components of contemporary education [3]. The increasing adoption of virtual worlds in education has also demonstrated significant potential for improving inclusion, accessibility, and learner participation in technology-enhanced learning environments [4]. These technological developments enable more personalized, adaptive, and flexible learning experiences while supporting learners' engagement, collaboration, and lifelong learning competencies. As educational institutions continue to adapt to the demands of digital societies, there is a growing need to design learning environments that effectively combine technological innovation with meaningful educational experiences.

Globally, the rapid advancement of digital technology and globalization has significantly transformed educational systems and language learning practices. Educational institutions are increasingly challenged to integrate digital literacy, multiliteracy competence, and intercultural communication skills into learning environments that align with the demands of 21st-century education [5-7]. According to Rahayu et al. [8], 21st-century learning emphasizes multiliteracy, critical thinking, communication, collaboration, and creativity as essential competencies for students. Similarly, Rosnaeni [9] argues that educational transformation requires learning approaches that are student-centered, technology-enhanced, and adaptable to rapidly changing social and technological contexts. Consequently, language education is no longer limited to linguistic mastery but must also support digital competence, cultural awareness, and lifelong learning skills.

Despite these educational transformations, many countries continue to face challenges in balancing national language preservation, regional language

sustainability, and foreign language mastery within formal education systems. Globalization often increases the dominance of international languages, particularly English, while local and national languages experience declining usage among younger generations [10]. In the Indonesian context, this issue becomes increasingly significant because Indonesia possesses extraordinary linguistic diversity with hundreds of regional languages that require preservation through educational practices. However, the implementation of Trigatra Bahasa within schools remains fragmented. Indonesian, regional, and foreign languages are generally taught separately without pedagogical integration that enables students to understand the interconnected roles of these languages in social, cultural, and global contexts.

Empirically, previous studies have shown that mobile learning and educational technology can support students' learning motivation, engagement, and language acquisition outcomes. Luo and Li [11] found that mobile applications create more interactive and flexible learning experiences compared to conventional methods. Likewise, Song et al. [12] emphasized that personalized mobile learning enhances students' participation and independent learning processes. Other studies have highlighted the effectiveness of integrating artificial intelligence, multimedia content, and adaptive learning systems into educational applications to improve language learning performance [13,14]. Furthermore, multimedia-based mobile learning environments have been shown to increase learner engagement and facilitate meaningful educational experiences [15,16].

However, existing studies predominantly focus on technical language acquisition, user interface design, application usability, or personalized digital learning systems. Limited attention has been given to how mobile-assisted learning can be utilized to integrate national language identity, regional language preservation, and foreign language competence within a unified educational framework. Most mobile language learning applications are designed primarily to improve vocabulary, pronunciation, or grammar skills, while the sociocultural and educational dimensions of multilingualism remain underexplored. This indicates an important empirical gap in current educational technology research, particularly regarding the integration of local cultural values and national language policies into digital learning environments.

In addition to the empirical gap, a significant research gap also exists in the literature concerning Trigatra Bahasa within 21st-century education. A number of earlier studies have addressed the subject of Trigatra Bahasa, but with a focus on language policy, curriculum discourse and conceptual educational frameworks, rather than on the integration of digital learning innovation into practical implementation [2]. Meanwhile, research on mobile learning applications rarely addresses how educational technology can simultaneously support multiliteracy competence, cultural identity, and multilingual language learning in the context of national education. As a result, there remains limited understanding of how mobile-assisted learning can function not only as a technological tool but also as a pedagogical medium for strengthening students' awareness of linguistic diversity and national identity in the digital era.

Consequently, the present study has developed and evaluated a mobile-assisted language learning application based on Trigatra language principles. While the present study focuses on evaluating the Usability and Educational Effectiveness of the Mobile Platform, it should be noted that the proposed architecture also provides a conceptual pathway through which future immersive technologies may progressively be incorporated into language education. Accordingly, the metaverse dimension is

positioned as a long-term educational vision rather than the primary technological artifact evaluated in this study. Rather than conceptualizing the application as a standalone mobile learning tool, the study positions it as the foundational layer of an evolving educational ecosystem that may progressively incorporate immersive technologies, virtual learning environments, artificial intelligence, and collaborative metaverse-based learning experiences [17,18].

The recent literature further supports this future direction. Research on dynamic human digital twin deployment demonstrates how edge computing enables accurate real-time synchronization between physical users and their virtual counterparts for adaptive task execution. Similarly, generative AI-assisted resource allocation has been shown to improve interaction quality and intelligent service delivery in evolving digital twin environments [19-21]. Furthermore, comprehensive networking architectures for human digital twins highlight the importance of scalable communication infrastructures capable of supporting continuous data synchronization, intelligent decision-making, and personalized digital services. Collectively, these technological developments reinforce the feasibility of extending the proposed Trigatra platform toward a next-generation multilingual learning ecosystem that integrates artificial intelligence, immersive environments, and digital twin technologies while preserving the pedagogical principles of multilingual education.

The novelty of this study lies in several aspects. First, this research integrates Trigatra language principles into a mobile-assisted learning environment specifically designed for 21st-century education. Second, the study combines language education, multiliteracy learning, and digital pedagogy within a single educational framework, which remains relatively underexplored in previous literature. Third, unlike conventional mobile learning applications that emphasize technical language skills alone, the Trigatra application incorporates educational values related to national identity, local language preservation, and multicultural awareness. Fourth, this study contributes to the development of culturally responsive educational technology by demonstrating how mobile learning can support both global competence and local cultural sustainability. Furthermore, the proposed Trigatra mobile application contributes to the development of smart and culturally responsive learning environments by integrating multilingual education within a mobile learning ecosystem that supports the principles of Education 5.0. The study further introduces a conceptual pathway through which culturally responsive mobile learning ecosystems can evolve into metaverse-supported educational environments for multilingual and intercultural learning. Unlike conventional multilingual education models that address these language domains independently, the proposed Trigatra framework conceptualizes them as an interconnected pedagogical system that simultaneously promotes national identity, cultural sustainability, and global competence through a unified mobile-assisted learning environment.

This study contributes theoretically by enriching the literature on language education, mobile learning, and multiliteracy pedagogy through the integration of Trigatra language principles into digital learning environments. Practically, the study provides insights for educators, curriculum developers, and policymakers regarding the implementation of technology-supported language education that promotes linguistic diversity, national identity, and 21st-century competencies. Furthermore, the study offers an innovative educational model that can support the transformation of language learning into a more interactive, student-centered, and culturally meaningful

learning experience in the digital era.

To illustrate the theoretical relationship between Trigatra language principles, mobile-assisted learning, multiliteracy development, and future digital learning ecosystems, this study proposes the conceptual framework presented in **Figure 1**. **Figure 1** illustrates the evolutionary pathway through which the Trigatra mobile learning platform functions as the foundational layer of a future metaverse-ready language learning ecosystem. The framework explains how multilingual learning, multiliteracy development, smart learning environments, and Education 5.0 are conceptually interconnected to support culturally responsive and technology-enhanced language education. This conceptual framework serves as the theoretical foundation that guides the design, development, and evaluation of the proposed mobile-assisted learning platform.

