Mobile Augmented Reality Genetics to Improve Students' Mastery of Genetic Concepts

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Abstract **– Genetics is the fundamental framework for comprehending biological principles in secondary education. Nevertheless, the intricate nature and conceptualization of genetics pose several challenges for students, leading to difficulties in comprehension. The present study attempted to enhance students' mastery of genetic concepts by implementing a Mobile Augmented Reality Genetics (MAR-Gen) application inside the learning process. The study employed a mixed-methods approach and was conducted on experts, biology teachers, and 120 respondents in their final year of high school. The respondents were allocated into experimental and control groups. The experimental group received instruction integrating mobile learning, whereas the control group received instruction using teaching methods that did not incorporate the mobile learning media. The findings indicated that the students in the experimental group achieved superior scores in genetics content compared to those in the control group. This study showed that mobile learning media could enhance genetic concept mastery and elicit a favourable student reaction.**

This study provides valuable mobile applications in biology education to enhance high school students' understanding of genetic concepts.

Keywords **– Mobile learning, augmented reality, genetics, concept mastery.**

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1. Introduction

Genetics is a field of study within the biological sciences that plays a vital role in the lives of individuals [1]. The study of genetics has developed rapidly since Watson and Crick discovered the structure of DNA [2], [3]. Genetics is widely discussed in human health [1], [4]. It is also widely regarded as a fundamental component of scientific literacy [5], [6]. Considering the growing significance of genetics in contemporary society, it is imperative to ascertain that education can enhance students' comprehension of genetic concepts. Thus, biology curricula worldwide prioritize including genetics as a fundamental subject to be taught at the secondary school level [3], [7].

Nevertheless, numerous educational establishments, particularly those operating at the high school level, need help imparting genetic knowledge to their students. Many students perceive genetics as challenging to learn and comprehend [8], [9], [10]. Genetics is predominantly theoretical and sometimes needs more contextualization. Furthermore, genetics encompasses a wide range of subject matter, employs many intricate terminologies, and entails complex notions difficult for students to understand. These challenges contribute to students' limited comprehension and proficiency of concepts [3].

Individuals across various age groups encounter challenges when attempting to comprehend fundamental principles in genetics [11]. Many students need clarification and exhibit limited genetic literacy as they progress to higher levels of education [1], [12].

The primary impediments that hinder students' comprehension of genetics are their challenges in learning the subject, misconceptions regarding its ideas, and limited literacy skills [10], [13]. This problem can be attributed to the inclusion of extra topics within the genetics unit, as provided in biology textbooks. Biology textbooks often provide inadequate visual representations of genetic concepts and mechanisms [11]. The absence of coherence and logical connections among crucial genetic ideas necessary for comprehensively elucidating intricate genetic processes further intensifies this state [15]. Ultimately, students' misconceptions regarding genetics will persist and permeate into advanced educational settings. If promptly rectified, these misconceptions may positively impact students' biology learning [1], [14], [15], [16].

Applying suitable educational media might mitigate the challenges associated with comprehending and acquiring knowledge about genetic concepts [15]. The findings of a survey revealed a significant inclination among teachers toward the development of genetics instructional materials. The educators acknowledged the necessity of revising the genetics curriculum and creating engaging and pertinent resources to teach genetics at the secondary school level [10]. According to other scholars, acquiring genetic knowledge necessitates integrating interactive multimedia into mobile learning platforms. However, the integration of interactive media in genetic classrooms needs to be improved [15], given that interactive media, such as movies and animations, can enhance students' enthusiasm to learn and deepen their comprehension of genetics [11].

In contemporary times, mobile device utilization is growing in educational establishments [17], [18], [19]. The emergence of mobile gadgets has significantly transformed the modes of communication, work, and education for individuals in the 21st century. As smartphones and tablets become more accessible and powerful, they can become effective learning tools inside and outside the classroom [20], [21]. The proliferation of mobile devices continues to change how we interact and learn, giving rise to the term mobile learning. Mobile learning (m-learning) can be defined as the process of acquiring knowledge or skills via mobile devices, allowing individuals to engage in learning activities at any location and at any time [17], [18]. M-learning is part of digital-based learning [20], [22].

Multimedia content inside mobile applications can facilitate student learning, provided that the methods of delivery, storage, and display are appropriately tailored to the capabilities of the m-learning device and students' cognitive ability [23], [24].

M-learning can decrease cognitive burden, enhance the visualization of complex scientific processes, and facilitate the communication of scientific concepts and content [25]. Multiple scholars have reported the advantages of incorporating m-learning into educational practices [20], [26], [27], [28]. Hence, the development of m-learning as an instructional media becomes imperative, particularly in genetics education. The existing body of research on m-learning focused on genetics education still needs to be expanded.

The current study introduces Mobile Augmented Reality Genetics (MAR-Gen) as a media platform based on m-learning. The MAR-Gen application is an educational tool that combines augmented reality technology with genetic content. Research has demonstrated the efficacy of augmented reality in enhancing students' comprehension of biology concepts [29], [30], [31]. There is an expectation that integrating the m-learning application into education will be employed with efficacy, particularly in genetics. The m-learning media has been designed to support mobile learning methodologies and increase students' mastery of concepts, especially genetic ones. Hence, the current study attempted to enhance high school students' mastery of genetic concepts by incorporating MAR-Gen into the classroom.

2. Methodology

This research is a type of mixed-methods research that combines qualitative and quantitative research, which was carried out in high school. A detailed explanation regarding respondent characteristics, procedures of research, data collection and data analysis tools used in this research are presented as follows.

