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ORIGINAL

Creation of an Android-Based Augmented Reality Application for the Cultivation of Large Red Chili (Capsicum annuum L.)

Creación de una aplicación de realidad aumentada basada en Android para el cultivo de chile rojo grande (Capsicum annuum L.)

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ABSTRACT

Introduction: the rising demand for large red chili (Capsicum annuum L.) driven by high market prices and culinary significance has encouraged cultivation efforts. However, inadequate farming knowledge creates challenges for both growers and consumers, necessitating innovative educational approaches.
Objective: this study aimed to develop and evaluate an Android-based Augmented Reality (AR) application for educating users on proper large red chili cultivation techniques, and assess its effectiveness in enhancing agricultural knowledge transfer.
Method: the research employed the Multimedia Development Life Cycle (MDLC) methodology, utilizing Unity and Vuforia platforms to create an interactive AR application. The application used smartphone cameras to scan tag cards that triggered educational videos providing step-by-step cultivation guidance. A structured questionnaire survey was conducted with 20 respondents using purposive sampling to evaluate application usability and effectiveness across seven criteria using a 5-point Likert scale.
Results: the AR application achieved an overall satisfaction score of 89 % (623 out of 700 points), with the highest criterion scoring 93 % and the lowest 79 %. User feedback indicated the application was useful and informative for learning chili cultivation practices. The AR functionality performed effectively even when tag cards were partially obscured (up to 50 % coverage), demonstrating robust technical performance under varying conditions.
Conclusions: the AR-based application proved to be an effective educational tool for chili cultivation, successfully bridging knowledge gaps in agricultural practices. The high user satisfaction rates and positive feedback support the practical application of AR technology in agricultural education, offering an accessible and engaging method for learning essential cultivation techniques.

Keywords: Android; Augmented Reality; Cultivation; Large Red Chili.

RESUMEN

Introducción: la creciente demanda de chile rojo grande (Capsicum annuum L.), impulsada por los altos precios de mercado y su importancia culinaria, ha incentivado los esfuerzos de cultivo. Sin embargo, el conocimiento agrícola insuficiente genera desafíos tanto para los cultivadores como para los consumidores, lo que hace necesaria la implementación de enfoques educativos innovadores.
Objetivo: este estudio tuvo como objetivo desarrollar y evaluar una aplicación de Realidad Aumentada (RA)

para Android destinada a educar a los usuarios sobre técnicas adecuadas de cultivo de chile rojo grande, y analizar su efectividad en la mejora de la transferencia de conocimientos agrícolas.
Método: la investigación utilizó la metodología del Ciclo de Vida del Desarrollo Multimedia (MDLC), empleando las plataformas Unity y Vuforia para crear una aplicación interactiva de RA. La aplicación usaba la cámara del teléfono inteligente para escanear tarjetas etiquetadas que activaban videos educativos con instrucciones paso a paso sobre el cultivo. Se aplicó una encuesta estructurada a 20 personas seleccionadas mediante muestreo intencional para evaluar la usabilidad y efectividad de la aplicación en siete criterios, utilizando una escala de Likert de 5 puntos.
Resultados: la aplicación de RA obtuvo una puntuación de satisfacción general del 89 % (623 de 700 puntos), con el criterio más alto alcanzando un 93 % y el más bajo un 79 %. Los comentarios de los usuarios indicaron que la aplicación fue útil e informativa para aprender prácticas de cultivo de chile. La funcionalidad de RA funcionó eficazmente incluso cuando las tarjetas estaban parcialmente cubiertas (hasta un 50 % de obstrucción), demostrando un rendimiento técnico robusto en condiciones variables.
Conclusiones: la aplicación basada en RA demostró ser una herramienta educativa eficaz para el cultivo de chile, logrando cerrar las brechas de conocimiento en las prácticas agrícolas. Las altas tasas de satisfacción de los usuarios y la retroalimentación positiva respaldan la aplicación práctica de la tecnología de RA en la educación agrícola, ofreciendo un método accesible y atractivo para aprender técnicas esenciales de cultivo.

Palabras clave: Android; Realidad Aumentada; Cultivo; Chile Rojo Grande.

INTRODUCTION

Background of The Study

Large red chili (Capsicum annuum L.) is a significant agricultural commodity, renowned for its culinary, health, and industrial applications. The primary bioactive compound in large red chili is capsaicin, which provides health benefits including pain relief, anti-inflammatory properties, and metabolic enhancement.[1,2] Research indicates that capsaicin exhibits antimicrobial properties and may contribute to cardiovascular health.[3,4]

Despite these benefits, the cultivation of large red chili faces numerous challenges, primarily due to a lack of knowledge regarding effective agricultural practices. Many farmers struggle with essential aspects of chili cultivation, including seed selection, land management, pest control, and crop care.[5] This knowledge gap often results in suboptimal yields and reduced profitability for farmers.

To address these challenges, it is crucial to enhance access to accurate agricultural information. Digital technologies, particularly Augmented Reality (AR), present a promising solution by providing interactive and engaging educational resources that can help farmers understand best practices for growing large red chili without requiring formal training.[5,6]

The integration of digital tools in agriculture can significantly improve farmers' knowledge and skills, thereby increasing productivity and sustainability in chili cultivation. AR applications can simulate various cultivation scenarios, allowing farmers to visualize the impact of different techniques on crop yield and health.[7] Furthermore, enhancing digital literacy among farmers through targeted training initiatives can empower them to adopt these technologies effectively, leading to better management practices and improved crop outcomes.[8]

Large Red Chili Cultivation and The Role of Augmented Reality (AR)

Chili cultivation, specifically of Capsicum annuum L., is a significant agricultural practice due to its culinary and nutritional importance. This species, belonging to the Solanaceae family, thrives in diverse climatic conditions, particularly in lowland and highland regions. The nutritional benefits of chili include being rich in vitamins A and C, which are essential for maintaining healthy vision, enhancing immune function, and promoting skin health.[9,10]

Table 1. Classification of Chili Plants

No	Information	
1	Division	Spermatophyta
2	Sub Division	Angiospermae
3	Class	Dicotyledoneae
4	Ordo	Solanales
5	Family	Solanaceae
6	Genus	Capsicum
7	Spesies	Capsicum annum .L

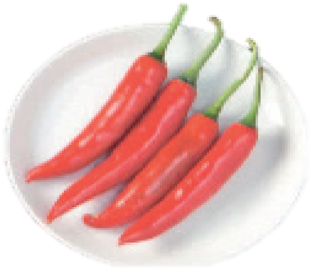

Figure 1. Capsicum annum .L.