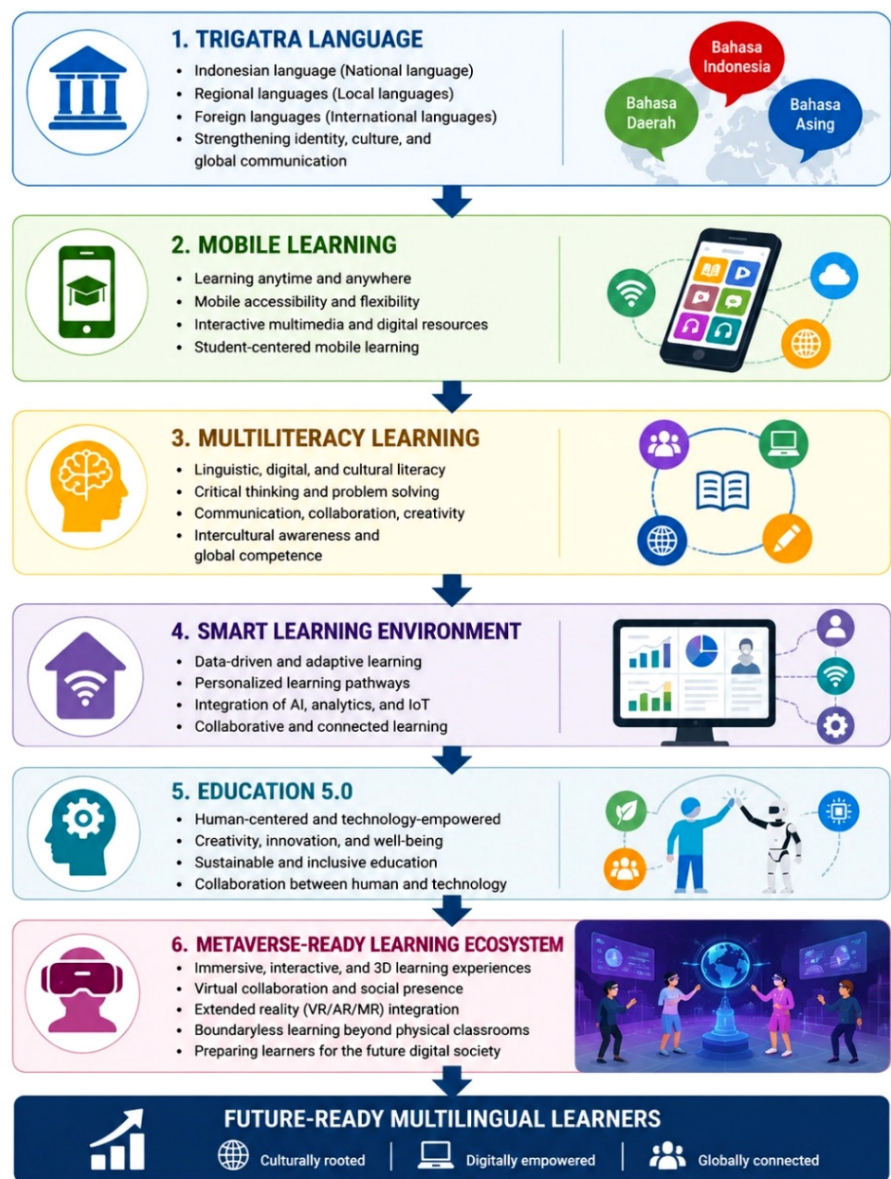


Figure 1. Conceptual Evolution of the Trigatra Mobile Learning Platform Toward a Future Metaverse-Ready Educational Ecosystem

Figure 1 conceptualizes the evolutionary pathway from mobile-assisted multilingual learning toward a metaverse-ready educational ecosystem. Rather

than representing a linear technological progression, the framework illustrates how multilingual pedagogy, smart learning environments, and Education 5.0 collectively establish the pedagogical architecture necessary for future immersive learning.

The framework is, therefore, best interpreted as a phased technological and pedagogical roadmap, rather than as a representation of the current system implementation. Each stage of this process serves to extend the functionality of the preceding stage, whilst preserving the underlying multilingual learning architecture.

It is important to emphasize that the present study does not claim to implement a metaverse learning environment. Instead, the empirical findings validate the usability and pedagogical feasibility of the mobile platform, which is proposed as a foundational educational infrastructure for future metaverse-supported language learning.

2. Literature Review

2.1. Mobile Application in Language Education

The development of mobile applications has become increasingly important in contemporary education, particularly in supporting 21st-century learning environments that emphasize flexibility, student-centered learning, digital literacy, and multiliteracy competence. Mobile learning applications enable students to access learning materials anytime and anywhere, thereby promoting autonomous learning, interactive engagement, and personalized educational experiences [8-9]. In the domain of language education, mobile applications are increasingly acknowledged as innovative tools with the potential to enhance students' language acquisition, communication skills, and learning motivation through technology-enhanced learning environments.

The literature on mobile application development for language learning highlights several important educational aspects related to the design, implementation, and effectiveness of digital learning applications. Previous studies on user interface and user experience (UI/UX) design emphasize that intuitive navigation, effective layouts, and appropriate visual and audio elements significantly influence students' learning experiences and engagement in digital learning environments [22-24]. From an educational perspective, well-designed interfaces can improve learning accessibility, facilitate student interaction with learning materials, and support meaningful learning processes.

Furthermore, current educational technology research increasingly explores the integration of advanced technologies such as artificial intelligence (AI) and augmented reality (AR) into language learning applications. These technologies allow educational applications to adapt learning content to students' individual abilities, learning styles, and educational needs, thereby supporting personalized learning and adaptive pedagogy [25-27]. In addition, AI-based educational systems can provide immediate feedback, monitor learning progress, and facilitate individualized instruction, which are considered essential components of effective 21st-century education [13].

Another important issue discussed in the literature is the personalization of learning within mobile-assisted language education. Educational researchers emphasize that mobile learning applications should be capable of adjusting curriculum content, learning activities, and instructional strategies according to students' proficiency levels, preferences, and learning objectives [12,28,29]. Personalized learning environments not only enhance students' academic performance but also

increase learner autonomy, motivation, and engagement in educational activities.

Previous studies have also evaluated the effectiveness of mobile applications in improving language competencies, including speaking, listening, reading, and writing skills. Various educational evaluation methods have been employed, such as language proficiency assessments, user satisfaction surveys, and learning analytics to examine the impact of mobile learning on educational outcomes [30-32]. The findings generally indicate that mobile learning applications contribute positively to students' learning performance, participation, and communication abilities.

In addition to cognitive outcomes, several studies focus on psychological and pedagogical dimensions such as learning motivation, student engagement, and collaborative learning. These studies demonstrate that interactive mobile learning environments can foster students' interest, active participation, and commitment to language learning activities [30-32]. Such findings are highly relevant to the current educational transformation toward student-centered and technology-supported learning environments.

The use of multimedia elements in mobile learning applications has also received considerable attention in educational research. Audio, video, images, animations, and interactive content are widely utilized to improve students' language comprehension, pronunciation, and communication skills [15,16,33]. Multimedia-supported learning environments are considered effective in facilitating deeper understanding, increasing learning engagement, and accommodating diverse learning styles among students.

Moreover, some educational applications integrate social learning features such as discussion forums, collaborative tasks, virtual classrooms, and shared learning challenges. These social and collaborative features help students develop communication skills, peer interaction, and collaborative learning experiences that align with the competencies required in 21st-century education [34-36].

Despite the significant educational potential of mobile learning applications, previous studies also identify several challenges in their implementation, including limited technological infrastructure, unequal access to digital devices, internet connectivity issues, and difficulties in designing pedagogically effective learning experiences [37-39]. These challenges indicate that successful integration of mobile learning into education requires not only technological innovation but also pedagogical considerations that align with students' educational needs and sociocultural contexts.

2.2. Trigatra Language Practice-Based Learning

The Trigatra Language Practice-Based Learning model is an integrative educational approach rooted in Indonesia's language education policy. It has been designed to support multilingual language learning. The model under discussion places significant emphasis on the interconnected roles of Indonesian, regional, and foreign languages within the context of educational practice. As indicated by the national curriculum, these three language dimensions are recognised in a formal capacity. It is expected that they will contribute to the development of students' linguistic competence, cultural awareness, and national identity [2]. However, in educational practice, Indonesian, regional, and foreign language instruction is frequently conducted separately, with limited pedagogical integration among these language domains.