2.1. Respondent Characteristics

Before conducting the research, informed consent forms were presented to the student respondents. The practice of informed consent was employed to secure the voluntary agreement of students to partake in research activities. Students had the right to express disagreement. Participation in the research was contingent upon the expression of agreement by the students.

Table 1 displays the distribution of respondents in this study. We involved 120 respondents with secondary education qualifications, namely students in the twelfth grade at public high schools in Jeneponto Regency, South Sulawesi, Indonesia. Ten additional respondents were biology instructors and four experts in media and genetic concepts. Respondents (students) were chosen randomly and shared similar characteristics.

Respondents were separated into those at the media trial stage and those at the quasi-experiment stage. In the media trial phase, 40 students and 10 teachers participated as respondents. Apart from that, two media experts and two material experts were also used at this stage. Next, respondents at the quasi-experimental stage were divided into two groups: an experimental group of 40 students (77.5% female and 22.5% male) and a control group of 40 students (75% female and 25% male).

2.2. Procedure of Research

This research used a mixed methods approach, namely research and development (R&D), experiment, and survey methods. This study consisted of two main phases: the development of m-learning media (MAR-Gen) and a quasi-experimental study. In addition, a survey was also carried out. The media development phase preceded the quasi-experimental phase. Development studies encompass a study methodology employed for designing and evaluating a product. The outcome of this study was a m-learning platform that integrates augmented reality (AR) technology. The product developmental stages followed those outlined by Lee and Owens [32], which include assessment/analysis, design, development, implementation, and evaluation.

Table 1. Respondent characteristics (N = 134)

Phase	Group	Gender		Total
		Male	Female	
Development of Media	Experts	2	2	4
	Teacher	0	10	10
	Student	11	29	40
Quasi-Experiment	Experimental group	9	31	40
	Control Group	10	30	40
Total		30	90	134

The initial phase of the product development process was conducting an assessment and analysis to determine the needs of educators and learners for genetic instruction. The current stage comprised two distinct components: needs assessment and front-end analysis. The needs assessment was conducted to ascertain the actual and desired states of genetics education.

The indicators measured in the analysis included the media and instructional frameworks employed by educators in genetics education, the subject matter that posed challenges for students in comprehending genetic concepts, and the utilization of technology by both students and instructors in the classroom. Concurrently, a front-end study was conducted to acquire comprehensive insights into genetic learning and identify the challenges encountered therein, thereby facilitating the creation of genetic learning media.

The design stage encompassed several tasks, including developing a timetable, project team, media specifications, content organization, configuration control, and review cycle. The third stage of the process involved the development phase, which focused on transforming the product from the design stage into a tangible form, specifically in the context of m-learning through genetic learning media. The initial phase of this process involved the development of a storyboard, which was subsequently subjected to a thorough review and validation process. The storyboard included elements such as interface design, layout, and conceptualization. Then, we proceeded to elaborate on genetic principles in the application. The genetic principles that can be studied via this application are cell division, inheritance patterns, heredity patterns, and mutations. The development of this application utilized a combination of software tools, including Unity 3D server, DSpace, Blender, Corel Draw, and Adobe Flash Professional CS.5.5. The application demonstrates compatibility with smartphone platforms based on the Android operating system.

The implementation phase was the fourth stage of product development. The primary objective of the implementation phase was to execute the development process and evaluate the product's efficacy under development. The implementation stage included preparing both teachers and students to use the application. The last phase entailed the process of product evaluation. This stage aimed to assess the validity and practicality of the media in addressing current challenges in genetics education and to contribute to attaining predetermined objectives.

A quasi-experimental study was done to evaluate the efficacy of the media in facilitating the acquisition of genetic concepts. This study involved using MAR-Gen as a learning media in an experimental class. Conversely, the control group engaged in studying without the implementation of MAR-Gen. This research was carried out using a pretest-posttest control group design. This study also surveyed to see students' responses to MAR-Gen media.

2.3. Data Collection Tools

To gather data pertinent to this study, we employed the following data collection instruments:

- Validity and practicality questionnaire: this instrument was used to measure data on the validity and practicality of the MAR-Gen media being developed. The validity questionnaire was given to media and material experts, while the practicality questionnaire was given to teachers and students.
- Pretest and posttest: A pretest was employed to establish homogeneity among the research groups at the outset. This test aimed to evaluate the students' baseline proficiency in genetics. In the present study, the posttest assessed how incorporating m-learning media into genetics education affects students' comprehension of vital genetic topics. In addition, the posttest was utilized to compare the student responses across the control and experimental groups. Each test consisted of twenty multiple-choice questions and five essay prompts that pertain to the field of genetics. The topics covered encompass cell division, Mendelian inheritance, hereditary patterns, and mutations. Respondents were required to select a single accurate response from a set of five options in the context of multiple-choice questions. Each correct selection was awarded one point to the student's score.
- Student response questionnaire: This questionnaire was used to determine student responses after using m-learning media in studying genetic concepts.

2.4. Data Analysis Tools

The data obtained from the experimental study was analyzed using the statistical program SPSS version 26. The employed methodology encompassed a descriptive analysis of the mean score and standard deviation. In addition to this, we conducted inferential analysis utilizing the independent sample t-test. The findings of the inferential analysis were interpreted based on $p < 0.05$.