Despite the advantages associated with chili cultivation, many farmers encounter challenges that hinder optimal production. Common issues include improper planting techniques, ineffective pest management, and a limited understanding of soil health and irrigation practices.[11,12] These challenges can significantly impact the yield and quality of chili crops, necessitating effective educational interventions to equip farmers with the necessary knowledge and skills.[13]

One innovative approach to address these educational challenges is the integration of Augmented Reality (AR) into agricultural education. AR technology enhances the learning experience by blending digital information with the physical environment, allowing users to interact with both simultaneously. This interactive capability makes AR a powerful tool for teaching complex agricultural concepts, such as proper planting techniques, irrigation systems, and pest control measures.[14,15] AR applications can provide animated 3D models of chili plants, enabling farmers to visualize and understand the cultivation process in real time.[16]

The functionality of AR relies on video streaming and image recognition, where a camera captures the real-world environment and overlays digital content when specific markers are detected. In the context of chili cultivation, a farmer can scan a marker to trigger a virtual model that demonstrates step-by-step cultivation instructions.[17] This method not only makes learning more engaging but also helps bridge the gap between theoretical knowledge and practical application, ultimately leading to improved cultivation practices and higher crop yields.[18]

Research indicates that AR can significantly enhance knowledge transfer in various fields, including agriculture. By providing context-specific information tailored to local farming conditions, AR can help farmers adopt best practices more effectively.[19] Furthermore, the immersive nature of AR can foster greater retention of information, making it easier for farmers to implement new techniques in their cultivation practices.[20]

Application Development and Implementation Plan

The development of the Android-based application incorporating Augmented Reality (AR) for educating large red chili cultivation proceeds through several key phases. The first phase involves the design of the application, focusing on selecting the appropriate content and creating easily understandable animated videos. The content covers various aspects of large red chili cultivation, including seed selection, planting methods, crop care, pest management, and harvesting. Each cultivation phase is detailed using animations that visually demonstrate the necessary steps, ensuring the content is both informative and engaging for the users.[20,21]

Following the content design, the technical development of the application begins, utilizing the Android platform, which is widely adopted by mobile device users. Android's popularity and accessibility make it an ideal choice for reaching a larger audience, especially considering its affordability and widespread usage across various devices.[22,23] The application leverages AR technology to detect images or tag cards, triggering the display of animated videos that explain specific steps in large red chili cultivation based on the image captured by the camera.[24,25] This integration of AR allows for an interactive learning experience that enhances users' understanding of the cultivation process.

The third phase of development involves the application's testing to ensure its functionality across different Android devices. It is essential to confirm that the application operates smoothly and provides accurate, useful information to users. The effectiveness of the application is evaluated by collecting feedback from users who engage with the app and analyzing its impact on the productivity of farmers using the application as a guide for their cultivation practices.[26] This phase helps refine the application to ensure it meets its educational objectives and serves its intended purpose effectively.

Android is a versatile operating system for smartphones and tablets, acting as a "bridge" between the device and the user. This enables users to interact with the device and run applications efficiently.[27] The Android platform's flexibility allows developers to create applications that can be used across various devices, making it an ideal choice for the cultivation education app. Mobile devices, such as smartphones, are essential tools for accessing network services and, in this case, for delivering educational content through the application.[28]

The development of the application also utilizes Unity 3D, a cross-platform game engine that supports the creation of interactive and immersive applications. Unity can be used to develop games or applications for a variety of devices, including Android smartphones, iPhones, and even gaming consoles such as PS3 and X-Box. Unity's capabilities, such as audio reverb zones, particle effects, and skyboxes, enhance the application's visual experience. Moreover, Unity supports multiple programming languages, including JavaScript, C#, and Boo, enabling developers to implement flexible and easy-to-manage code to manipulate objects, animate models, and implement real-time interactivity in the app.

To enhance the AR functionality, the application integrates Vuforia, an Augmented Reality Software Development Kit (SDK) designed to simplify the creation of AR applications. Vuforia allows the detection of markers, flat planes, or faces and displays visual objects in 3D or 2D through the camera. By combining Vuforia with Unity, the app can deliver an AR experience, providing users with interactive and educational content about large red chili cultivation.[29,30] Vuforia's ability to integrate with Unity is crucial for ensuring that the AR features are fully functional and optimized for mobile platforms such as Android, enhancing the overall user experience and effectiveness of the application.

Purpose of This Study

The primary objective of this study is to develop an Android-based application that utilizes Augmented Reality (AR) to educate farmers and the general public on the proper cultivation techniques for large red chili (Capsicum annuum L.). By integrating AR technology, the application aims to provide an interactive and engaging learning experience that allows users to visualize the various stages of chili cultivation, from seed selection and planting to pest management and harvesting. This innovative approach is expected to overcome traditional educational barriers, such as limited access to training or instructional materials, by delivering accessible and easily understandable content through mobile devices.

Additionally, this study seeks to assess the effectiveness of the AR-based application in enhancing farmers' knowledge and practices related to chili cultivation. The study evaluates how well the application contributes to improving cultivation methods and whether it positively impacts the productivity of large red chili plants. Through user feedback and data analysis, this research aims to identify the potential benefits of incorporating AR into agricultural education, helping to bridge knowledge gaps and promote sustainable farming practices for chili cultivation.

METHOD

Research Design

This study employs a multimedia development life cycle (MDLC) methodology, a structured approach widely used for creating interactive and multimedia-based educational applications. The research design follows the stages of the MDLC, which include concept development, design, material collection, assembly, testing, and distribution.[28,31]

Concept

Concept is the stage for determining the purpose and who are the users of the program (audience identification). Additionally determine the type of Video (presentation, interactive, and others) and the purpose of the Video (entertainment, training, learning, and others).

Design

Design is the stage of making specifications regarding program architecture, style, appearance and material requirements for the program.

Collecting Materials

Material collecting is the stage where the collection of materials according to the needs is carried out. This stage can be done in parallel with the assembly stage. In some cases, the material collecting stage and the assembly stage will be carried out linearly, not parallel.

Assembly

Assembly (manufacture) is the stage where all objects or multimedia materials are made. Application creation is based on the design stage.

Testing

Testing is conducted after the completion of the assembly stage by running the application and identifying any errors or functionality issues. This stage is also known as the alpha testing stage where the test is carried out by the developer within the development environment.

Distributions

The stage where the application is stored in a storage medium. At this stage if the storage media is not sufficient to accommodate the application, compression is applied. This stage can also be called the evaluation stage for the development of finished products for continuous improvement.

In this study, the development of an Android-based augmented reality (AR) application for educating users on large red chili cultivation is the focus. The application integrates AR technology, Unity, and Vuforia to create an interactive learning experience. The design process involves selecting the educational content related to chili cultivation and incorporating it into interactive animations displayed via AR, making learning more engaging and accessible for users.

Participants and Sampling

A total of 20 respondents participated in this study, selected through purposive sampling based on their familiarity with mobile applications and interest in agricultural practices. The sample size of 20 participants was determined following established guidelines for usability testing in mobile applications. According to Nielsen and Landauer (1993), 20 users can identify approximately 95 % of usability problems in interface testing, making this sample size appropriate for detecting major usability issues. This sample size is also consistent with previous AR application studies in educational contexts, where samples of 15-25 participants are commonly used for initial usability evaluation and effectiveness assessment.(19,20)

The selection criteria for participants included: (1) basic familiarity with smartphone applications, (2) interest in agricultural practices or chili cultivation, and (3) willingness to participate in the evaluation process. Participants were recruited from local farming communities and university students with agricultural backgrounds to ensure diverse perspectives on the application's utility and usability.