From an educational perspective, the Trigatra language framework reflects the broader goals of language education in multilingual societies, namely preserving national identity, maintaining local cultural heritage, and preparing students for global

communication. The model is closely associated with Indonesia's historical and sociocultural development, particularly the role of language in national unity since the Youth Pledge of 1928 and the establishment of Indonesian independence in 1945. The implementation of Trigatra language principles is further supported by Article 36 of the 1945 Constitution and Law No. 24 of 2009 concerning the National Flag, Language, State Emblem, and National Anthem.

In the context of 21st-century education, the Trigatra language model is highly relevant because it supports multiliteracy education, intercultural competence, and culturally responsive pedagogy. The model encourages students not only to master linguistic skills but also to develop awareness of linguistic diversity, multicultural communication, and national identity within globalized learning environments. Nevertheless, despite its educational importance, the implementation of Trigatra language principles in schools remains limited and requires innovative pedagogical approaches capable of integrating technology into language learning processes [2].

Therefore, integrating Trigatra language principles into mobile-assisted learning environments offers significant educational opportunities. Educational applications can facilitate interactive, flexible, and student-centered learning experiences while simultaneously promoting multiliteracy competence, cultural preservation, and digital literacy. Through technology-supported language education, the Trigatra learning model can contribute to the development of meaningful educational experiences that align with the demands of 21st-century learning and digital pedagogy.

2.3. Metaverse-Based Language Learning

The rapid advancement of digital technologies has accelerated the emergence of the educational metaverse as an innovative paradigm for future learning environments. Unlike conventional online learning platforms, the educational metaverse integrates immersive technologies such as virtual reality (VR), augmented reality (AR), artificial intelligence (AI), extended reality (XR), digital avatars, blockchain, and persistent virtual environments to create interactive, collaborative, and learner-centered educational experiences [40-43]. These technologies enable learners to actively participate in authentic learning situations where communication, collaboration, and experiential learning occur simultaneously. Consequently, the educational metaverse represents a significant transformation from technology-assisted learning toward immersive and intelligent educational ecosystems.

Recent studies suggest that metaverse-based learning extends beyond technological innovation by transforming the way knowledge is constructed and shared. Rather than merely delivering digital content, immersive virtual environments encourage active learner participation, social interaction, collaborative problem-solving, and contextual learning experiences that enhance learners' motivation and engagement [41,44-46]. These characteristics closely align with the principles of Education 5.0, which emphasize human-centered learning, creativity, innovation, digital literacy, and sustainable educational development. Therefore, the educational metaverse is increasingly recognized as a strategic platform for supporting future-oriented education capable of integrating advanced technologies with meaningful pedagogical practices.

Within language education, the educational metaverse offers substantial opportunities to improve language acquisition through authentic communication and immersive interaction. Previous studies indicate that virtual learning environments facilitate language practice through avatar-mediated communication, role-playing activities, collaborative dialogue, and simulated real-world contexts that cannot easily

be replicated in conventional classrooms [47-49]. Such environments provide learners with opportunities to develop speaking, listening, intercultural communication, and collaborative competencies while simultaneously increasing motivation, confidence, and learner autonomy. Accordingly, virtual world language learning has become an emerging research area that complements conventional mobile-assisted language learning by providing richer social and contextual learning experiences.

Despite these developments, existing studies remain predominantly technology-oriented. Most research focuses on immersive hardware, virtual reality platforms, avatar systems, or application development, while relatively limited attention has been devoted to pedagogical architectures capable of integrating multilingual education, cultural sustainability, and learner-centered instructional design within metaverse environments [42,50]. Similarly, studies on mobile-assisted language learning primarily emphasize vocabulary acquisition, pronunciation improvement, personalized learning, and application usability without examining how mobile learning can function as the initial technological layer of future immersive educational ecosystems. This separation between mobile learning research and educational metaverse literature reveals an important theoretical gap regarding the evolutionary relationship between current digital learning platforms and future metaverse-supported language education.

In response to this gap, the present study positions the proposed Trigatra platform not merely as a mobile-assisted learning application but as the foundational architecture of a metaverse-ready language learning ecosystem. By integrating Indonesian, regional, and foreign languages within a smart mobile learning environment, the platform establishes the pedagogical and technological foundations necessary for the gradual evolution toward immersive multilingual education. Rather than viewing the metaverse as a complete replacement for existing educational systems, this study conceptualizes mobile learning as the entry point through which more advanced immersive technologies—including virtual reality, augmented reality, artificial intelligence, digital avatars, learning analytics, and collaborative virtual classrooms—may progressively be integrated into language education. Consequently, the proposed Trigatra platform contributes not only to the advancement of mobile-assisted language learning but also to the broader academic discourse on educational metaverse by demonstrating how culturally responsive pedagogy, multilingual learning, and digital literacy can collectively support the development of sustainable, learner-centered, and metaverse-ready educational ecosystems.

3. Materials and methods

The Design Science Research (DSR) methodology is a research approach that focuses on developing practical solutions to specific problems by integrating theoretical foundations with practical implementation [17,18,51]. In the context of educational research, DSR has gained considerable traction as a tool for the development of innovative learning models, digital learning environments, and technology-enhanced educational applications. These applications address contemporary challenges in education by harnessing the potential afforded by digital technologies. This methodology is highly relevant to the development of the Trigatra language mobile application because it enables researchers to integrate language education principles, multiliteracy learning, and educational technology into a practical learning solution for 21st-century education.

This study adopts the DSR methodology to develop a mobile-assisted learning

application designed to strengthen students' understanding of Indonesian, regional, and foreign languages through the Trigatra language framework. The application development process emphasizes not only technological functionality but also pedagogical effectiveness, student engagement, and meaningful learning experiences. The stages of the DSR process applied in this study are illustrated in **Figure 2**.

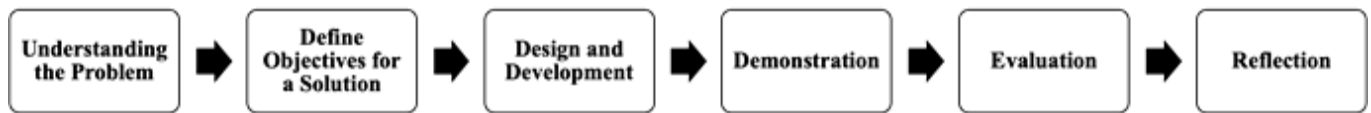


Figure 2. Design Science Research (DSR) Method Applied in This Study

1. Understanding the Problem

The initial stage in DSR is the identification and comprehension of the educational problems and challenges to be addressed. In this study, the researchers examined the challenges of implementing Trigatra language principles in contemporary language education. Despite the formal inclusion of Indonesian, regional and foreign languages in the educational curriculum, these languages are often taught separately, without integrated pedagogical approaches. Consequently, students may possess an incomplete understanding of the interconnected roles of these languages in supporting national identity, cultural preservation, and global communication competence. Moreover, the accelerated digital transformation in education necessitates the development of innovative learning methodologies that are aligned with students' digital learning habits and 21st-century competencies, such as communication, collaboration, critical thinking, and digital literacy.

2. Define Objectives for a Solution

After identifying the educational challenges, the next stage involves defining the objectives of the proposed learning solution. The primary objective of this study is to develop a mobile learning application capable of integrating Trigatra language principles into language education. The application is expected to support students in improving their proficiency in Indonesian, regional, and foreign languages while simultaneously enhancing multiliteracy competence, cultural awareness, and appreciation for linguistic diversity. In addition, the application aims to create a more interactive, flexible, and student-centered learning environment that supports independent and technology-assisted learning experiences.