3. Results

This section explains the results of developing genetic learning media, i.e. the MAR-Gen interface design. Apart from that, we also discuss the results of validity and practicality tests on the media. The validity test results were obtained based on the assessment of media experts and genetic material experts. Meanwhile, the practicality test results were obtained based on the assessments of teachers and students of class XII high school. Media that has been declared valid and practical is then tested for its effectiveness on students' mastery of concepts using experimental design. A more detailed explanation is presented as follows.

3.1. MAR-Gen Interface

Figure 1 illustrates the presentation of the front-page menu on the MAR-Gen application, encompassing the introduction and homepage. On the introductory page, users will be presented with an initial visual representation in the form of an animated video that showcases a dynamic loading icon, animated chromosomes, and the application's title. This visual display will last 5 seconds before users are directed to the primary or home menu. In addition, the homepage of the application presents a prominent display consisting of feature buttons that include a close icon, a home icon, the application's title or name, the user's profile, the user guide, essential competencies to learn, phenomena, learning content, augmented reality (AR), and evaluation (Figure 1).

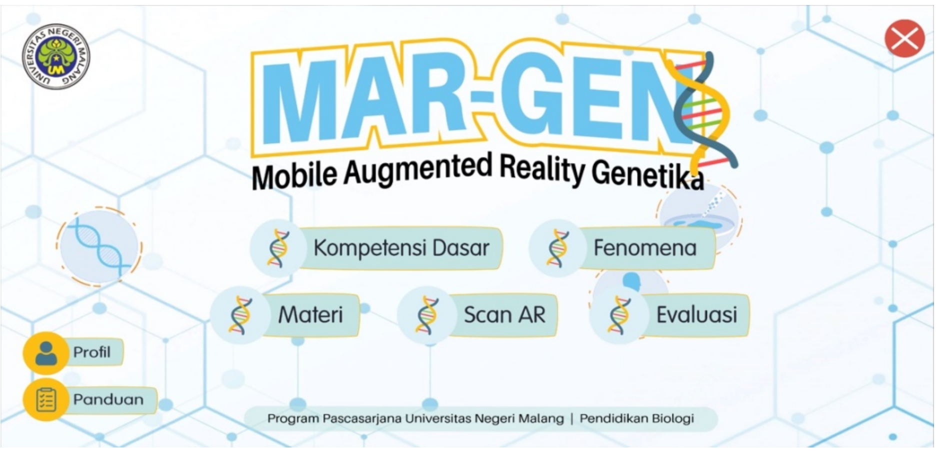


Figure 1. The opening page of MAR-Gen displays the menu profile, user guide, essential competencies, phenomena, content, AR scan, and evaluation

Figure 2. illustrates the presentation of the phenomenon page. Within the phenomena menu, viewers can access animated videos showcasing phenomena directly associated with genetic content being studied. The phenomena menu also includes an option dedicated to simulations. The simulation menu facilitates students in simulating a range of crossing and heredity processes.

