

International Journal of New Media Technology

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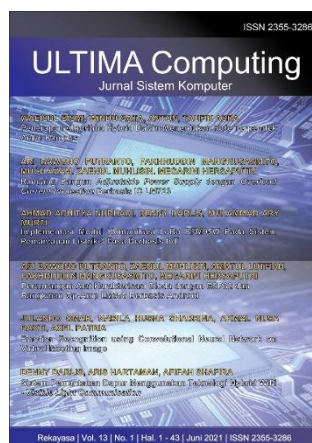
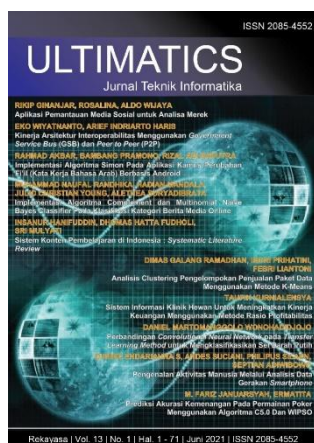


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FOREWORD

Greetings!

IJNMT (International Journal of New Media Technology) is a scholarly open access, peer-reviewed, and interdisciplinary journal focusing on theories, methods and implementations of new media technology. Topics include, but not limited to digital technology for creative industry, infrastructure technology, computing communication and networking, signal and image processing, intelligent system, control and embedded system, mobile and web based system, and robotics. IJNMT is published regularly twice a year (June and December) by Faculty of Engineering and Informatics, Universitas Multimedia Nusantara in cooperation with UMN Press.

In this June 2026 edition, IJNMT enters the 1st Edition of Volume 13 No 1. In this edition there are ten scientific papers from researchers, academics and practitioners in the fields covered by IJNMT. Some of the topics raised in this journal are: Preserving Balinese Folklore: The Development of 'The Origins of Buleleng and Singaraja' via Augmented Reality, Design and Build 3D Animation Soto Banjar Using Luther Sutopo's Method for Blender-Based Cultural Introduction, Performance Analysis of X3D-XS Architecture for Cross-Domain Real-World Violence Detection, Implementation and Evaluation of a Nutrition Information Chatbot Using UTAUT and TAM, Performance Comparison of AES and Blowfish Algorithm, Singular Value Decomposition for Deep Space Image Compression: A Hubble Case Study, Integrating Generative Artificial Intelligence in Higher Education: Opportunities, Challenges, and Pedagogical Implications, A Hierarchical Two Stage BERT Model for Cyberbullying Detection, Optimization of Posyandu Data Collection using Web Information System and Plan Do Check Act Model, An Analysis of the Knowledge-AttitudeBehavior Approach to Personal Data Security Resilience Among Students in West Java, An IoT-Based Intelligent Waste Segregation System with Real-Time Capacity Monitoring, Enhancing Operational Efficiency in FMCG Customer Care: Design and Implementation of a High-Performance Web-Based Knowledge Management System Using Next.js with Hybrid Rendering Architecture, Determinants of Student Test Scores: Academic, Family, and Learning Environment Factors a Multiple Linear Regression Analysis, Immersive Culinary Simulation With FSM-Based NPCs in a 3D Game for Promoting Sundanese Restaurants, CNN-Transformer Fusion for Indonesian Traditional Cake Recognition: An EfficientNet-ViT Approach with Grad-CAM Explainability, Enhancing Public Knowledge on Sugar Consumption Limits Through Educational Games with Fuzzy Logic Implementation

On this occasion we would also like to invite the participation of our dear readers, researchers, academics, and practitioners, in the field of Engineering and Informatics, to submit quality scientific papers to: International Journal of New Media Technology (IJNMT), Ultimatics : Jurnal Teknik Informatics, Ultima Infosys: Journal of Information Systems and Ultima Computing: Journal of Computer Systems. Information regarding writing guidelines and templates, as well as other related information can be obtained through the email address ultimajnmmt@umn.ac.id and the web page of our Journal [here](#).