3. Design and Development

This stage focuses on designing and developing the Trigatra mobile learning application. The development process incorporates educational technology principles, mobile learning concepts, and user-centered design approaches to ensure that the application provides meaningful learning experiences for students. The application interface was designed based on user interface and user experience (UI/UX) principles to improve accessibility, usability, and learner engagement. Furthermore, the application integrates multimedia learning features such as visual content, interactive activities, and language exercises to facilitate students' language comprehension and communication skills. From an educational perspective, the application was developed to support student-centered learning, autonomous learning, and multiliteracy-based language education in digital learning environments.

4. System Architecture and Technical Implementation

The Trigatra mobile learning platform was developed as a modular mobile application following the Design Science Research (DSR) methodology. The system

architecture consists of three primary layers: (1) the presentation layer, which provides an intuitive user interface for accessing multilingual learning materials, quizzes, videos, and interactive educational content; (2) the application layer, which manages learning logic, user interaction, navigation, and assessment activities; and (3) the data layer, which stores and manages learning resources, user progress, and multimedia content. Such a layered architecture improves system maintainability, flexibility, and future extensibility.

From a technological evolution perspective, the proposed architecture is intended to support a staged development process rather than an immediate transition to a fully immersive metaverse environment. The present implementation constitutes the inaugural stage, with a focus on mobile-assisted multilingual learning, multimedia integration, and user-centred interaction. In the subsequent phase, the integration of cloud-based services, learning analytics, and artificial intelligence is poised to facilitate adaptive learning support and personalised educational experiences. The third stage of this process involves the integration of immersive technologies, including but not limited to virtual reality, augmented reality, digital avatars, and collaborative virtual environments. The objective of this integration is to establish the technological characteristics of a metaverse-ready language learning ecosystem. The phased architecture employed ensures that each technological enhancement builds upon a body of validated educational functionality, thereby maintaining pedagogical continuity throughout the platform's evolution.

The application integrates text-based learning materials, multimedia resources, interactive quizzes, and external educational video content within a unified mobile learning environment. Rather than relying on a monolithic design, the platform adopts a modular architecture in which learning modules can be updated independently without affecting the overall system functionality. This modular approach facilitates future enhancement through the integration of cloud-based services, learning analytics, artificial intelligence, adaptive learning algorithms, and immersive technologies.

Although the present study focuses on evaluating the usability and educational effectiveness of the mobile learning platform, the proposed architecture was intentionally designed to support future scalability. Additional components such as virtual reality, augmented reality, digital avatars, collaborative virtual classrooms, and metaverse-based interaction modules can be incorporated into the existing architecture without requiring substantial redesign. Consequently, the developed artifact represents not only a functional educational application but also a scalable technological foundation for future smart and immersive language learning environments.

The application was developed using Android Studio with Java/Kotlin, while learning resources and multimedia content were organized using a structured local database supported by cloud-accessible educational resources.

5. Development Environment and System Requirements

The Trigatra mobile application was developed as an Android-based mobile application using Android Studio with the Java/Kotlin programming language within the Android Software Development Kit (SDK). The development process was carried out in a standard desktop computing environment equipped with a minimum Intel Core i5 processor, 8 GB RAM, and the Android SDK to support application development, debugging, and testing. The application is compatible with Android smartphones running Android 8.0 (Oreo) or later and requires an internet connection

to access cloud-based multimedia learning resources. Learning content is organized through a structured local database integrated with external educational resources, enabling efficient content management and future updates. By documenting the development environment and minimum system requirements, the proposed artifact becomes more transparent, reproducible, and easier to extend in future Design Science Research implementations.

6. Demonstration

The demonstration stage involves implementing and testing the application in educational settings to evaluate its functionality and pedagogical relevance. In this study, the Trigatra application was introduced to students as users of the mobile learning platform. The demonstration process aimed to examine whether the application could effectively support language learning activities, facilitate students' understanding of Trigatra language principles, and create engaging educational experiences. This stage also ensured that the technological and instructional components of the application functioned properly before further evaluation was conducted.

7. Evaluation

The evaluation phase was conducted to assess both the usability of the developed application and its educational effectiveness in supporting language learning. Consistent with the Design Science Research (DSR) methodology, this stage focused on validating the developed artifact by examining users' experiences and determining whether the application adequately fulfilled its intended educational objectives. The evaluation employed the User Experience Questionnaire (UEQ), which measures six dimensions of user experience: attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty. In addition to usability, the evaluation also explored students' perceptions of the application's contribution to learning motivation, language understanding, and engagement in educational activities. From an educational perspective, this evaluation provides important evidence regarding how mobile-assisted learning environments can enhance students' learning experiences while supporting the development of 21st-century language competencies.

The UEQ evaluation involved 30 participants, reflecting the preliminary design evaluation stage of the Design Science Research process. At this stage, the primary objective was not to achieve statistical generalization but rather to evaluate the artifact's usability, user experience, and pedagogical feasibility through formative user feedback. Accordingly, the evaluation sought to identify the strengths and limitations of the proposed Trigatra mobile learning application, providing empirical evidence to support iterative refinement and future large-scale implementation. This approach is consistent with DSR principles, which emphasize artifact validation and design improvement before broader deployment and experimental evaluation.

To ensure transparency in data interpretation, it should be noted that the frequencies reported in the Results section do not represent the number of respondents. Instead, they represent the aggregated responses across all questionnaire items within each evaluation dimension. Because each participant completed multiple questionnaire items, the cumulative frequencies exceed the sample size ($N = 30$). These aggregated responses were subsequently used to calculate the descriptive statistics and percentage scores for each evaluation construct. This reporting approach provides a comprehensive representation of participants' evaluations while maintaining consistency with the analytical procedures adopted in this study.

8. Reflection

The final stage of DSR involves reflection on the development process,

implementation outcomes, and educational implications of the study. Researchers reviewed the effectiveness of integrating Trigatra language principles into mobile-assisted learning environments and evaluated the challenges encountered during the application development and testing processes. Reflection also focused on how educational technology can support multiliteracy learning, cultural preservation, and student-centered pedagogy in language education. The insights obtained from this stage are expected to contribute to future research and the continuous improvement of digital language learning applications.

In the context of language education, the DSR methodology provides a systematic framework for integrating educational theory, mobile learning, and digital pedagogy into practical instructional solutions. This approach enables researchers to develop technology-supported learning environments that not only improve students' language competencies but also strengthen cultural awareness, multiliteracy skills, and engagement in 21st-century education. Therefore, the Trigatra mobile application represents not merely a technological innovation but also an educational innovation designed to support meaningful, interactive, and culturally responsive language learning experiences.

4. Results

4.1. Design and Development

Figure 3 shows the architectural design of the Trigatra language mobile application, which was implemented and evaluated on Android smartphones. The application was developed using Android Studio and Java/Kotlin and was designed to support mobile-assisted language learning within the Trigatra framework.