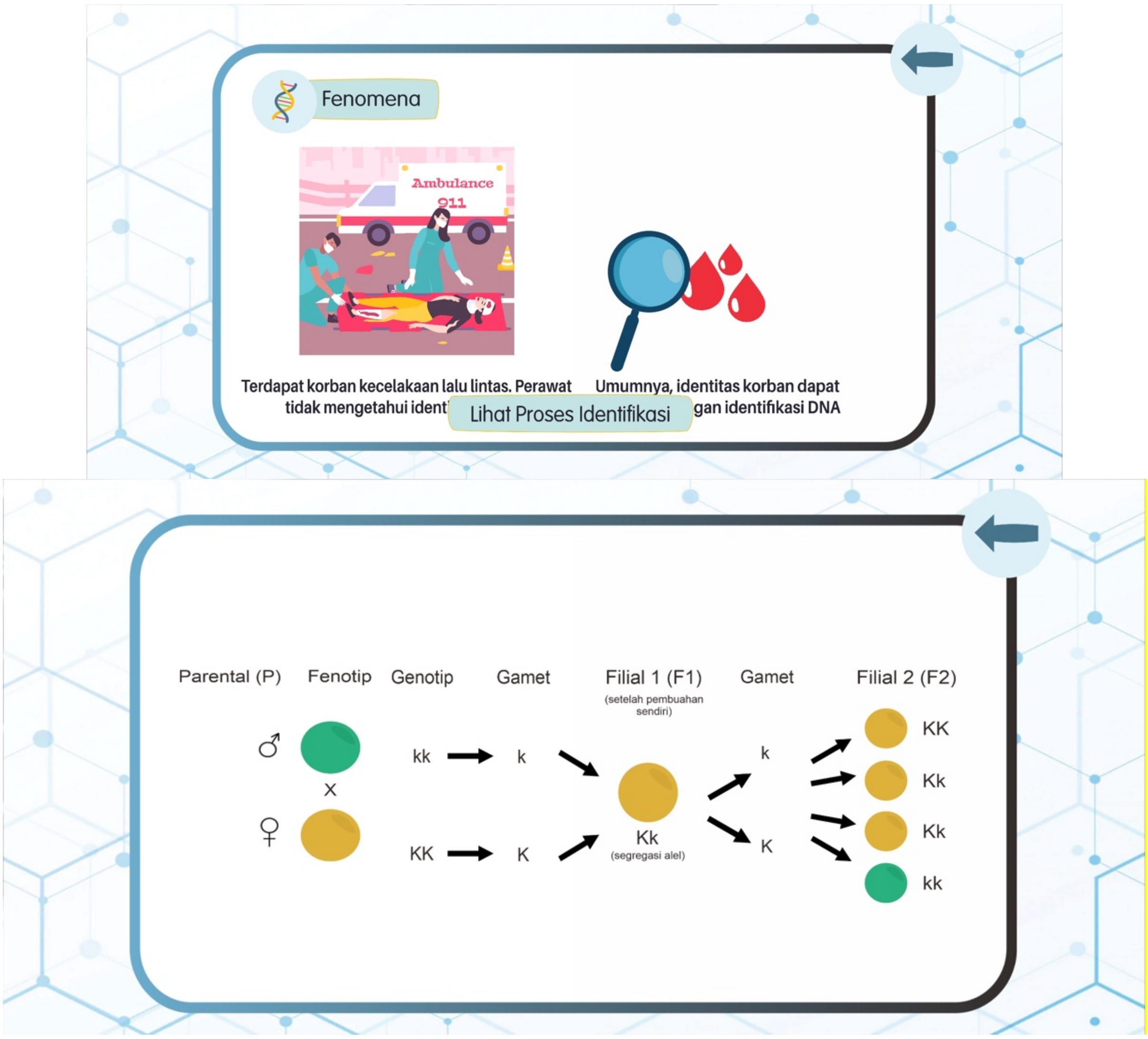
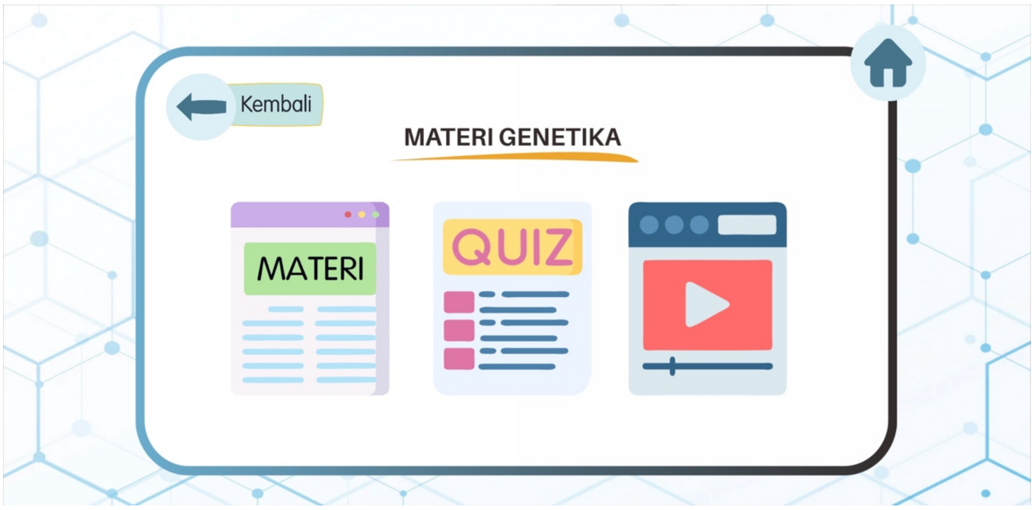


Figure 2. The phenomena menu displays animated videos and simulations of genetic processes

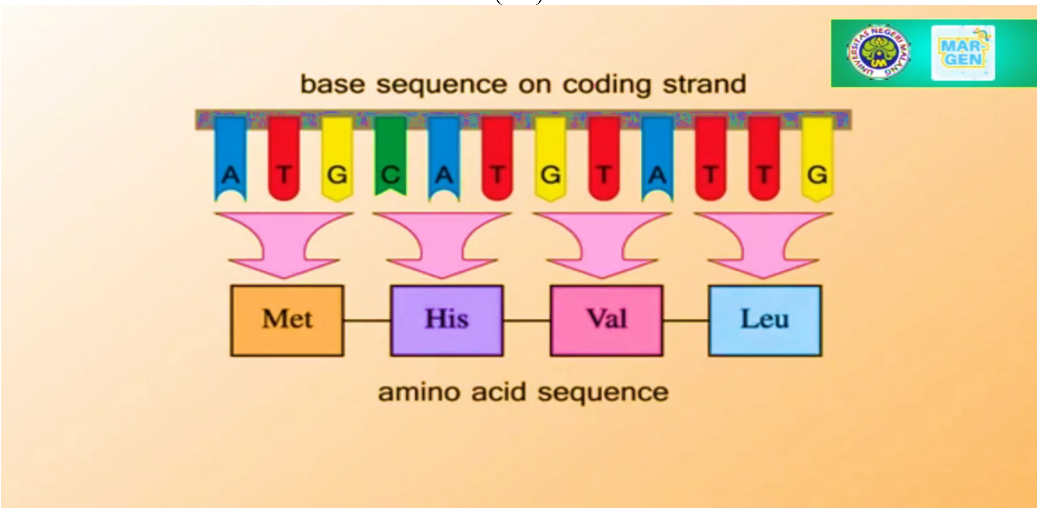
The appearance of the learning content menu is depicted in Figure 3. The content page displays three feature icons for users to access: learning materials, quizzes, and YouTube (Figure 3.a). Within the interface, individuals can navigate between various materials by swiping in either the right or left direction, indicating their selection of the desired resource for further access (Figure 3.b). If the icon is selected, it will increase in size and display a page containing the material concept. Students can choose six icons for learning materials to symbolize and reflect each basic competency.