Data Collection Instrument

Questionnaire Design

To evaluate the effectiveness of the AR-based application, the study utilized a structured questionnaire as the primary data collection instrument. The questionnaire was designed to assess various aspects of the application, including user satisfaction, ease of use, educational content clarity, and overall effectiveness. The instrument consisted of seven statements that participants responded to using a 5-point Likert scale (1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree).

The questionnaire was developed based on established usability evaluation frameworks, including the System Usability Scale (SUS) principles and Technology Acceptance Model (TAM) constructs. Content validity was ensured through expert review by three professionals in educational technology and agricultural extension.

Observational Protocol

In addition to the questionnaire, systematic observational data was collected to gain deeper understanding of user interactions with the AR features. A structured observation protocol was developed to record:

- User navigation patterns within the application.
- Difficulties encountered during AR marker scanning.
- Time spent on different application sections.
- User engagement levels with interactive content.
- Technical issues or errors encountered.

Data Analysis Techniques

Quantitative Analysis

The quantitative data analysis employed both descriptive and inferential statistical methods:

1. Descriptive Statistics: mean scores, standard deviations, and frequency distributions were calculated for each questionnaire item to assess central tendencies and variability in responses.
2. Reliability Analysis: internal consistency of the questionnaire was assessed using Cronbach's alpha coefficient to ensure the reliability of the measurement instrument.
3. Usability Scoring: individual responses were summed to create total usability scores out of a maximum possible score of 700 points (20 participants × 7 items × 5 maximum points per item). Percentage scores were calculated to determine overall user satisfaction levels.
4. Categorical Analysis: responses were categorized into satisfaction levels:
    - 91 %-100 % = Strongly Agree (SS)
    - 70 %-90 % = Agree (S)
    - 50 %-69 % = Neutral (N)
    - 30 %-49 % = Disagree (TS)
    - 0 %-29 % = Strongly Disagree (STS)

Qualitative Analysis

Qualitative data from user observations underwent thematic analysis following Braun and Clarke's framework:

1. Data Familiarization: observation notes were reviewed repeatedly to gain familiarity with the data.
2. Initial Coding: systematic coding of interesting features and patterns in user behavior was conducted.
3. Theme Development: codes were organized into potential themes related to usability issues, user engagement, and learning effectiveness.
4. Theme Review: themes were reviewed and refined to ensure they accurately represented the data.
5. Theme Definition: final themes were defined and named to capture the essence of user experiences with the AR application.

Mixed-Methods Integration

The quantitative and qualitative data were integrated using a convergent parallel design, where both data types were collected simultaneously and analyzed separately before being merged for interpretation. This approach provided a comprehensive evaluation of the application's effectiveness by combining statistical measures of user satisfaction with detailed insights into user behavior and experiences.

Ethical Considerations

Prior to data collection, informed consent was obtained from all participants. The study protocol was designed to ensure participant confidentiality and voluntary participation. Participants were informed about the study's purpose, procedures, and their right to withdraw at any time without consequences.

System Framework

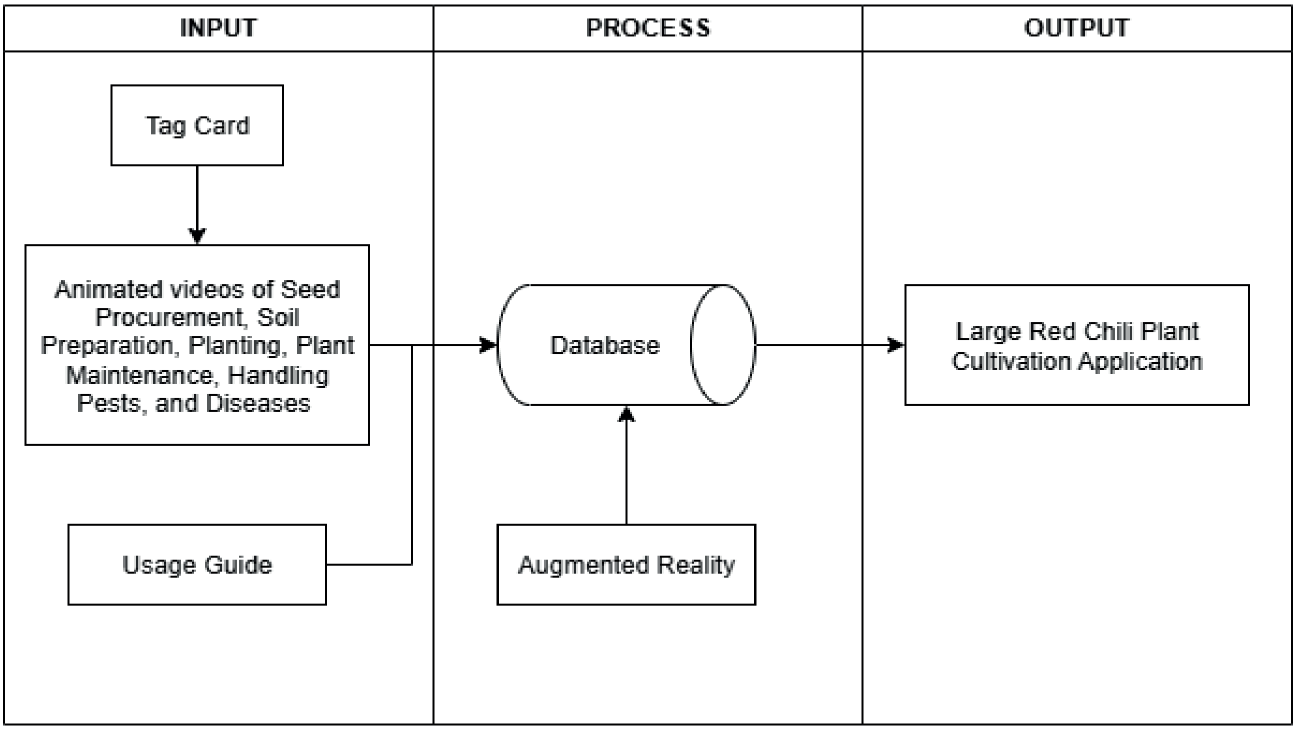

Figure 2. Information System Framework

The diagram illustrates the workflow of the Large Red Chili Plant Cultivation Application System. The process begins with the input stage, which includes a tag card containing markers that trigger specific actions. The tag card, when scanned, activates animated videos related to key stages of chili cultivation, such as seed procurement, soil preparation, planting, plant maintenance, and handling pests and diseases. This input data is then processed through a database that stores all the relevant information. Augmented Reality (AR) is utilized to present the videos and interactive content in a dynamic, engaging format. Finally, the output of this process is the large red chili plant cultivation application, which delivers educational content to users through an AR interface, guiding them step-by-step in the cultivation process.