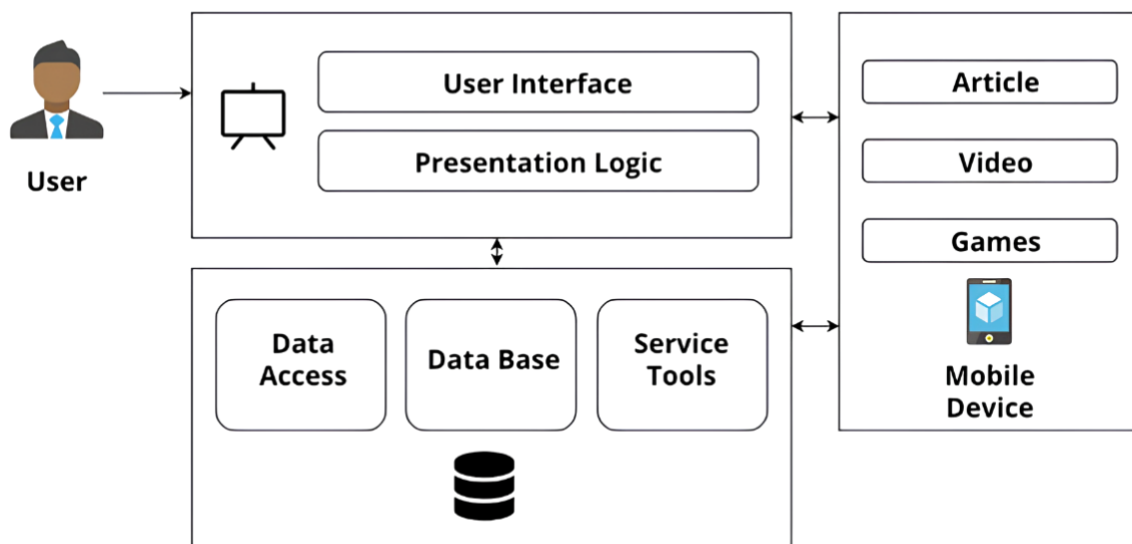


Figure 3. Architecture of the Trigatra Platform as the Entry Point to a Metaverse-Ready Language Learning Ecosystem

Figure 3 illustrates the architectural design of the Trigatra language mobile application, which was implemented and evaluated on Android mobile devices. The application was designed as a mobile-assisted learning platform to support 21st-century language education by integrating Indonesian, regional, and foreign language learning into a single digital learning environment. From an educational perspective, the application architecture was developed to facilitate flexible, interactive, and student-centered learning experiences that align with current digital learning practices.

The current implementation represents an Android-based mobile-assisted learning platform developed and evaluated within this study. From a conceptual perspective, its modular architecture may serve as the initial digital infrastructure upon which future immersive learning technologies could be progressively integrated.

The Trigatra mobile application was designed not only as a technological tool but also as an educational medium that supports multiliteracy learning, digital literacy, and cultural awareness among students. Through mobile accessibility, students are able to engage in language learning activities independently anytime and anywhere, thereby promoting autonomous learning and increasing learning flexibility. In addition, the integration of multimedia features and interactive learning activities was intended to enhance students' engagement, communication skills, and understanding of linguistic diversity in the Indonesian educational context.

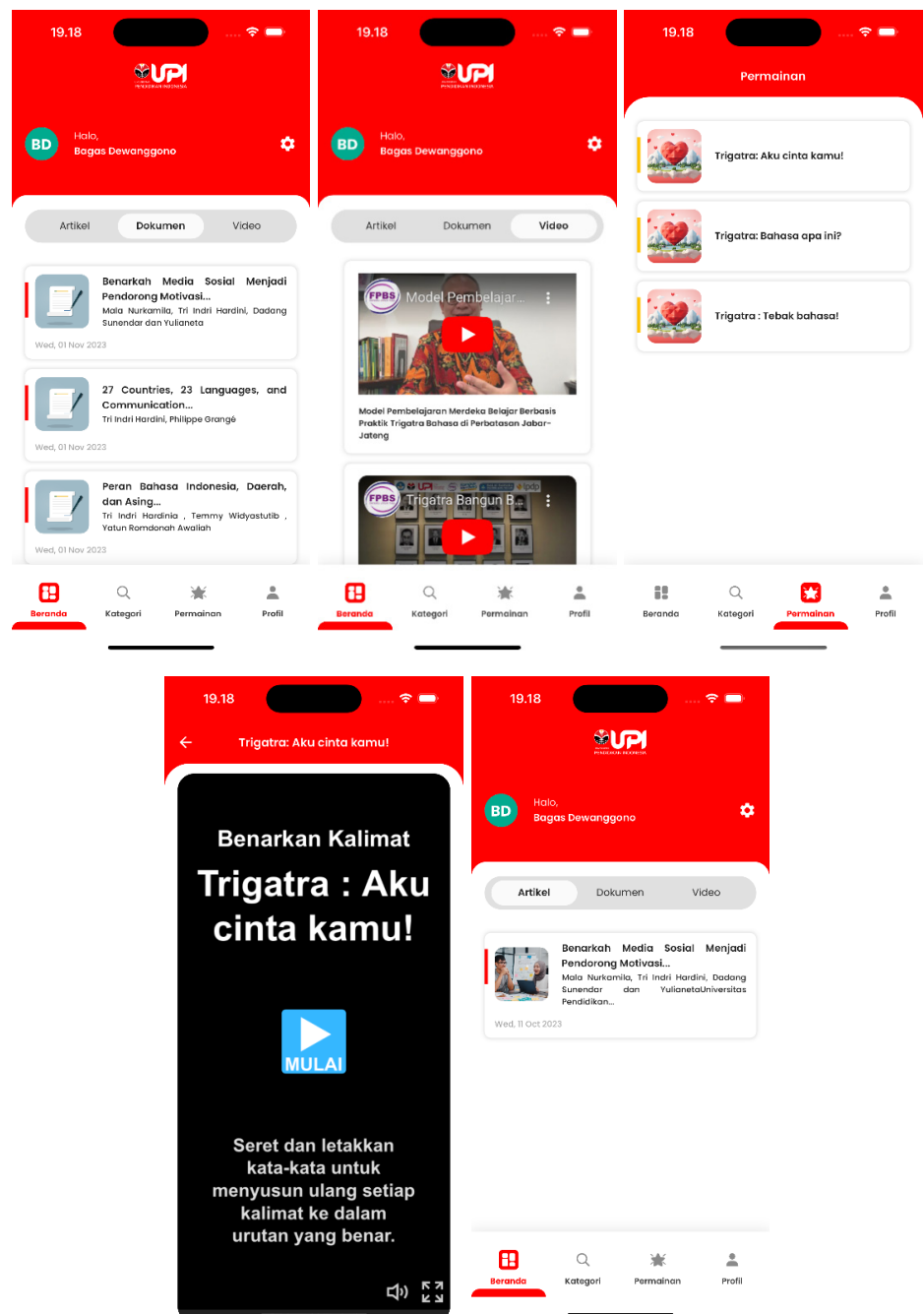


Figure 4. Implementation of the Trigatra language mobile application interface.

Figure 4 presents the user interface design of the Trigatra language mobile application. The interface was developed using user-centered design principles to ensure accessibility, usability, and meaningful educational interaction. In language education, effective interface design is important because it influences students' motivation, participation, and learning experience. Therefore, the application interface was designed to create a supportive digital learning environment capable of facilitating meaningful and enjoyable language learning experiences.

4.2. Trigatra Language Application Interface Display Test

The user interface of the Trigatra language application was evaluated by 30 respondents using 17 questionnaire items that measured several dimensions of user experience, including attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty. The results showed positive evaluations across all dimensions, with average scores exceeding 0.8. Educationally, these findings indicate that the application successfully created a positive digital learning environment capable of supporting students' interaction and engagement in language learning activities.

Table 1. UEQ Scale Scores for the Trigatra Language Application

Aspect	UEQ Scales (Mean and Variance)	
Attractiveness	1.867	0.98
Perspicuity	2.025	1.46
Efficiency	1.975	0.68
Dependability	1.675	0.85
Stimulation	1.658	1.21
Novelty	1.142	1.45

Table 1 demonstrates that the application achieved high scores in attractiveness (1.867), perspicuity (2.025), and efficiency (1.975), indicating that students perceived the application as easy to use, understandable, and supportive of learning activities. In the context of educational technology, these findings suggest that the Trigatra application can facilitate effective learning experiences by reducing technical barriers and supporting students' independent learning processes. The high perspicuity score also reflects the application's ability to present learning materials clearly and systematically, which is essential in mobile-assisted language education.