Finally, we would like to thank all contributors to this June 2024 Edition of IJNMT. We hope that scientific articles from research in this journal can be useful and contribute to the development of research and science in Indonesia.

June 2026,

David Agustriawan, S.Kom., M.Sc., Ph.D.
Editor-in-Chief

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Preserving Balinese Folklore: The Development of 'The Origins of Buleleng and Singaraja' via Augmented Reality

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Abstract— This study presents the development and validation of an Augmented Reality (AR) application centered on the Balinese folklore "The Origins of Buleleng and Singaraja." Utilizing the Multimedia Development Life Cycle (MDLC) model, which includes six stages—concept, design, material collection, assembly, testing, and distribution—the research aims to enhance public engagement, awareness, and understanding of Balinese cultural heritage. The application underwent rigorous testing, including expert content validation, media expert assessment, and user response evaluation. The content and media tests, analyzed using Gregory's formula, yielded a perfect validity score of 1.00, indicating a "very high" level of accuracy and effectiveness in both historical narrative presentation and AR content delivery. User feedback, collected from 35 respondents, showed a 97.30% response rate in the "very positive" and "very good" categories, with the remaining 2.70% in the "good" category. These results demonstrate strong user approval and the potential of AR technology to preserve and promote Balinese folklore.

Index Terms— augmented reality; Balinese folklore; development.

I. INTRODUCTION

Indonesia has a rich cultural heritage, history and traditions that are of value to each generation and thus require preservation. One efficacious method for the conservation of culture is the introduction and education of that culture itself, extending to the teaching of literature [1]. The Indonesian literary tradition is replete with prose narratives [1], [2]. Some of these have been collated and subjected to critical analysis; however, a considerable number remain in the oral tradition. One of prose narratives is folktale.

The term 'folktale' denotes a type of oral tradition that has been transmitted from one generation to the next within the context of specific communities. Folktales are also a distinctive feature of each nation, reflecting its diverse cultural and historical background [3]. Folktales frequently convey ethical or moral teachings whose applicability extends beyond the realm of fiction. These are narratives from bygone eras,

transmitted orally and subsequently acknowledged on a vast scale, thus constituting a significant cultural legacy that must be safeguarded. The Balinese folktales convey a wealth of values that are integral to Balinese culture. These include the values of honesty, loyalty, dedication, and politeness. When these stories are communicated effectively and accurately, the younger generation is able to absorb them and internalize a set of values.

A multitude of Balinese folktales, encompassing a vast array of forms and variations, have been transmitted across generations. Among these, the regency of Buleleng has its own folktale, such as the "The Origins of Buleleng and Singaraja." The name "Singaraja" is thought to mean "mighty king," akin to a lion. An alternative interpretation is that the term 'Singaraja' refers to a 'king's resting place', derived from the phrase '*singgarah raja*' (king's stopover). With the passage of time, the Balinese community has gradually lost familiarity with some of its local folktales, including "The Origins of Buleleng and Singaraja." This is due to the fact that these stories are primarily documented in books, which has resulted in limited accessibility.

The prevalence of digital devices has also contributed to a decline in interest in Balinese folktales. The transmission of local folktales among the Balinese population has become less common recently, reflecting a decline in the retention of these traditional narratives. A survey on the public's knowledge of the Balinese folktale "The Origins of Buleleng and Singaraja" was conducted with 106 respondents across Bali, which provided evidence of a decline in familiarity with this particular tale. The survey was done by distributing simple survey through WhatsApp. The question of the survey only includes one question that is "Do you know The Origins of Buleleng and Singaraja folktale?" with five likert scale (not knowledgeable = 1, slightly knowledgeable = 2, neutral = 3, knowledgeable = 4, and very knowledgeable = 5). Based on the result of quantitative analysis with percentage, the survey revealed that 42.5% of respondents were unaware of the "The Origins of

Buleleng and Singaraja" folktale, 20.8% had limited knowledge, 23.6% were unsure, 7.5% knew about it, and 5.7% were very knowledgeable. The data suggests a low level of public awareness regarding the folklore of Buleleng and Singaraja, with only 7.5% of respondents claiming to be knowledgeable and just 5.7% indicating a high level of familiarity with these traditional stories. This data indicates that the folktale is still not well-known among the community.