RESULTS

Model Approach

The approach used in this study follows the Multimedia Development Life Cycle (MDLC) methodology, a structured framework for developing multimedia applications. This method includes six stages: concept, design, material collection, assembly, testing, and distribution. In this study, the focus is on developing an Android-based augmented reality (AR) application aimed at educating users on large red chili cultivation. The AR functionality, powered by Unity and Vuforia, allows users to scan tag cards and view animated videos that guide them through various stages of chili cultivation. By using this model, the researchers ensure that the application is not only educational but also engaging and accessible for farmers and other users interested in learning about the chili farming process.

The integration of AR into the application provides an immersive learning experience. As users scan the tag cards, the AR system detects markers and overlays digital content such as animated videos on their mobile screens, demonstrating cultivation processes such as seed procurement, soil preparation, planting, plant maintenance, and pest management. This approach makes it easier for users to understand complex agricultural concepts by providing visual and interactive content. The use of Unity and Vuforia further enhances the user experience, offering a smooth and interactive interface that supports a wide range of Android devices.

Card Making Modeling and Video Animation

Object modeling and video animation

At this stage, modeling or making animated objects and tag cards is carried out using the CorelDraw application. The design and asset collection for an application focused on large red chili cultivation. In CorelDraw, various assets are being created, including chili plants, pots, seeds, and tools, which will be used as interactive elements in the AR-based educational tool. The directory displays collected assets, such as images of chili plants at different stages, seed packets, and cultivation tools, which will be integrated into the application to guide users in proper chili cultivation techniques.

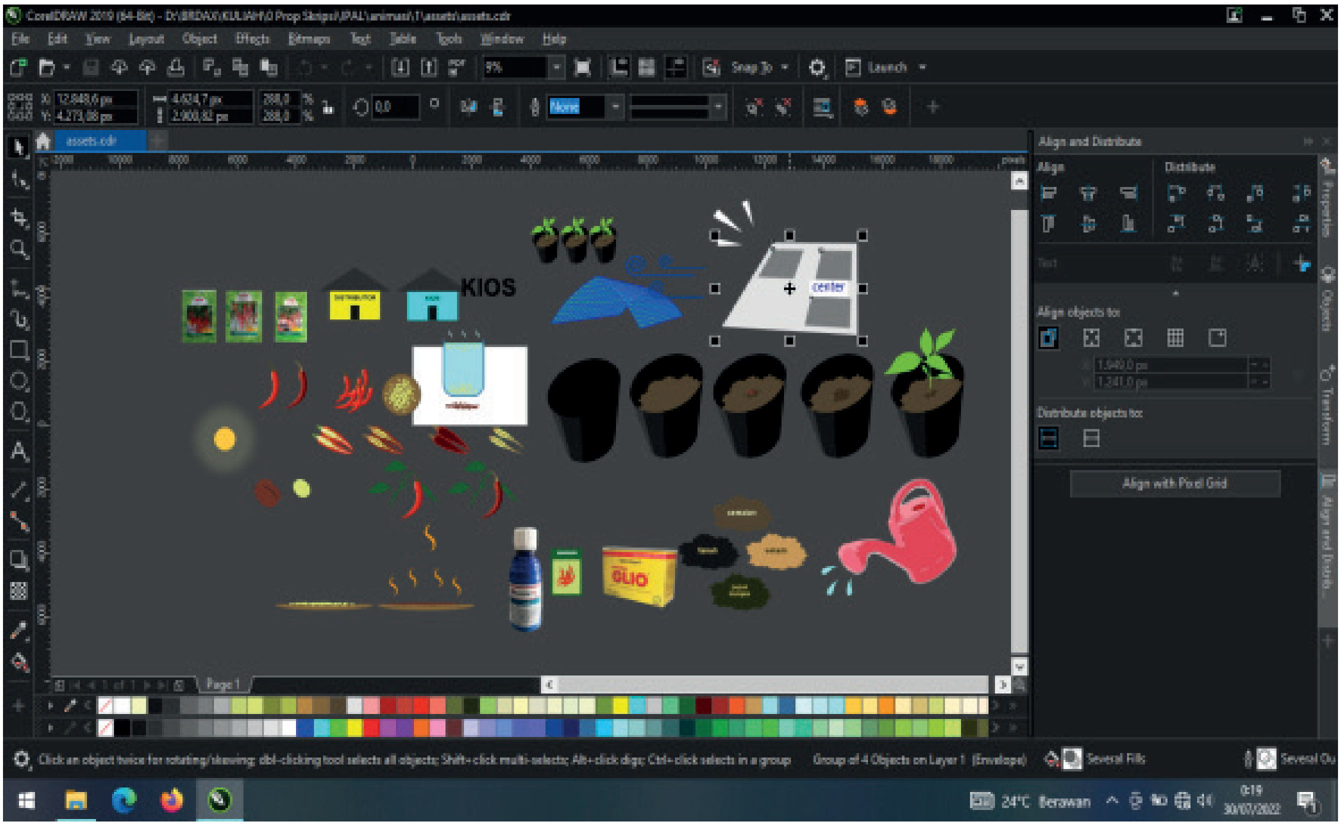

Figure 3. Making 2D Objects

The animation video modeling stage

At this stage modeling or making animated videos is carried out using the Adobe Premiere application and Microsoft Power Point. The stages of modeling the animated video of large red chili cultivation can be seen in Figures below.

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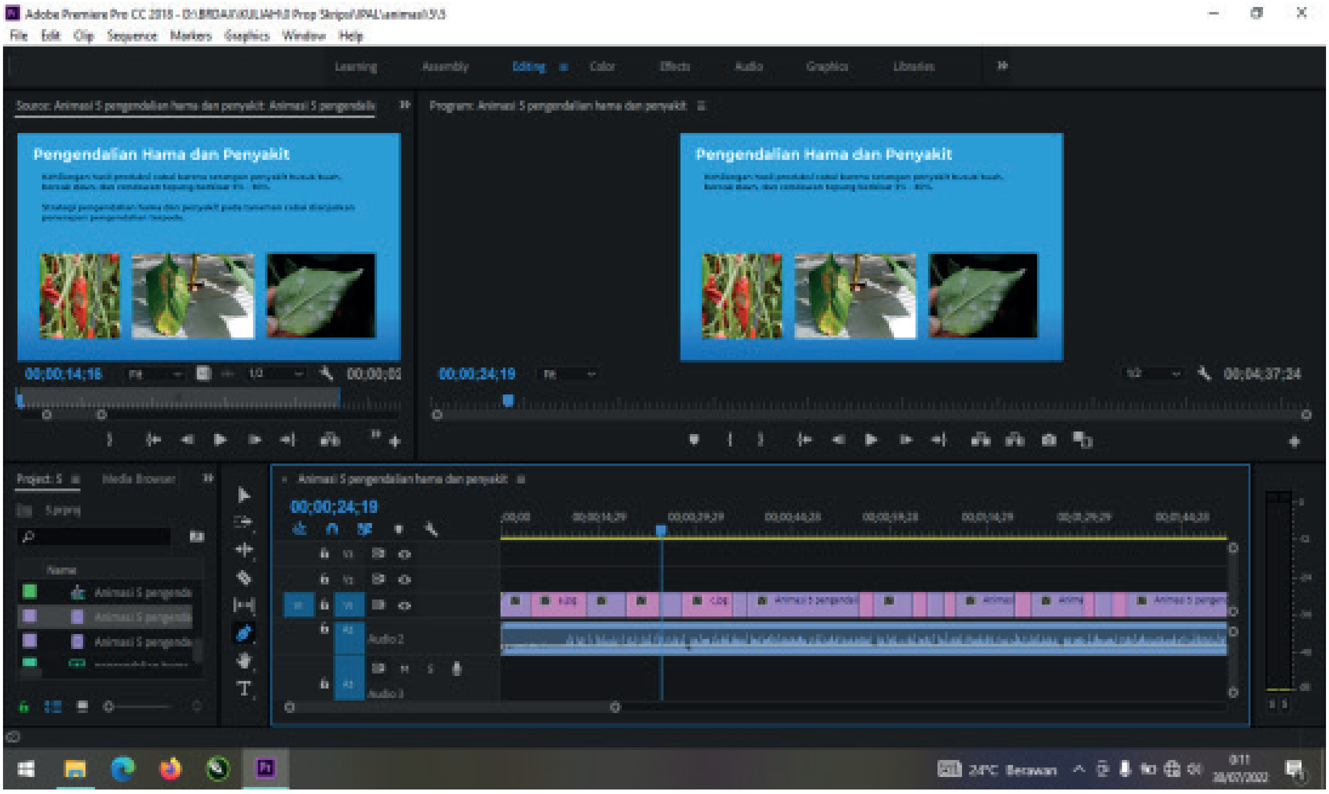