Furthermore, the dependability, stimulation, and novelty dimensions also received positive evaluations, indicating that the application was perceived as reliable, motivating, and innovative. From a pedagogical perspective, these aspects are important because engaging and innovative learning environments can increase students' learning motivation, participation, and interest in language education. The results imply that integrating Trigatra language principles into a mobile learning environment contributes positively to students' learning experiences and supports the implementation of technology-enhanced education.

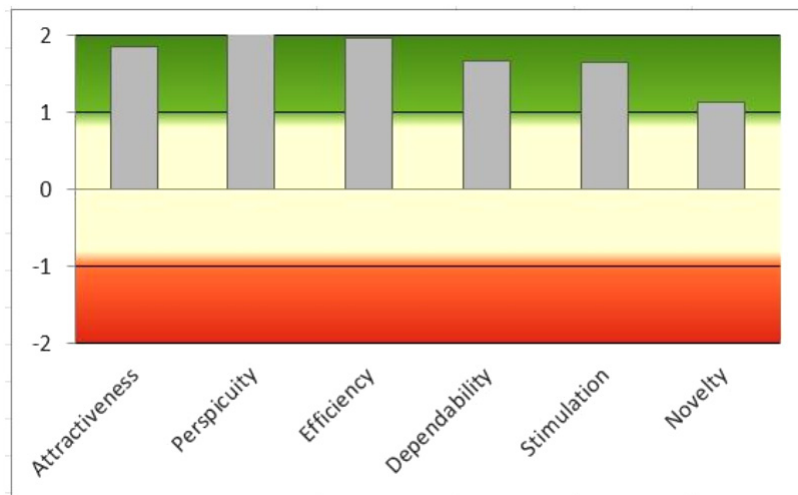


Figure 5. Diagram showing UEQ results for the Trigatra language application

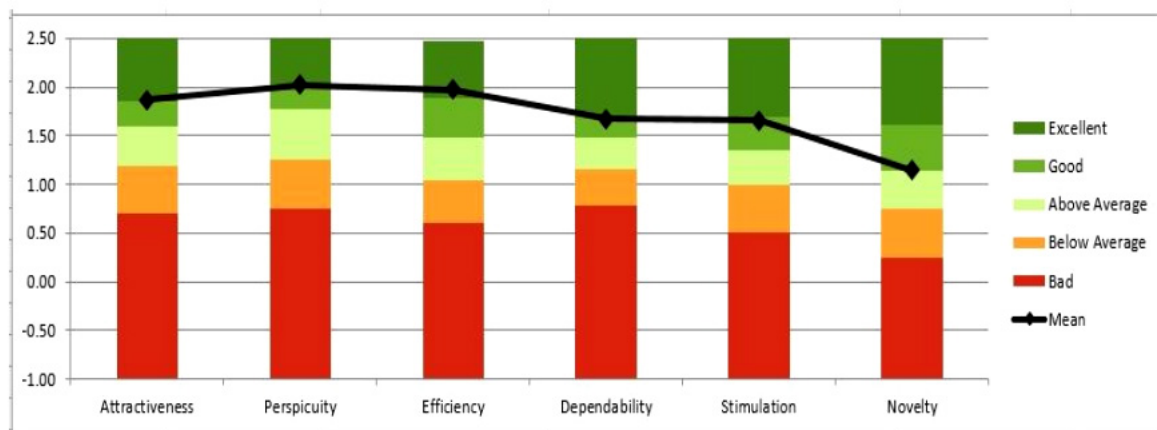


Figure 6. Benchmark analysis results for the Trigatra language application

Figure 5 visualizes the UEQ results obtained from the respondents across the six evaluation dimensions. Meanwhile, **Figure 6** presents the benchmark analysis comparing the Trigatra language application with 452 other studies. The benchmark analysis categorized attractiveness and efficiency as “excellent,” while perspicuity, dependability, stimulation, and novelty were categorized as “good.” These findings indicate that the application provides a positive overall educational experience and has strong potential to support digital language learning in 21st-century education.

4.3. Application User Testing Results

The application user testing evaluated students’ perceptions regarding their interest in the application, the implementation of the application in learning activities, their understanding of Trigatra language principles, and their overall evaluation of the Trigatra application. The assessment employed a five-point Likert scale ranging from strongly disagree (1) to strongly agree (5).

The evaluation involved 30 participants. To ensure mathematical consistency and avoid ambiguity in interpreting the response frequencies, the results are reported in **Table 2** using normalized percentage scores rather than raw frequency values for each response category. The percentage represents the obtained Likert score relative to the maximum possible score for each evaluation dimension. This reporting approach provides a more transparent representation of the descriptive results of the preliminary artifact evaluation.

Table 2. Summary of Application User Testing Results

Evaluation Dimension	No. of Items	Average (%)	Interpretation
Interest in the Application	13	86%	Very Strong
Application in Learning	3	91%	Very Strong
Understanding of Trigatra Language Principles	11	93%	Very Strong
Overall Trigatra Application Evaluation	4	93%	Very Strong

As shown in **Table 2**, participants reported very positive perceptions across all evaluation dimensions. Interest in the application reached 86%, while perceptions regarding the application in learning reached 91%. Participants' self-reported understanding of Trigatra language principles and their overall evaluation of the application both reached 93%. These results indicate a consistently positive perception of the Trigatra platform during the preliminary evaluation stage.

The findings should be interpreted as descriptive evidence of user acceptance, perceived learning support, and pedagogical feasibility rather than as empirical evidence of generalizable learning gains. In accordance with the Design Science Research approach adopted in this study, the purpose of this preliminary evaluation was to assess the usability, user experience, and perceived educational value of the developed artifact and to provide evidence for subsequent refinement and larger-scale evaluation.

Overall, the results presented in **Table 2** indicate that participants reported highly positive evaluations of the Trigatra language platform, with normalized scores ranging from 86% to 93% across the four evaluation dimensions. These findings suggest that the proposed platform demonstrates promising usability, learner acceptance, and perceived pedagogical feasibility during the preliminary Design Science Research (DSR) evaluation. The results provide an initial empirical basis for further refinement and larger-scale evaluation of the platform.

4.4. Discussion

The findings of this study suggest that the Trigatra language mobile application offers a meaningful contribution to 21st-century language education by creating an interactive, flexible, and student-centered learning environment. The high scores obtained in the User Experience Questionnaire (UEQ), particularly in attractiveness, efficiency, and perspicuity, indicate that the application successfully delivered a user-friendly and engaging digital learning experience. These findings support previous studies suggesting that well-designed mobile learning applications can enhance students' motivation, engagement, and overall learning satisfaction [11,37]. In educational settings, intuitive interfaces and accessible learning platforms are essential because they reduce cognitive barriers and encourage students' active participation in the learning process.

The favourable responses to the implementation of the application in learning activities further confirm the effectiveness of mobile-assisted learning in supporting student-centred education. The flexibility of mobile learning enables students to access learning materials at any time and in any location, thereby fostering autonomous and self-directed learning experiences. This finding is in accordance with the conclusions of previous research, which has highlighted that mobile learning technologies are conducive to personalised learning and enhance students' independent learning skills [12,28,40]. Moreover, mobile learning environments

encourage students to become active participants in constructing knowledge rather than passive recipients of information, which is consistent with constructivist learning theory and the principles of 21st-century pedagogy [8].

Another important finding of this study concerns students' reported understanding of Trigatra language principles following their engagement with the application. The integration of Indonesian, regional, and foreign languages into a unified digital learning environment contributed positively to students' multiliteracy competence, linguistic awareness, and intercultural understanding. In multilingual educational contexts, language learning should not merely focus on technical language proficiency but also promote cultural understanding, identity formation, and intercultural communication competence [41]. Therefore, the Trigatra application offers an important educational contribution by integrating linguistic diversity and national identity into technology-enhanced learning environments.