This gap is suspected to be caused by the influence of gadgets, which is one of the reasons for the declining interest in Balinese folktales. Therefore, a potential solution to enhance public knowledge of Balinese folktales is to leverage modern technology, such as Augmented Reality (AR). It is because Augmented reality is a technology-based medium that helps individuals acquire information through engaging audio and visual elements. [4], [5]. Augmented Reality (AR) is a field of computer research that combines 3D computer graphics with the real world [6]. Several experts also elucidate, augmented reality (AR) is a technology that fuses the tangible and the virtual realms, enabling the integration of virtual objects, such as videos or images, into the physical environment in three-dimensional form [7], [8]. Augmented Reality (AR) is one of the technologies for the communication of digital images and animations [9], [10], [11], [12]. It facilitates the visualization of abstract concepts.

Augmented Reality technology is increasingly being applied across various fields, offering diverse benefits in multiple sectors. In education, Augmented Reality is used as a learning tool to visualize objects, making learning more interactive [2], [13]. Using folklore-based virtual reality as a teaching tool can enhance learning experiences and foster a deeper understanding of cultural heritage and identity [14]. In entertainment, AR is utilized for game development. In industry, it speeds up tasks, controls quality, and provides real-time data access. In medicine, AR is crucial for surgical training, vaccine development, and understanding human anatomy [15]. In preserving culture, augmented reality aids to creating interactive culture learning [4], [7], [16], [17], [18]. Developing folklore based augmented reality offers benefits such as an appealing and easy-to-use design, incorporates language games, and is accessible via smartphones [19], [20].

Several studies on Augmented Reality have been extensively analyzed and published. A study was developing folklore application with object orientation method and the MDLC (Multimedia Development Lifecycle) prototype [21]. The findings showed that the design of the Ceria Mentari application could provide a new experience for children in reading folklore through digital equipment. The central concept of this application is to make children feel closer to the folkloric characters through the medium of ARs, giving a sense of interactive learning. An interactive folklore based application was also developed by [19] which revealed that the folklore application has been validated

by multimedia and language learning experts with a product validity level of 85.5%. A combined mean score of 93.3% was obtained from the usability questionnaire. Further, [22] creating Balinese folklore through augmented reality. The content validity test results indicated that SABAR has a high validity coefficient. Feedback from both practitioners and students revealed that SABAR is user-friendly, visually appealing, and beneficial for student learning. Augmented reality also developed to present Balinese folklore "Lubdaka" [23]. An investigated study found by [24] that the questionnaire results, assessing respondents' views on the application's content, storybook illustrations, and augmented reality animations, yielded a score of 88.76%, falling into the very good category.

A review of the literature reveals that Augmented Reality (AR) has been a highly researched area. However, this study is distinctive in its focus on the development of a Balinese folktale, entitled "The Origins of Buleleng and Singaraja," through the use of Augmented Reality (AR). The selection of AR technology over other digital platforms is based on its unique ability to merge virtual elements with the real environment, thereby creating immersive and interactive learning experiences. Unlike traditional digital applications that rely heavily on static text or two-dimensional visuals, AR enhances user engagement through dynamic 3D visuals, audio components, and real-time interaction, making it particularly effective in conveying abstract cultural values and oral narratives in a more tangible and memorable manner.

Furthermore, the novelty of this research lies in its integration of a specific, localized Balinese folktale "The Origins of Buleleng and Singaraja" into an interactive AR application, which has not been previously developed or documented in existing literature. While earlier studies have focused on AR-based folklore applications in general, this research pioneers the digital transformation of a regionally significant tale that is currently experiencing a steep decline in public awareness. The application not only serves as a cultural preservation tool but also offers a culturally responsive learning medium that aligns with the current digital behaviors of society, especially among the younger generation. Thus, this study contributes both to the preservation of local heritage and the innovation of educational technology by combining traditional content with advanced immersive media. The study has two purposes: 1) to develop an Augmented Reality application about the folktale "Origins of Buleleng and Singaraja," and 2) to analyze the public's response to the AR application for this Balinese folktale.