Figure 4. The Process of Making Videos Using Adobe Premiere

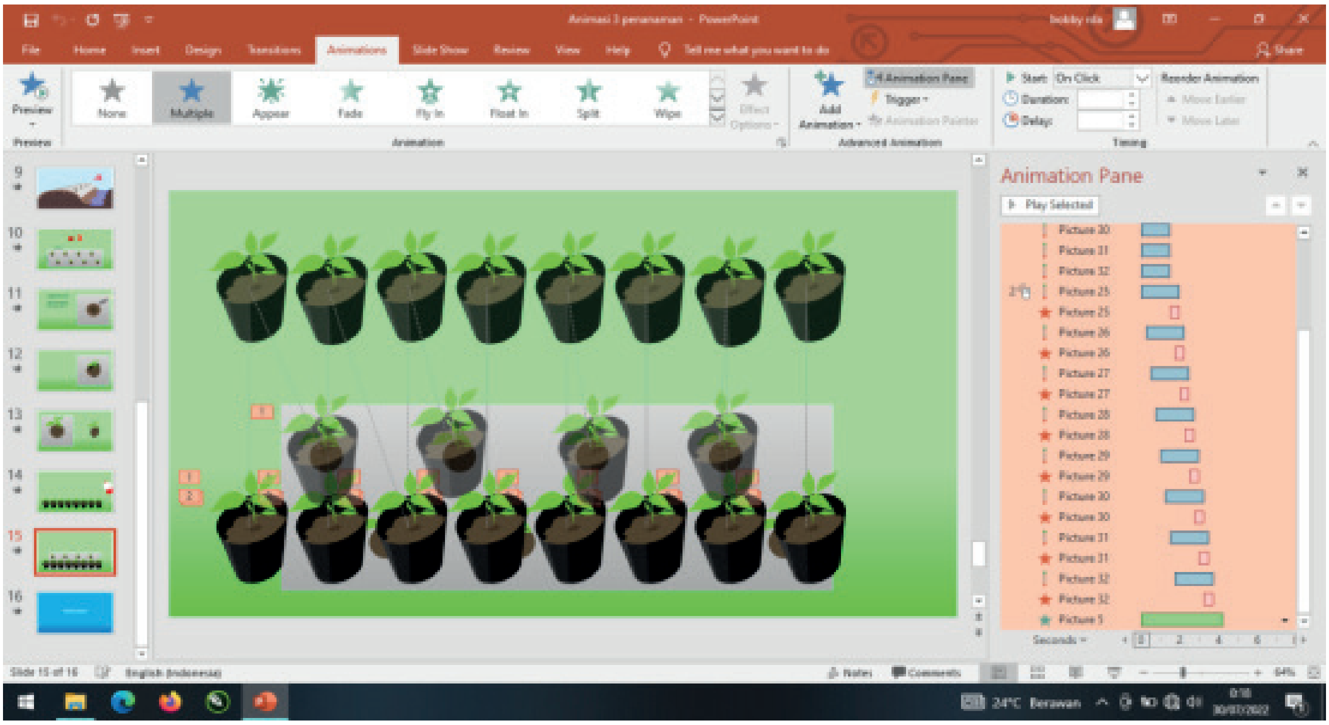

Figure 5. The Process of Uniting Objects to Make Videos Using Microsoft PowerPoint

Results of the import stage and arrangement of objects into unity

The stages of importing and compiling objects into unity can be seen in figures below.