The findings also highlight the importance of culturally responsive educational technology in creating meaningful learning experiences. The Trigatra application is distinguished from numerous mobile language learning applications that predominantly emphasise vocabulary acquisition, grammar, or pronunciation skills, by integrating national identity, regional language preservation, and foreign language competence within a unified educational platform. This approach reflects the principles of culturally responsive pedagogy, which emphasize the integration of students' cultural backgrounds and social identities into educational practices [42]. Consequently, the application not only supports language acquisition but also strengthens students' appreciation of linguistic diversity and cultural heritage.

From a pedagogical perspective, the incorporation of multimedia features and interactive learning activities substantially enhanced students' engagement, motivation, and learning experiences. Previous studies have demonstrated that multimedia learning environments improve students' comprehension, retention, and communication skills through the integration of audio, video, visual content, and interactive activities [15,43]. Likewise, interactive mobile learning environments promote collaboration, communication, and active participation, all of which are recognized as essential competencies in contemporary education [39]. The benchmark analysis further revealed that the Trigatra application performed competitively compared with other educational applications, particularly in terms of attractiveness and efficiency, indicating that the platform successfully integrates technological usability with perceived pedagogical value [13].

While the proposed platform primarily emphasizes student-centered learning, its educational value also depends substantially on the active pedagogical role of teachers and instructors. Rather than replacing classroom instruction, the Trigatra mobile-assisted learning platform is designed to complement teachers' professional practice by providing flexible digital learning resources that can be integrated into both face-to-face and blended learning environments. Teachers remain responsible for selecting appropriate learning activities, facilitating multilingual communication, encouraging collaborative learning, monitoring students' learning progress, and providing timely formative feedback. Accordingly, the platform should be viewed as a technology-enhanced instructional tool that strengthens pedagogically guided learning rather than as an autonomous learning system.

Beyond its pedagogical contribution, the modular architecture developed in this study represents an important Design Science Research (DSR) artifact. The empirical findings suggest that the proposed architecture is not only educationally promising but

also sufficiently flexible to accommodate future technological expansion. By adopting a modular design, the platform enables additional components—including artificial intelligence, adaptive learning systems, virtual reality, augmented reality, digital avatars, collaborative virtual classrooms, and learning analytics—to be progressively incorporated without fundamentally redesigning the existing system. Consequently, the developed artifact should be regarded not merely as a functional mobile learning application but as a scalable educational architecture capable of supporting the long-term evolution of smart learning environments.

These architectural characteristics further support the conceptual framework presented in **Figure 1**, demonstrating that the proposed Trigatra platform should be interpreted as the initial stage of an evolving metaverse-ready language learning ecosystem rather than as a fully immersive virtual learning environment. The positive user experience, high learner engagement, and strong understanding of the Trigatra language principles provide empirical evidence that the platform already possesses the pedagogical and technological foundations required for future immersive learning. Importantly, this evolution should not be interpreted as a direct transition from a conventional mobile application to a metaverse environment. Instead, the proposed framework advocates an incremental development strategy in which each technological layer is validated before additional immersive capabilities are introduced. Such an evolutionary approach is fully aligned with the Design Science Research methodology, which emphasizes iterative artifact refinement, evaluation, and progressive enhancement based on empirical evidence rather than immediate technological implementation.

Beyond immersive virtual environments, the proposed modular architecture also provides opportunities for future integration with human digital twin technologies. Although the current study does not implement or evaluate digital twin capabilities, the architecture provides a potential foundation for developing personalized learner representations and adaptive educational services. Recent studies have demonstrated that human digital twins supported by edge computing, intelligent networking, and generative artificial intelligence can enable real-time user modelling, adaptive task execution, intelligent resource allocation, and personalized interaction within digital environments [19-21]. In the context of language education, these capabilities could support adaptive multilingual learning pathways, intelligent tutoring systems, virtual learning companions, and more personalized learning experiences. Such developments may further strengthen the principles of Education 5.0 by combining human-centered pedagogy with intelligent and culturally responsive technologies. These capabilities, however, remain prospective extensions of the Trigatra platform and are not part of the artifact implemented or evaluated in the present study [44,45,47-50].

Overall, the findings demonstrate that the Trigatra platform provides a practical foundation for multilingual mobile learning while simultaneously establishing a scalable architecture for future intelligent educational ecosystems. Nevertheless, the evaluation involved only 30 participants and should therefore be interpreted within the context of Design Science Research, where preliminary artifact evaluation prioritizes usability assessment and formative feedback rather than statistical generalization. Although the relatively small sample may introduce potential sampling bias and limit broader generalizability, the results provide valuable evidence regarding the educational feasibility, user acceptance, and functional performance of the proposed artifact. Future studies are encouraged to validate the platform using larger and more

diverse participant groups while exploring the integration of immersive technologies, artificial intelligence, and digital twin capabilities in multilingual learning environments.

The present findings also contribute to the emerging academic discussion concerning educational metaverse by suggesting that immersive learning should not be understood solely as the adoption of virtual reality technologies. In the contemporary educational context, immersive learning experiences emerge from three fundamental concepts. Firstly, meaningful learner interaction is pivotal to the educational experience. Secondly, social participation is a crucial component in facilitating learning in an interactive environment. Thirdly, cultural responsiveness is essential to ensure that the educational content reflects and respects diverse cultural backgrounds. Finally, adaptive pedagogical design, which is responsive to individual learners' needs and abilities, is crucial in ensuring effective and engaging learning. In this regard, the Trigatra platform demonstrates that the pedagogical foundations of metaverse learning can be established before fully immersive virtual environments are implemented, thereby extending current discussions on metaverse-based education beyond technological determinism.

The findings of this study also have important implications for the future development of metaverse-based language education. Although the Trigatra application was developed as a mobile-assisted learning platform, its integration of multilingual learning, multimedia interaction, and student-centered pedagogy reflects several characteristics commonly associated with emerging metaverse learning environments. Recent studies suggest that metaverse-based education has the potential to create immersive, interactive, and socially connected learning experiences that extend beyond the limitations of conventional digital learning platforms [44,45,47,48]. In this regard, the Trigatra application can be viewed as an initial step toward the development of smart and culturally responsive virtual learning environments where students engage with Indonesian, regional, and foreign languages through interactive digital experiences. Furthermore, the integration of cultural content, linguistic diversity, and mobile accessibility aligns with the principles of Education 5.0, which emphasize human-centered learning, technological innovation, and sustainable cultural development. As educational technologies continue to evolve, future iterations of the Trigatra platform may incorporate immersive technologies such as virtual reality, augmented reality, and metaverse-based collaborative learning spaces to further enhance multilingual communication, intercultural competence, and learner engagement [49,50].

The findings validate the proposed conceptual architecture presented in **Figure 1**, demonstrating that the integration of Trigatra language principles within a smart mobile learning ecosystem extends beyond application usability toward the development of a metaverse-ready language learning architecture. Rather than functioning solely as a mobile application, the proposed architecture establishes interconnected relationships among multilingual learning, multiliteracy development, digital pedagogy, smart learning environments, and Education 5.0. These interrelated components collectively provide a conceptual foundation for future immersive educational ecosystems in which virtual learning environments, AI-assisted instruction, and metaverse technologies can be integrated to support culturally responsive multilingual education.

Despite these positive findings, several challenges remain in implementing mobile-assisted language learning. Differences in technological infrastructure,

digital access, and students' digital literacy levels may influence the effectiveness of mobile learning environments [38,52]. In addition, teachers' readiness to integrate educational technology into classroom practices remains an important factor influencing successful implementation. Therefore, educational institutions and policymakers should focus not only on technological innovation but also on teacher training, curriculum integration, and equitable access to digital learning resources.