II. METHOD

A. Design

The development of the Balinese folktale "Origins of Buleleng and Singaraja" using Augmented Reality in

this study employs a Research and Development (R&D) approach. R&D is described as a research method aimed at creating a specific product and testing the effectiveness of the produced product (Alisyafiq et al., 2021). The MDLC (Multimedia Development Life Cycle) model is an interactive learning media development model that involves six stages: Concept, Design, Material Collecting, Assembly, Testing, and Distribution (Alisyafiq et al., 2021). It could be seen in Figure 1.

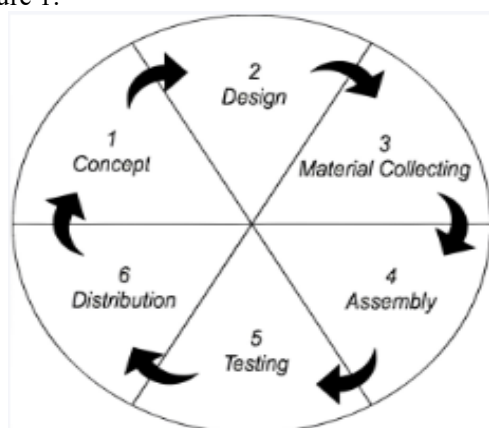


Fig. 1. Research design

The development through MDLC model can be specified explained in the following descriptions.

- **Concept**
In the concept development stage, the animation tells the story of the origins of Buleleng and Singaraja using a barcode marker. When the barcode is scanned, an animation depicting the folktale "Origins of Buleleng and Singaraja" will appear.
- **Design**
In the Design stage, the user interface layout is created as the application flow for the Augmented Reality folktale. The design flowchart outlines the user journey for interacting with the application.
- **Material Collecting**
Next, in the material collecting stage, materials needed for the application development are gathered. This includes 3D models and barcode images. The prepared materials consist of marker images, narrator voice recordings, background music, sound effects, 3D characters, and supporting backgrounds.
- **Assembly**
At this stage, the author is designing 3D characters of the Origins of Buleleng and Singaraja using Blender, Unity 3D, and Vuforia software.
- **Testing**
Subsequent to the completion of the application, the testing phase ensues. In this phase, the application is subjected to rigorous evaluation by experts in their respective fields and on a range of smartphones to assess its suitability for use in augmented reality. The testing phase encompasses a range of techniques, including

black-box testing, content expert testing, media expert testing, and user response testing.

- **Distribution**

In accordance with the MDLC model, the final stage is distribution, whereby the application is uploaded to online platforms such as the Play Store or Google Drive, ensuring its accessibility to users.

B. Instruments

The research instruments were questionnaire and the expert validity sheets (content experts and media experts). The test questionnaire is designed as a checklist with five options: Strongly Agree (SA), Agree (A), Neutral (N), Disagree (D), Strongly Disagree (SD). The objective of the test is to ensure that the folklore content within the application accurately reflects the original narrative and aligns with the specified criteria and user requirements.

The objective of content expert validity is to establish an assessment standard for the suitability of folklore content in the augmented reality application "The origins of Buleleng and Singaraja". The content expert testing process was conducted by two experts: a lecturer specializing in information technology and a lecturer specializing in history. The content expert instrument blueprint consists of three main aspects: content feasibility, language, and presentation, encompassing a total of 10 items. The content feasibility aspect covers the accuracy and alignment of the folk tale with the original version, the clarity of narrative delivery, and the logical flow of the storyline to ensure it is engaging and easy to follow. The language aspect evaluates readability, clarity of the conveyed information, and the appropriateness of language use in accordance with standard Indonesian grammar, ensuring the text is understandable for users, especially students. The presentation aspect focuses on user-friendliness, the accuracy and visual quality of 3D objects, the application's ability to present content effectively through multimedia elements, and the consistency of the presentation with the application's educational and cultural objectives.