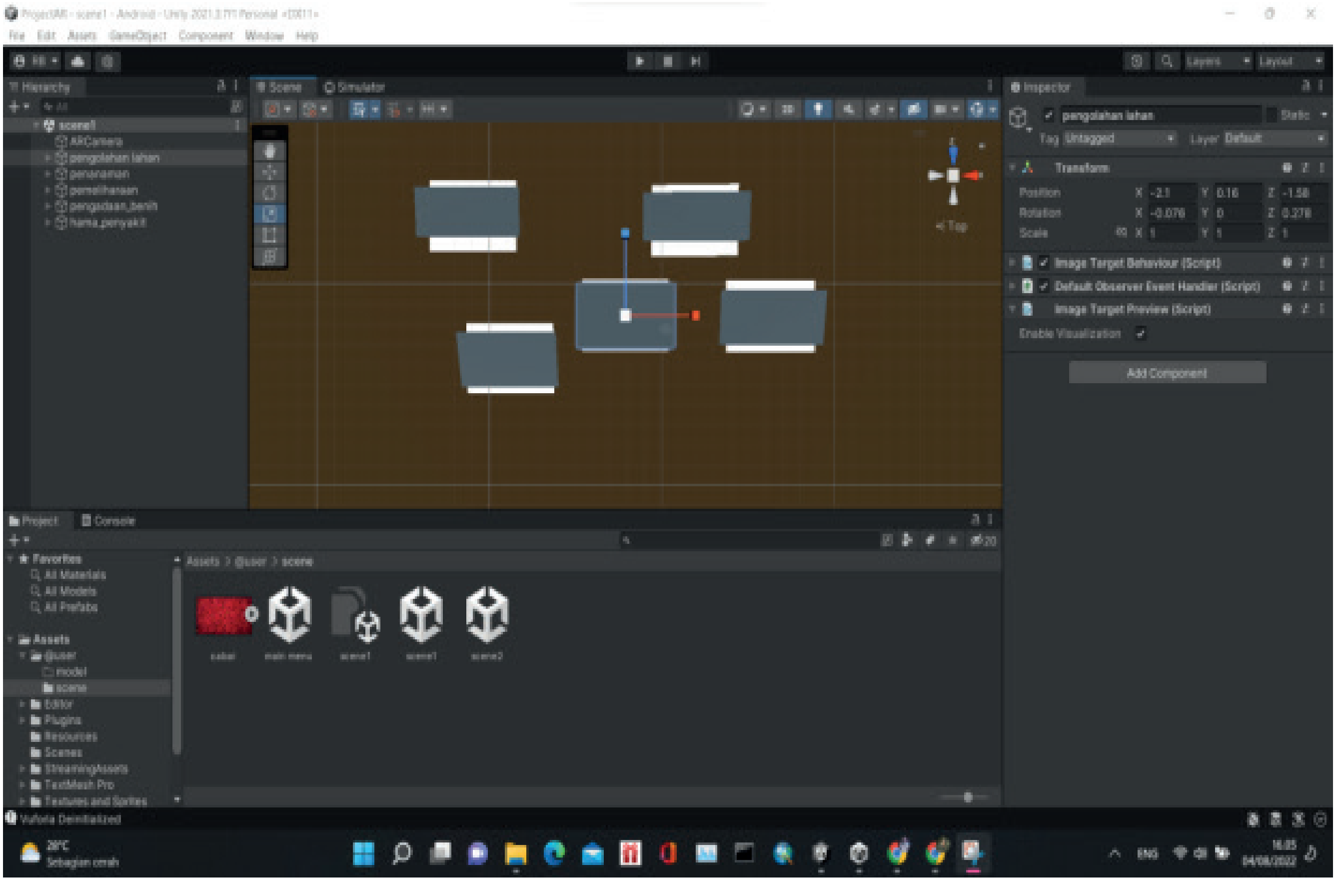

Figure 6. The Results of the Import and Preparation Stages of Objects and Videos Into Unity