Additionally, users are presented with the initial quiz page with a designated personal identification column within the quiz interface. This column serves as a space for students to provide relevant information when completing the question. In addition to this, a save and continue option is also made available. Moreover, users can access YouTube directly from the YouTube platform to watch various visualization videos about the chosen genetic material (Figure 3.c).



(3.a)

(3.b)



(3.c)

Figure 3. Content menu: (a) learning material, quizzes, YouTube videos (b) learning material title and learning material page that contains explanations on genetic content, and (c) videos related to the genetic learning material

Moreover, the *AR* scan menu display is depicted in Figure 4. The AR scan page allows users to observe a standard augmented reality (AR) three-dimensional representation of things associated with the chosen educational content. This is achieved by utilizing the device's camera to scan designated markers. The artefact is shown in a three-dimensional augmented reality format with animated features. The interface incorporates multiple buttons that enable users to adjust the zoom level and rotation of the object, facilitating comprehensive observation of the object.

Subsequently, Figure 5 displays the Evaluation menu. Users can assess their understanding of genetic concepts by taking multiple-choice exams on the evaluation page. If the user selects an incorrect answer, a symbol as a cross (X) will be displayed. Similarly, a check mark (√) will be displayed if the user selects the correct answer. Upon completion of the assessment, individuals will be able to see the score they have achieved.

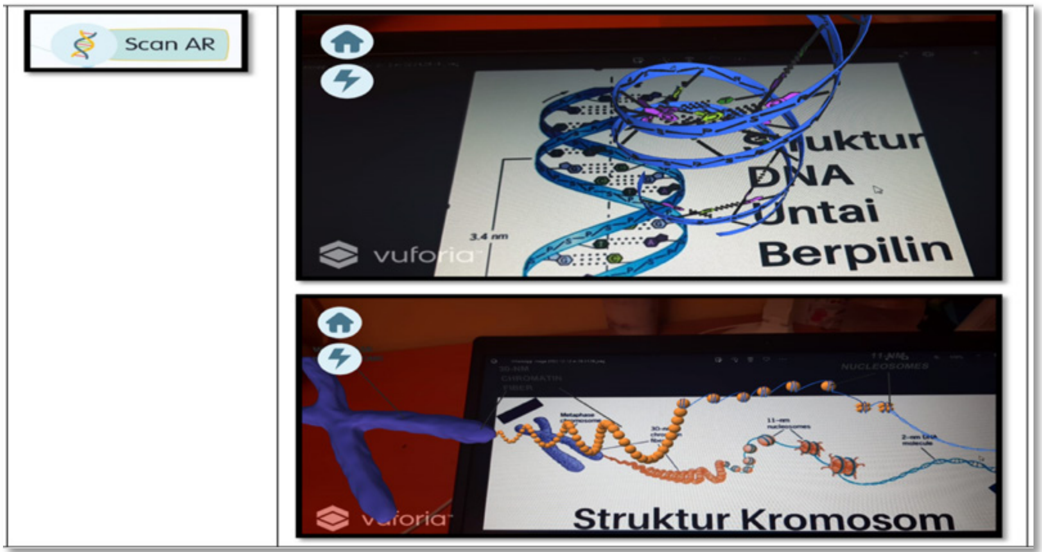


Figure 4. Augmented reality menu displaying a double-stranded DNA and chromosome structure

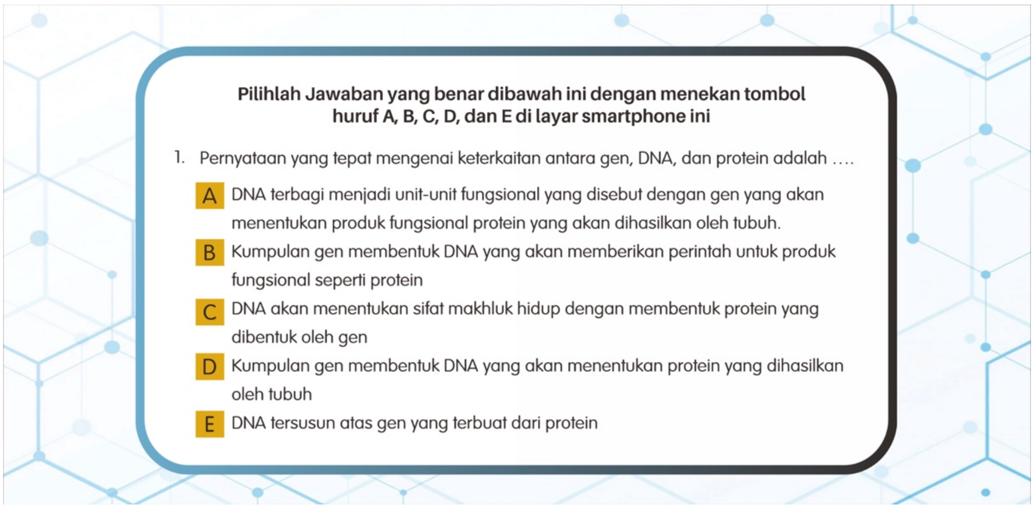


Figure 5. The evaluation menu displays a multiple-choice question on genetic content being learned

3.2. Validity and Practicality of MAR-Gen

Mar-Gen media that has been developed needs to be tested for validity and practicality. The media validity test includes the media's validity and the genetic material's validity. Meanwhile, practicality tests include tests based on teachers' and student assessments. Below is a detailed explanation regarding the validity and practicality of MAR-Gen media.