Meanwhile, the purpose of the media expert testing is to provide a reference point for the assessment of the suitability of the augmented reality application, "The origins of Buleleng and Singaraja", in terms of media aspects, including visual elements, audio, and other related aspects. The expert review instrument comprises two main aspects: media design and software, totaling 15 indicators. The media design aspect includes several components: media suitability (marker-object alignment and layout appropriateness), text (text readability and text placement), 3D objects (clarity, appropriate size, and proper coloring), audio (clarity and relevance of narration), and navigation buttons (layout and appearance, as well as accessibility). These components aim to assess the visual, auditory, and functional quality of the augmented reality application. Meanwhile, the software aspect evaluates the operation of the application, including its smooth performance and ease of use. It

also assesses communicativeness through the accuracy of information delivery and interactivity based on the appropriateness of how information is presented to engage users effectively.

C. Data Analysis

Before the Distribution stage in the final MDLC model, data analysis will be conducted through validity testing. The participants in this research include 2 content experts, 2 media experts, and 35 respondents as users. The experts were lecturers in Ganesha University of Education who master in content or multimedia. Further, the respondents were visitors in Museum Buleleng. The participants were chosen to fulfill the response in the questionnaire. Content validity testing will be performed using two different methods: Gregory's validity formula and a Likert scale. Following this, user response to the developed AR application will be analyzed. To assess the level of achievement in the development of the Augmented Reality application, refer to Table 1.

TABLE I. PERCENTAGE OF AUGMENTED REALITY APPLICATION FEASIBILITY

No	Interval	Qualification	Criteria
1	90% - 100%	Highly positive	No revision
2	75% - 89%	Positive	No revision
3	65% - 74%	Enough	Revised
4	55% - 64%	Negative	Revised
5	0% - 54%	Highly negative	Revised

III. RESULTS AND DISCUSSION

This research has produced an Augmented Reality application for introducing the folktale of the formation of Buleleng and Singaraja, called "AR The Origin of Buleleng and Singaraja". This AR application focuses on the origins of Buleleng and Singaraja. The results of this research can be described as follows.

A. The Specification of Balinese Folklore "The origin of Buleleng and Singaraja" based Augmented reality

The application was developed through several software such as Blender 3.1.2, Unity 2019.4.12f1, Vuforia SDK (Software Development Kit), Adobe Photoshop 2022, and Adobe Illustrator 2022. The results of the initial design/interface implementation for the AR application "Origins of Buleleng and Singaraja," created using features in Unity. During the design process, there were several features in this application i.e. splash screen, menu, camera AR, and instruction. It could be seen in Figure 2 until Figure 5.

The splash screen of the Augmented Reality application in Figure 2 presents a three-dimensional visual design featuring a traditional Balinese red-brick gate as the background, symbolizing the region's cultural heritage. Centrally positioned is the title "Balinese Folktale: The Origins of Buleleng and Singaraja," displayed in a clear and visually prominent typeface to emphasize the thematic focus of the

application. Institutional logos are placed in the upper-left corner, indicating formal affiliation with relevant educational and technological entities. Additionally, animated figures in traditional Balinese attire are depicted on the right side of the screen, contributing to the cultural ambiance and enhancing the application's interactive and educational appeal.



Fig. 2. Splash Screen of the AR application for "The Origins of Buleleng and Singaraja"



Fig. 3. Main navigation screen of the AR-based Balinese Folktale Application

Figure 3 showed that The main menu interface of the Augmented Reality application is visually designed with a vibrant 3D environment that reflects traditional Balinese culture. At the center of the screen stands a prominently featured male character dressed in traditional Balinese attire, holding a ceremonial weapon, symbolizing a key figure in the folktale narrative. In the background, a group of animated villagers is depicted standing in formation near a large stone monument and lush tropical trees, reinforcing the cultural and historical setting of the story. The left side of the screen presents a vertical menu with four interactive buttons labeled: "Mulai Cerita" (Start Story), "Panduan" (Guide), "Tentang" (About), and "Keluar" (Exit), offering intuitive navigation for users. Institutional logos are displayed in the top-left corner, indicating the application's official backing. The menu design is straightforward and user-friendly, facilitating easy access to the main features of the application while maintaining cultural relevance through its visual elements.