Beyond validating the proposed conceptual framework, the empirical findings provide an initial evidence base for the development of immersive metaverse-supported language learning. The high levels of user satisfaction, positive learning engagement, and favorable perceptions of multilingual interaction indicate that learners readily accept technology-enhanced educational experiences when they are supported by intuitive interfaces, meaningful learning activities, and culturally responsive content. Although the present study evaluates a mobile learning platform rather than a fully immersive virtual environment, these empirical outcomes establish important design principles for future metaverse learning experiences, including learner interaction, digital engagement, collaborative participation, and adaptive multilingual communication. Accordingly, the results provide empirical support for the gradual transition from conventional mobile-assisted learning toward immersive metaverse education ecosystems. These empirical findings indicate that positive usability, learner engagement, and multilingual interaction constitute measurable educational attributes that may underpin future immersive metaverse learning experiences.

Collectively, these dimensions represent the core characteristics of immersive educational experiences, where learners actively interact with digital content, collaborate within technology-mediated environments, and develop sustained engagement through meaningful educational participation. Therefore, the present findings provide measurable educational evidence supporting the future design of metaverse-based language learning environments.

Overall, this study contributes to the growing literature on language education, mobile learning, and digital pedagogy by demonstrating that the integration of Trigatra language principles into mobile-assisted learning environments can support multiliteracy competence, cultural awareness, and student-centered learning. The study also extends the theoretical discussion on culturally responsive pedagogy and multilingual education by showing that mobile learning technologies can simultaneously strengthen linguistic competence, national identity, and intercultural understanding. Practically, the findings suggest that the Trigatra application can serve as an innovative educational tool for schools and higher education institutions in promoting meaningful and technology-enhanced language learning. From a policy perspective, this study highlights the importance of integrating digital language education into curriculum development and educational transformation strategies to support linguistic diversity and prepare students for globalized and technology-driven educational environments.

5. Conclusion

This study suggests that the integration of Trigatra language principles into a mobile-assisted learning environment offers a meaningful contribution to 21st-century language education. The development of the Trigatra mobile application successfully combined Indonesian, regional, and foreign language learning within a single digital learning platform designed to support multiliteracy competence, cultural awareness,

and student-centered learning. The findings indicate that the application achieved positive evaluations in terms of attractiveness, efficiency, perspicuity, dependability, stimulation, and novelty, reflecting a positive user experience and perceived educational functionality. These results suggest that mobile learning technologies can support meaningful and engaging language learning experiences aligned with the demands of digital-era education.

Furthermore, the user testing results revealed that students showed very strong levels of interest, positive learning engagement, and reported understanding of Trigatra language principles based on their perceptions following use of the application. The application not only functioned as a technological innovation but also as an educational medium capable of strengthening students' awareness of linguistic diversity, national identity, and multilingual communication. From a pedagogical perspective, the study confirms that mobile-assisted learning environments can facilitate flexible, interactive, and autonomous learning experiences while simultaneously promoting communication skills, digital literacy, and multiliteracy competencies required in 21st-century education.

This study contributes theoretically to the literature on language education, mobile learning, multiliteracy pedagogy, and culturally responsive educational technology by demonstrating how multilingual language learning can be integrated within a technology-enhanced educational ecosystem. While previous research has largely focused on language acquisition, usability, or personalized mobile learning, this study extends existing knowledge by positioning mobile-assisted language learning as a medium for simultaneously fostering linguistic competence, cultural identity, and multiliteracy development. Furthermore, the findings contribute to emerging discussions on Education 5.0 and metaverse-based education by illustrating how culturally responsive mobile learning environments can serve as foundational components of future immersive learning ecosystems. The integration of Trigatra language principles, digital pedagogy, and multilingual learning provides a conceptual framework for understanding how educational technologies may evolve from conventional mobile learning platforms into metaverse-supported learning environments that facilitate interactive, socially connected, and culturally meaningful educational experiences.

From a practical perspective, the findings demonstrate that the Trigatra mobile application can function as an innovative educational platform that supports student-centered language learning, multiliteracy competence, and cultural awareness within digital environments. The positive user experience and strong student engagement indicate that mobile-assisted learning may facilitate meaningful educational experiences while promoting linguistic diversity and national identity. More importantly, the application represents an early-stage model of a smart learning environment that integrates multimedia interaction, mobile accessibility, and personalized learning opportunities. These characteristics are closely aligned with the core features of future metaverse-based educational systems, where learners are expected to engage in immersive, collaborative, and technology-mediated learning experiences. Therefore, educators and educational institutions may utilize the Trigatra platform not only as a language learning tool but also as a preparatory framework for the gradual adoption of virtual learning environments, immersive technologies, and metaverse-enabled educational practices.

From a policy perspective, this study highlights the strategic importance of integrating digital language education into broader educational transformation

agendas that support Education 5.0 and the development of future-ready learning ecosystems. The findings suggest that language preservation, cultural sustainability, and technological innovation should not be treated as separate policy domains but rather as interconnected components of contemporary educational development. Policymakers should encourage the adoption of culturally responsive digital learning platforms capable of supporting multilingual education while preparing learners for increasingly digital and immersive educational environments. Investment in digital infrastructure, teacher professional development, mobile learning ecosystems, and emerging technologies such as virtual reality, augmented reality, and metaverse-based learning platforms will be essential for achieving this goal. In the long term, the Trigatra mobile application may serve as a policy model for developing metaverse-ready educational ecosystems that strengthen national identity, preserve linguistic diversity, and enhance global competencies within a technologically advanced and culturally inclusive educational framework.

This study has several limitations that should be considered when interpreting the findings. First, the study involved a relatively limited number of respondents, which may affect the generalizability of the results to broader educational contexts. However, this limitation should be interpreted within the context of Design Science Research, where the present study was intended as a preliminary design evaluation aimed at assessing usability and user experience rather than producing statistically generalizable findings. Second, the evaluation primarily focused on user experience, students' perceptions, and learning engagement rather than measuring long-term learning outcomes or language proficiency improvements through experimental approaches. Third, the implementation of the Trigatra mobile application was conducted within a limited educational setting, so differences in technological infrastructure, digital literacy levels, and institutional readiness across schools or regions were not comprehensively examined. In addition, the study mainly emphasized mobile-assisted learning from the students' perspective, while teachers' perceptions, instructional readiness, and classroom integration strategies were not extensively explored.

Future research should expand the scope of this study by involving larger and more diverse participant groups across different educational levels, institutions, and geographical regions to improve the generalizability of the findings. Longitudinal and experimental research designs are also recommended to examine the long-term effects of the proposed learning architecture on students' multilingual competence, multiliteracy development, digital literacy, cultural awareness, and overall learning achievement. In addition, future investigations should explore the integration of emerging technologies such as artificial intelligence, adaptive learning systems, learning analytics, virtual reality, augmented reality, digital avatars, and extended reality (XR) to create more personalized, immersive, and collaborative language learning experiences. Examining teachers' digital readiness, institutional support, curriculum integration, and policy implementation will further strengthen the practical adoption of Trigatra language principles within technology-enhanced educational environments and accelerate the transition toward metaverse-enabled education.

The present study demonstrates that the contribution of the proposed Trigatra platform extends far beyond the development of a mobile-assisted learning application. Instead, it introduces a scalable language learning architecture that integrates multilingual education, culturally responsive pedagogy, smart learning environments, and Education 5.0 within a unified conceptual framework. The

proposed architecture is supported by positive empirical findings regarding usability, learner engagement, and pedagogical effectiveness. It provides an initial evidence base for designing future immersive learning environments in which multilingual interaction, digital literacy, and cultural sustainability can coexist within intelligent educational ecosystems.

Although the present study evaluates a conventional mobile-assisted learning application rather than a fully immersive metaverse environment, the findings demonstrate that the proposed educational architecture provides an important foundation for future research on metaverse-supported language learning. Future studies are encouraged to integrate immersive technologies such as virtual reality, augmented reality, intelligent avatars, and collaborative virtual learning spaces to empirically validate the proposed metaverse learning architecture.

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