3.2.1. Result of Media Expert Validation

The questionnaire for media expert validation consisted of 23 statements. These statements corresponded to each indicator, precisely the ease of use of the application, the appearance of the application, the design of the content, user engagement, and language usage. The statement was evaluated on a scale ranging from 1 to 5, and its evaluation was based on the following assessment criteria: a validity (V) index of 0 indicates that the statement is invalid. In contrast, a V index 1.0 indicates the statement is highly valid. The comprehensive data is depicted in Figure 6.

The mean score for the application was 0.88 on the indicator measuring ease of use, 0.9 on the indicator measuring appearance, 0.9 on the indicator measuring content design, 0.88 on the indicator measuring user engagement, and 1.0 on the indicator measuring language use (Figure 6).

The mean value for all indicators was 0.91 (valid). This number demonstrated that the application was highly effective educational media for genetic learning.

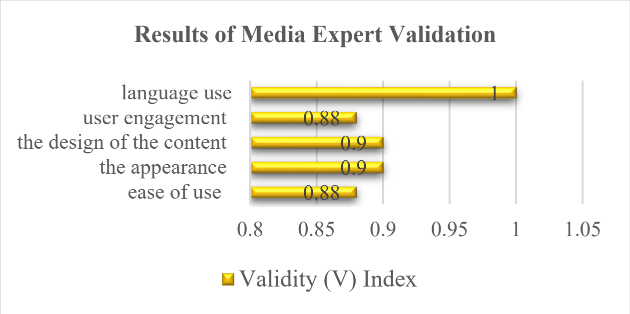


Figure 6. Results of Media Experts Validation

3.2.2. Results of Concept Experts' Validation

Concept experts also validated the application to test whether the genetic concepts in the application were valid and easy to understand. The instrument for expert validation comprised a set of 12 statements. These items encompassed various indicators, including content accuracy, material depth, clarity, user convenience, evaluation, and user benefits. Data obtained from concept expert validation is shown in Figure 7. According to Figure 7, the mean percentage value for all indicators was 0.88 (valid). The percentage indicated that the application in question exhibited a high level of quality in terms of its content, rendering it a suitable tool for educational purposes.

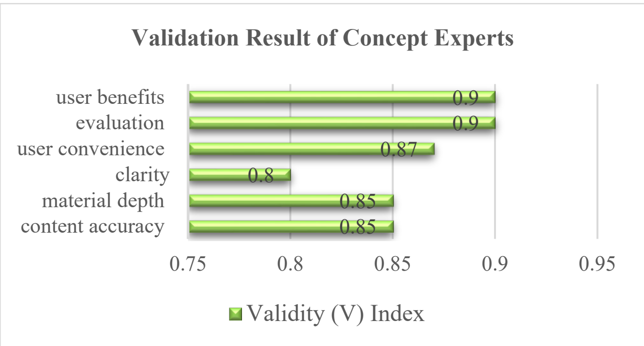


Figure 7. Validation results of concept experts

3.2.3. Results of the MAR-Gen Practicality Test

The application that had been revised based on expert suggestions was subsequently tested and evaluated by biology educators and students to ascertain its practicality for integration into the pedagogical framework. Figure 8 displays an analysis of practical data derived from the responses provided by teachers.

The findings from the examination of instructor feedback indicated that media was practical, with an average percentage of 95.2%. The practicality test measured clarity (95.2%), user convenience (92.8%), suitability and usefulness (96.8%), and language (96.0%) of the application.

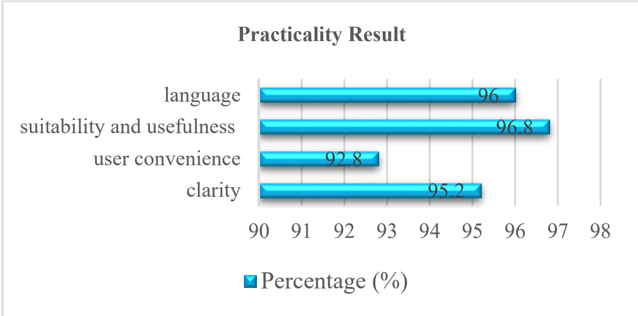


Figure 8. Results of MAR-Gen practicality test by biology teachers

Then, practicality data were derived from student responses (Figure 9). The findings indicated that the media was practical, with a percentage of 92.2%. The practicality test encompassed four key dimensions: clarity (94.4%), ease and usefulness (89.0%), appeal (93.3%), and language use (92.0%).

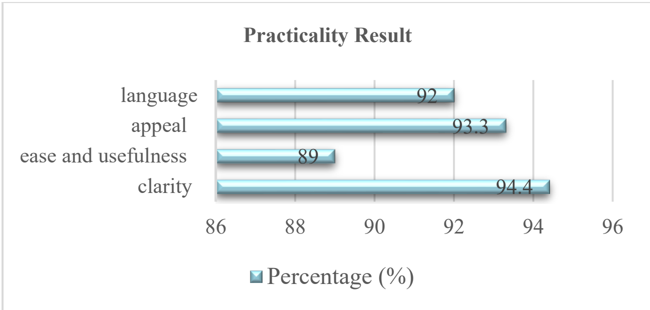


Figure 9. Results of MAR-Gen practicality test by students

3.3. The Quasy-Experimental Study Results

Table 2 compares the two treatment groups' mean scores on the pretest for genetic concept mastery. The data analysis revealed a marginal mean discrepancy of 0.08 between the control group (CG) and the experimental group (EG). This study's findings indicated no significant difference in genetic concept mastery between the two groups.