Figure 4 illustrates the implementation of the Augmented Reality (AR) camera interface as developed in this study, utilizing the Vuforia platform for marker-based tracking. The interface projects two three-dimensional animated characters standing on a

circular virtual stage designed with traditional Balinese motifs, integrated seamlessly onto a real-world surface through a mobile device screen. This stage represents a narrative scene from the folktale *"The Origins of Buleleng and Singaraja."* Functional control icons are aligned at the bottom, enabling users to interact with the digital content, including options to rotate, zoom, or play animations.

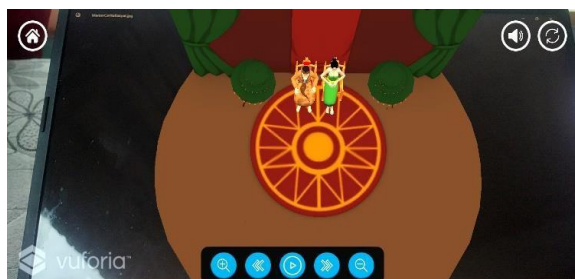


Fig. 4. Camera AR of *"The Origins of Buleleng and Singaraja"* folktale



Fig. 5. User manual of AR-based Balinese Folktale Application

The image presents the user manual interface of the AR-based Balinese folktale application. It provides step-by-step instructions for operating the augmented reality features. The manual includes directions such as selecting the story menu, preparing a marker image, choosing a language, ensuring good lighting, and scanning the marker slowly to activate the 3D content. The instructional text is displayed in a green dialog box, centrally placed against a background scene featuring animated Balinese characters and traditional architecture. This interface is designed to assist users, especially beginners in accessing and experiencing the AR content smoothly and effectively.

In addition to the application interface design, there are also 3D object designs for the Augmented Reality application *"The origins of Buleleng and Singaraja."* The application consisted of 31 scenes which described the story. The results of the 3D object designs used in the augmented reality application entitled *"Origins of Buleleng and Singaraja"*, created with the computer graphics software Blender, it is presented in Figure 6.



Fig. 6. Scene 1 and Scene 2 of *"The Origins of Buleleng and Singaraja"* folktale

Scenes 1 and 2 are set in a kingdom showcasing King Sri Bagening and Queen Ni Luh Pasek.

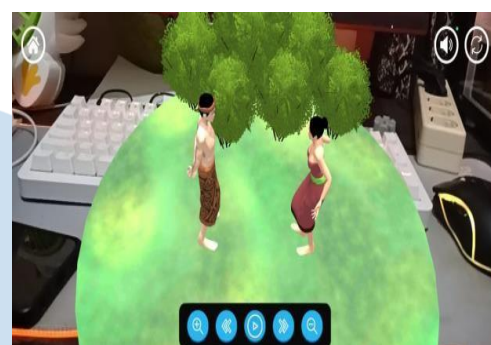


Fig. 7. Scene 3 of *"The Origins of Buleleng and Singaraja"* folktale

Scene 3 depicts the king and queen who are respected by their people.

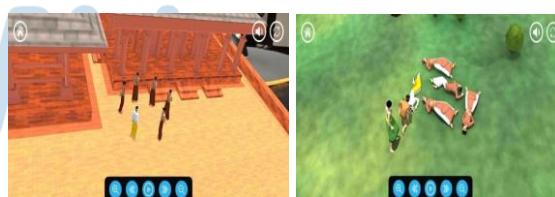


Fig. 8. Scene 4-7 of *"The Origins of Buleleng and Singaraja"* folktale

The king and queen are blessed with a son, Ki Barak Panji, who is also highly esteemed by the populace, as shown in Scenes 4, 5, 6, and 7.



Fig. 9. Scene 8 of *"The Origins of Buleleng and Singaraja"* folktale

One day, the king instructs Ki Barak Panji to travel to Den Bukit, as depicted in Scene 8.