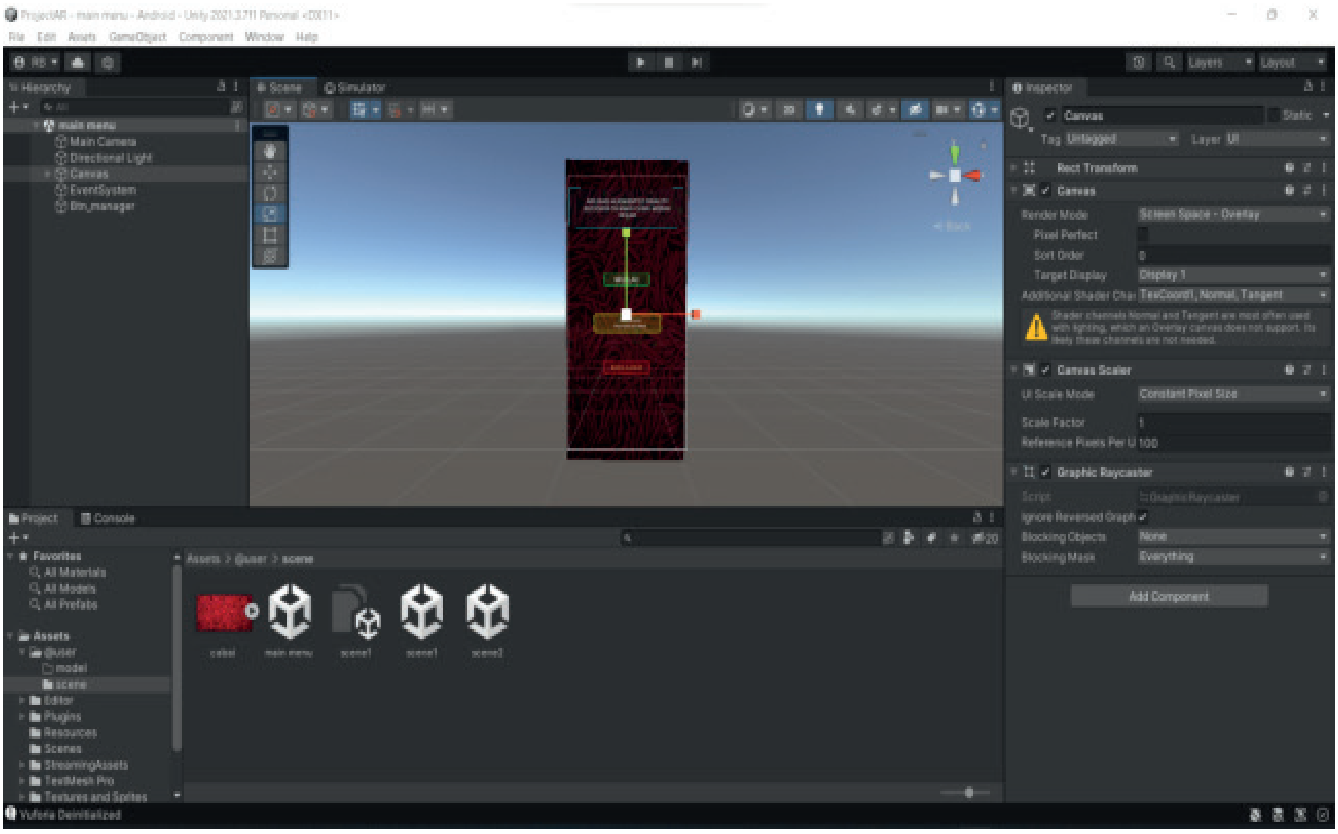

Figure 7. The Results of the Main Menu Creation Stage in Unity

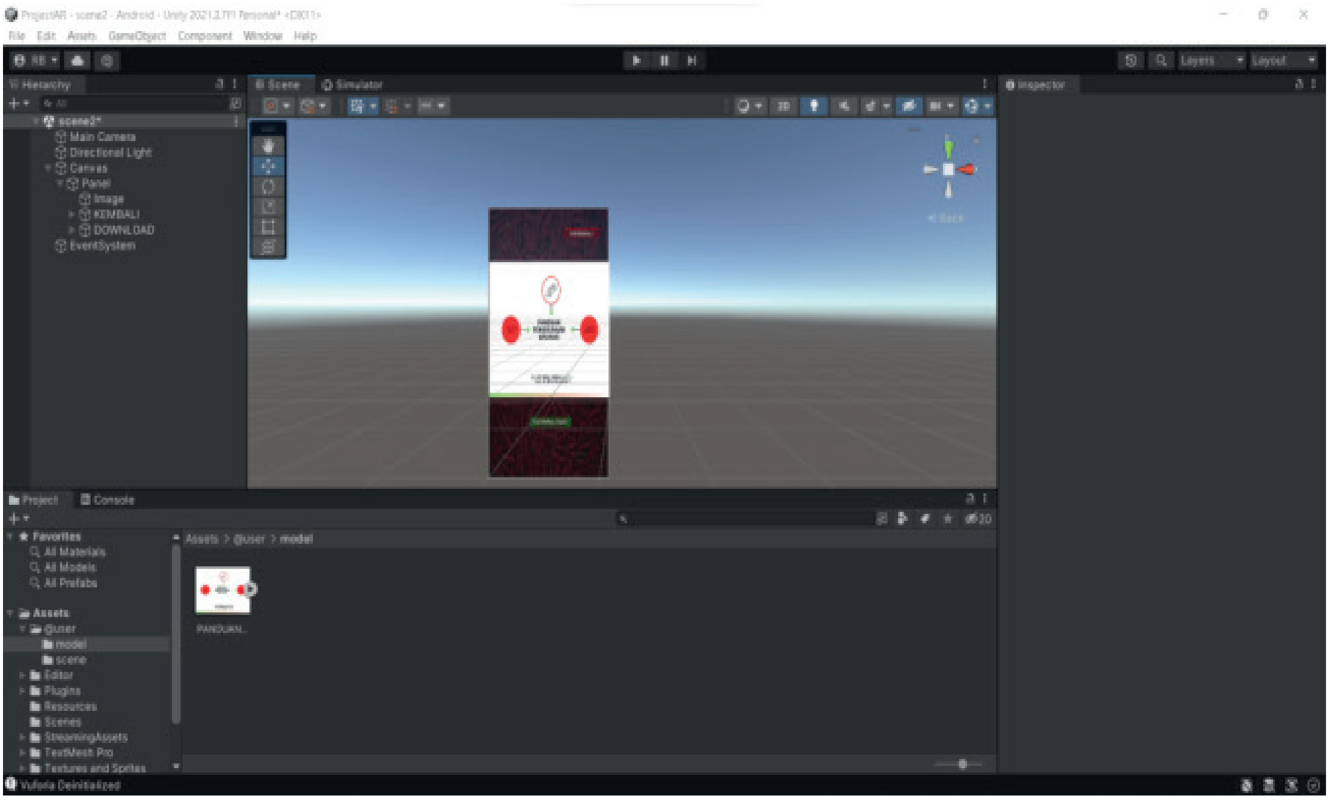

Figure 8. The Results of the Usage Guide Scene Creation Stage

The images above show the stages of importing and compiling assets into Unity for the development of the Large Red Chili Cultivation application. Figure 6 illustrates the initial stage where objects and videos are imported and prepared within Unity, setting up the foundation for the application's interface. Figure 7 demonstrates the creation of the main menu, showcasing the layout and design of the application's introductory screen. Lastly, Figure 8 displays the creation of the usage guide scene, where instructional content for the users is organized and displayed. These stages are crucial for building the interactive and educational features of the application using Unity.

Display results (interface) of the application

Figure 9. Main Menu and User Guide Menu Display

The images above showcase various stages of the application interface for the Large Red Chili Cultivation educational tool. Figure 9 displays the main menu, which serves as the starting point for users, with options to begin or exit the application. Next, the user guide menu, offering additional information or instructions to help users navigate through the application and utilize its features effectively. These stages illustrate the user interface and interaction flow of the AR-based educational tool.

Tag card display

The following is a picture of the tag cards.

Figure 10. Harvest, Hatchery, Plant Care, Planting, Pest and Disease Management, and Land Managemenet Tag Cardcs

The image shows the tag cards used in the Large Red Chili Cultivation application, each representing a different stage or aspect of the cultivation process. These tag cards include icons related to harvesting, hatchery (seedling), plant care, planting, pest and disease management, and land management. Each card, when scanned with the application, triggers the display of relevant educational content, such as animated videos or instructional material, guiding users through the respective phase of chili cultivation. These tag cards play a key role in providing interactive, step-by-step guidance for users, helping them understand the necessary actions at each stage of growing large red chili plants.

Data Analysis and Findings

The data collected from the questionnaire survey indicates that the AR-based application received highly positive feedback from users. A total of 20 respondents were asked to evaluate seven statements regarding the application's usability and effectiveness in teaching chili cultivation techniques. The overall score was 623 out of 700, which equates to 89 %, showing that the majority of respondents found the application functional and effective in delivering educational content. The highest-rated statement, with a 93 % agreement, confirmed that users found the application to be a useful tool for learning about chili cultivation. However, the lowest-rated statement (79 %) highlighted minor concerns regarding some aspects of the user interface.

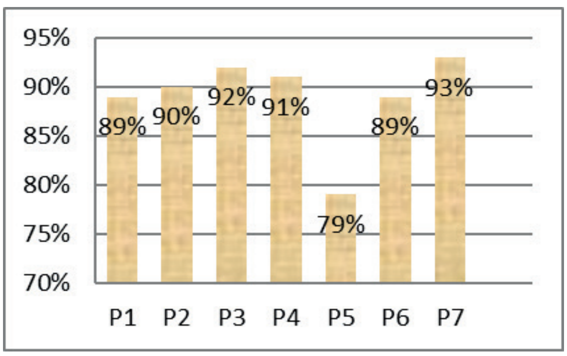

Figure 11. Graph of Questionnaire Results

Information:
P1 - P7 = Statements submitted.
R1 - R20 = Respondents.

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700 = total perfect answers.
91 % - 100 % = (SS) Strongly Agree.
70 % - 90 % = (S) Agree.
50 % = (N) Neutral.
30 % = (TS) Disagree.
0 % = (STS) Strongly Disagree.

Calculation:
623/700 x100 % = 89 %

In addition to the questionnaire, user feedback and observations regarding the AR functionality were also considered. The results suggest that the AR experience effectively engaged users, with many expressing satisfaction with the interactive nature of the application. Despite this positive feedback, some users mentioned that improvements could be made to enhance the clarity of the animated videos and the responsiveness of the AR markers, especially in varying lighting conditions. These insights provide valuable information for further refinement, helping the application meet user needs more effectively.

The application, developed using Unity and Vuforia and following the Multimedia Development Life Cycle (MDLC) methodology, functions as an educational tool for users interested in cultivating large red chili plants. It is designed to run on Android devices and operates offline, though downloading the tag cards requires an internet connection. The application uses the phone's camera to scan tag cards containing specific markers, which trigger the display of videos that offer relevant information on the cultivation process. This method of delivering educational content ensures a dynamic and engaging learning experience for users.

DISCUSSION

The integration of Augmented Reality (AR) in agricultural education, specifically for large red chili cultivation, marks a significant step forward in addressing the challenges faced by farmers due to the lack of knowledge in modern farming techniques. As discussed in the literature, AR has proven to be a powerful tool in education, providing interactive, engaging, and visual learning experiences that can overcome traditional educational barriers. Previous studies have demonstrated that AR significantly enhances knowledge transfer by allowing users to interact with 3D models and animated videos, making complex agricultural processes easier to understand and apply.