The normality of the data for both groups is shown in Table 3. Based on the results of the data analysis, the data in both groups were normally distributed. Pretest normality for EG and CG was indicated by p-value (0.178 and 0.083) > α (0.05), whereas posttest normality was shown by p-value (0.106 and 0.070) > α (0.05).

Based on Table 4, the results of Levene's test for homogeneity of variance indicated that the population of variants was homogeneous with an F value of 0.969 and p (0.328) > α (0.05). Furthermore, the results of the inferential analysis results indicated that there was a slight disparity in the mean pretest scores between the CG and EG groups, which is 0.075 with a significance value of (0.949) > α (0.05). The difference in the values was between -2.397 to 2.247. This analysis showed that the two groups' initial knowledge (pretest) was not significantly different or equal.

Table 5 compares the mean scores achieved by both groups on the concept mastery posttest. The findings derived from the data analysis indicated a mean difference of 4.15 between the control group (CG) and the experimental group (EG). The highest attainable score on the control group posttest was 81, but the experimental group posttest had a maximum score of 85.

Table 6 shows the outcomes of the inferential analysis conducted on the students' posttest data. Based on Table 6, the results of Levene's test for homogeneity of variance indicated that the population of variants was homogeneous with an F value of 0.720 and p (0.399) > α (0.05). Furthermore, the results of the analytical findings indicated a notable disparity between the control group (CG) and experimental group (EG), where the mean score of EG, employing MAR-Gen, was 4.150 units greater than the mean score of CG, which did not utilize MAR-Gen. The difference in the values was between 2.047 and 6.253. These findings suggested that implementing MAR-Gen in the classroom effectively enhanced high school students' mastery of genetic concepts.

Moreover, the data analysis findings revealed that students reacted favourably to integrating MAR-Gen into genetic instruction. The mean percentage value of students' "agree" responses was 86.5%. The comprehensive analysis of student responses is presented in Table 7.

Table 2. Descriptive statistics of the mean pretest scores

Group	N	Minimum	Maximum	Mean Scores	Standard Deviation
Control group (CG)	40	11	29	20.08	5.535
Experimental group (EG)	40	12	29	20.00	4.878

Table 3. Normality of the data

Group	Shapiro-Wilk				
	Statistics		N	p-value	
	Pretest	Posttest		Pretest	Posttest
Control group (CG)	0.951	0.949	40	0.083	0.070
Experimental group (EG)	0.961	0.954	40	0.178	0.106

Table 4. Independent sample T-Test for pretest in both groups

Levene's Test for Equality of Variances			T-Test for Equality of Means					
	F	p-value	t	p-value (2-tailed)	Mean Difference	Standard Error Difference	Confidence Interval of the Difference at 95%	
							Lower	Upper
Assumption of equal variances	**0.969**	**0.328**	-0.064	0.949	-0.075	1.167	-2.397	2.247
Unequal variances assumption			-0.064	0.949	-0.075	1.167	-2.398	2.248

Table 5. Descriptive statistics of the mean posttest scores

Group	N	Minimum	Maximum	Mean Scores	Standard Deviation
Control group (CG)	40	65	81	72.83	4.956
Experimental group (EG)	40	70	85	76.98	4.481

Table 6. Independent sample T-test for posttest in both groups

Levene's Test for Equality of Variances			T-Test for Equality of Means					
	F	**p-value**	**t**	**p-value (2-tailed)**	**Mean Difference**	**Standard Error Difference**	**Confidence Interval of the Difference at 95%**	
							Lower	**Upper**
Assumption of equal variances	**0.720**	**0.399**	3.929	0.000	4.150	1.056	2.047	6.253
Unequal variances assumption			3.929	0.000	4.150	1.056	2.047	6.253

Table 7. Analysis of students' response to MAR-Gen

No.	Questionnaire Statement	Percentage of Agree (%)
1	Acquiring knowledge in genetics through mobile learning with the MAR-Gen application is enjoyable	85.5
2	Utilizing the MAR-Gen application can facilitate a seamless and comprehensible learning experience in genetics	87.3
3	Mobile learning-based genetic learning (MAR-Gen) uses videos, simulations, and 3D visualization to make learning more exciting and easier to understand	85.5
4	It is convenient to apply the knowledge of genetics through the utilization of MAR-Gen	88.2
5	The utilization of MAR-Gen facilitates the acquisition of knowledge and information on genetics	80.5
6	Engaging in genetics instruction through mobile learning platforms, such as MAR-Gen, fosters a heightened enthusiasm for genetics	88.2
7	Acquiring knowledge in genetics through utilizing MAR-Gen is a new experience for me	89.4
8	Mobile learning-based genetics learning using MAR-Gen enables collaborative learning opportunities	85.5
9	Mobile learning-based genetics learning using MAR-Gen adds clarity to learning material	89.4
10	Mobile learning-based genetics learning using MAR-Gen improves my thinking skills	85.5
11	Mobile learning-based genetics learning using MAR-Gen helps me understand genetic material	87.3
12	Mobile learning-based genetics learning using MAR-Gen helps me evaluate my learning process	85.5
Mean		**86.5**

4. Discussion

The current study showed a significant difference between students taught using Android-based and AR-integrated m-learning and students not taught with this media. Students who studied with MAR-Gen performed better, and their mastery of genetic concepts increased significantly.

These results are relevant to several research results [33], [34], [35], which explain that m-learning, especially AR-based, can simulate reality and help students understand complex and abstract concepts. Furthermore, application-based m-learning can make the learning process more timely and user-friendly [36], [37].

In addition, the use of videos, interactive simulations, and AR in applications allows students to understand and interpret abstract concepts [35], [38], [39]. This study's findings additionally demonstrated this media's efficacy in imparting new scientific knowledge to students in middle school. The findings of this investigation align with the outcomes of other comparable investigations [30], [31]. M-learning has a positive effect on students studying biology in general [40], [41] and genetics in particular [2].

Integrating m-learning with AR enables the depiction of content at a sub-microscopic level. This integration benefits students who encounter challenges in comprehending abstract concepts and gene-scale phenomena that necessitate visual representation. Furthermore, the integration of AR in m-learning has the potential to mitigate the development of prevalent fallacies associated with genetics. The outcomes of this study align with the conclusions drawn by several experts [21], [42], [43], [44] suggesting that the incorporation of m-learning into educational practices can enhance students' comprehension of instructional content. AR technology offers novel educational opportunities for comprehending learning material and enhancing academic performance, positively influencing students' learning outcomes [45], [46], [47], [48].

Moreover, the findings of comparable studies also demonstrate that mobile learning (m-learning) offers supplementary benefits by facilitating unattainable activities through traditional instructional methods. For instance, learners can manipulate molecules by rotating them, observing them from various perspectives, and visualizing molecules in animated three-dimensional formats [49], [50]. The utilization of three-dimensional (3D) models serves to enhance the understanding of deoxyribonucleic acid (DNA) and human body organs, resulting in a reduction of cognitive burden experienced by students [2]. Previous studies have also reached a similar conclusion, showing that incorporating 3D animation media in the experimental group yielded superior cognitive performance compared to the control group. These findings suggest that using such media facilitated enhanced student comprehension of the subject matter. The utilization of 3D media presentations has been shown to enhance the overall quality of the learning process, resulting in increased effectiveness and efficiency [51]. Research has demonstrated that using three-dimensional (3D) media has effectively enhanced students' concept knowledge and academic achievements [52].

The findings of this study showed that students who utilized m-learning-based media actively engaged and interacted with the learning materials during the integration process.

These results are corroborated by the findings of previous studies demonstrating the ability of m-learning to positively and significantly influence students' learning experience and effectiveness [48], [50]. Moreover, this study's findings indicated that using m-learning as a media for instruction could enhance favourable reactions and active engagement among students during the educational experience. These results are consistent with several findings [38], [48], [53], which concluded that m-learning positively impacted students' responses and willingness to participate actively in learning. In addition, m-learning has the potential to facilitate the integration of students into an autonomous learning setting [54]. The MAR-Gen application is available for download via the following hyperlink: https://bit.ly/MAR-Gen.

Nevertheless, this research has identified several limitations that need to be mentioned, namely:

- The m-learning-based media utilized in this study underwent a single testing phase involving two distinct groups of students. Additional experiments involving a greater sample size are required to be conducted.
- The application developed in this study exclusively encompasses a selection of genetic ideas that are typically taught in high schools in Indonesia.
- This learning application can only be installed on Android-based devices. Therefore, developing similar applications for iOS-based devices is highly recommended.
- The application's integration of simulation and augmented reality (AR) technology has limitations regarding its capacity to see objects in three dimensions (3D) effectively. Thus, additional investigation is required to obtain enhanced accurate or 4D object visualization, such as by incorporating virtual reality (VR) technology into m-learning-based media.

5. Conclusion and Recommendation

This study has demonstrated the effect of m-learning-based media MAR-Gen on the concept mastery of biology students, particularly those studying genetics-related concepts. Incorporating augmented reality in such m-learning-based media might create a valuable exploratory learning environment in which students can acquire knowledge of various genetic concepts. The results of this study also showed that the integration of m-learning and augmented reality positively and significantly affected students' concept mastery. Our analysis indicated a substantial disparity in students' understanding of genetic concepts.

Some available features, such as augmented reality scans and simulations, can considerably enhance students' genetic knowledge and proficiency. The study results also showed that the simulation and AR features could increase student response and involvement in the learning process. This impressive impact underscores the importance of simulations and AR for learning.

Based on the findings of this study, the utilization of m-learning, specifically including simulation and AR elements in genetics education, yields positive outcomes in enhancing the learning process compared to conventional approaches. This educational resource facilitates students in acquiring proficiency in genetics, particularly in understanding genetic material and the principles of heredity. In addition, m-learning media can enhance knowledge acquisition about intricate and abstract concepts, rendering these concepts more understandable and attainable for students.

In response to the current circumstances, teachers are tasked with creating innovative teaching strategies that utilize m-learning media. We also hope that the results of this research can trigger further studies on the impact of m-learning applications on the abilities and skills needed today. To accomplish this objective, gathering a substantial sample size of respondents, which may be utilized for future investigations and interviews, is imperative. It is also essential to perform comparable studies involving other concepts in biology and other scientific disciplines better to understand the strengths and weaknesses of m-learning-based media and determine the best way to integrate this learning media into the classroom. In light of our investigation, we propose that educators in science and biology incorporate m-learning as a pedagogical tool that integrates diverse characteristics, such as simulation and augmented reality, into their instructional practices. This form of media has the potential to effectively assist educators in elucidating the intricacies of genetics. As exemplified by our research, incorporating video, simulation, and augmented reality features in biology instruction can help educators teach abstract genetic concepts. These multimedia tools can captivate students' attention and facilitate a more comprehensive grasp of scientific principles.

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