Comparison with Previous AR Educational Studies

The 89 % approval rating achieved in this study demonstrates notably higher user satisfaction compared to several previous AR educational applications. Contrasting with Buditjahjanto et al.[6] who reported mixed results regarding AR's impact on academic achievement and found that effectiveness varied significantly based on students' creative thinking levels, our study showed consistent positive responses across all user categories regardless of their agricultural background. While their study revealed that AR benefits were primarily observed in students with higher creative thinking abilities, our agricultural AR application achieved high satisfaction rates (89 %) even among users with limited prior agricultural knowledge, suggesting that domain-specific AR applications may be more universally effective than general educational AR tools.

In contrast to Liu et al.[7] whose research on mobile AR technology in agriculture primarily focused on technical feasibility and system architecture without comprehensive user evaluation, our study provides concrete evidence of user acceptance and learning effectiveness. Liu et al.[7] emphasized the potential of AR in agriculture but lacked quantitative user feedback data. Our research fills this gap by demonstrating that 93 % of users found the AR application useful for learning chili cultivation, providing empirical evidence that supports Liu et al.'s theoretical projections about AR's agricultural potential.

Comparing with Sukmawati et al.[20] who designed mobile AR to enhance critical thinking skills in vocational education and reported improved learning outcomes, our study shows both similarities and differences. While Sukmawati et al. focused on cognitive skill development and found AR effective for enhancing analytical thinking, our agricultural AR application demonstrated effectiveness in practical skill transfer and procedural knowledge acquisition. Their study emphasized individual cognitive development, whereas our research shows AR's effectiveness in conveying step-by-step practical procedures. However, both studies confirm AR's superior engagement compared to traditional instructional methods, though through different learning mechanisms.

Technical Performance Contrasts

Regarding technical performance, our study revealed that the AR application maintained functionality even when tag cards were partially obscured (up to 50 % coverage), which represents a significant improvement over earlier AR educational applications. Previous studies, such as those discussed by Asadi et al.[25] identified environmental factors like lighting conditions and marker visibility as major limitations for AR applications in practical settings. Our application's robust marker detection capabilities address these commonly reported technical barriers, demonstrating advancement in AR implementation for field-based agricultural education.

The offline functionality of our application also distinguishes it from many previous AR educational tools that require constant internet connectivity. This feature addresses the connectivity challenges highlighted by Edi et al.[12] in their analysis of rural agricultural education barriers. While many previous AR applications were limited by infrastructure requirements, our solution's offline capability makes it more accessible for rural farming communities where internet connectivity may be unreliable.

Learning Effectiveness Comparison

In terms of learning effectiveness, our study's results show distinct advantages over traditional agricultural extension methods. While Wardah et al.[8] found that conventional agricultural training programs had limited reach and effectiveness due to resource constraints and accessibility issues, our AR application achieved 89 % user satisfaction with minimal resource requirements after initial development. This represents a significant improvement in educational delivery efficiency compared to traditional face-to-face training methods that typically show lower engagement rates and higher implementation costs.

The interactive nature of our AR application also showed superior engagement compared to static educational materials. Previous research by Nigam et al.[19] on AR in education systems noted that while AR increased engagement, the learning retention rates varied significantly across different subject areas. Our study specifically measured user satisfaction with content clarity and practical applicability, finding that 93 % of respondents rated the application as useful for learning cultivation practices, suggesting that AR may be particularly effective for procedural and practical knowledge domains like agriculture.

Limitations and Areas for Improvement

Despite the positive outcomes, our study identified specific limitations that contrast with more optimistic projections in previous research. User feedback highlighted issues with video clarity and AR marker responsiveness under varying lighting conditions, problems that were also noted in earlier studies but remain unresolved. Unlike Novaliendry et al.[26] who reported seamless AR experiences in controlled educational environments, our field-based agricultural application revealed that real-world conditions significantly impact AR performance, requiring further optimization for outdoor use.

The feedback regarding video clarity represents a persistent challenge in AR educational applications. While previous studies often reported on AR's visual appeal, our research provides specific user feedback indicating that 79 % satisfaction (the lowest score) was related to content presentation quality. This finding contrasts with more general positive assessments in earlier AR educational research and highlights the importance of content quality alongside technical functionality.

Implications for Agricultural Education

The success of our AR application in agricultural education contexts demonstrates significant potential for scaling similar technologies across different crops and farming practices. Unlike previous studies that focused on theoretical applications, our research provides practical evidence that AR can effectively bridge the knowledge gap between agricultural research and farm-level implementation. The 89 % approval rating and specific positive feedback on procedural guidance suggest that AR may be particularly well-suited for agricultural education, where visual demonstration of techniques is crucial for effective learning.

The application's performance in real-world conditions also offers insights that contrast with laboratory-based AR studies. While controlled environment studies often report higher success rates, our field-applicable AR solution demonstrates that practical agricultural AR applications can achieve high user satisfaction even under variable conditions, providing a more realistic assessment of AR's potential in agricultural extension services.

Future Research Directions

Based on our findings and their contrast with previous research, future studies should focus on addressing the technical limitations identified in real-world applications while building upon the demonstrated effectiveness of AR in agricultural education. The gap between laboratory-based AR research and field-applicable solutions highlighted by our study suggests that more emphasis should be placed on developing AR applications that can perform reliably under diverse environmental conditions.

The success of our domain-specific approach also suggests that future AR educational research should consider subject-specific design principles rather than general educational AR frameworks. Our results indicate that AR applications tailored to specific practical domains may achieve higher effectiveness than generic educational AR tools, an insight that differs from previous research that often assumed universal applicability of AR educational benefits.

Overall, this study contributes to the growing body of research on AR in agricultural education by providing empirical evidence that both supports and challenges previous theoretical projections, while offering practical insights for developing effective AR applications for rural and agricultural contexts.

CONCLUSIONS

This study successfully developed and evaluated an Android-based Augmented Reality application for large red chili cultivation education, demonstrating significant effectiveness in agricultural knowledge transfer. The application, developed using Unity and Vuforia through the Multimedia Development Life Cycle methodology, achieved an overall user satisfaction rating of 89 % (623 out of 700 points), with the highest satisfaction score of 93 % for learning usefulness and the lowest at 79 % for technical aspects. The AR application maintained robust functionality even when tag cards were partially obscured (up to 50 % coverage), and its offline capability addressed connectivity challenges in rural settings. User feedback confirmed that the interactive AR interface enhanced engagement and understanding of complex cultivation processes through step-by-step video guidance covering seed selection, planting techniques, plant care, and pest management.

The study's findings provide empirical evidence supporting AR technology's effectiveness in agricultural education, specifically demonstrating that domain-specific AR applications can achieve high user satisfaction across diverse backgrounds. The 89 % approval rating indicates strong user acceptance and perceived value, suggesting significant potential for scaling similar technologies across different crops and farming practices. However, the research identified limitations requiring future attention, particularly regarding video clarity and AR marker responsiveness under varying lighting conditions. This study establishes a foundation for advancing AR technology in agricultural education, providing both technical validation and user acceptance evidence that supports the broader adoption of AR-based educational tools in agricultural extension services. Future research should focus on addressing technical limitations while exploring scalability across different agricultural domains, as the success of this domain-specific approach suggests tailored AR solutions may be more effective than generic educational AR tools.

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