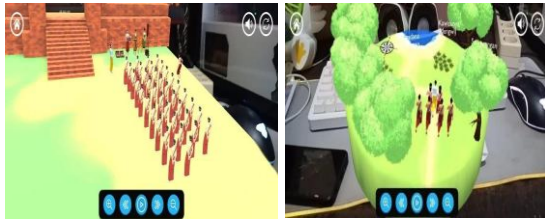


Fig. 10. Scene 9-15 of "The Origins of Buleleng and Singaraja" folktale

Ki Barak Panji, accompanied by forty guards led by Ki Dumpiung and Ki Dosot, along with his mother, embarks on their journey, which is illustrated in Scenes 9 through 15.



Fig. 11. Scene 16-17 of "The Origins of Buleleng and Singaraja" folktale

Scenes 16 and 17 introduce Panji Landung, who reveals a region that will eventually become Ki Barak Panji's domain.

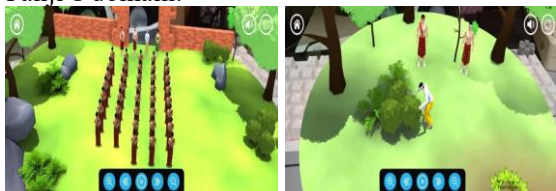


Fig. 12. Scene 18-19 of "The Origins of Buleleng and Singaraja" folktale

Then Ki Barak Panji continues his journey to the area indicated by Panji Landung, as shown in scenes 18 and 19.

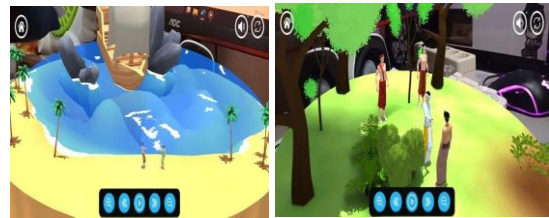


Fig. 13. Scene 20-23 of "The Origins of Buleleng and Singaraja" folktale

In Scenes 20 through 23, the character Ki Mpu Awang appears, appearing very distressed because his ship has sunk.



Fig. 14. Scene 24 of "The Origins of Buleleng and Singaraja" folktale

Then, he promises to reward anyone who helps him with all the treasures on the ship. Unable to find anyone capable, Ki Barak Panji successfully helps and receives the reward, as depicted in Scene 24.



Fig. 15. Scene 25-31 of "The Origins of Buleleng and Singaraja" folktale

With the treasure, Ki Barak Panji and his followers begin to clear the forest and establish a kingdom, portrayed in Scenes 25 through 31.

B. The Results of validity and user feasibility on the developed Augmented Reality of Balinese Folklore "The origin of Buleleng and Singaraja"

The results of this data analysis were obtained through expert feasibility tests and user response testing. The content validity results tested by content experts can be found in Table 2.

TABLE II. THE RESULTS OF CONTENT VALIDITY

Tabulated data		Judges 1	
		Irrelevant	Relevant
Judges 2	Irrelevant	(A)	(B)
	Relevant	(C)	(D)
	1,2,3,4,5,6,7,8,9,10		
Total of validity content = 1.00			

Based on the validity criteria table for content experts, a score of 1.00 indicates a "Very High" level of validity.

Further, the results of the media expert testing demonstrate an exceptionally high level of suitability. The evaluation was conducted in accordance with Gregory's formula. The results of the media expert testing are presented as follows.

$$\text{Media validity} = \frac{D}{A+B+C+D} = \frac{15}{15} = 1.00$$

The media expert testing, using Gregory's validity formula, yielded a validity score of 1.00, indicating a "Very High" level of validity.

After distributing the product of AR application which developed based on Balinese folklore, the user feasibility was measured through the data of questionnaire. A usability test was conducted to evaluate user satisfaction with the augmented reality application, "Origins of Buleleng and Singaraja." A questionnaire was distributed to the general public, particularly visitors to the Buleleng Museum, as part of the aforementioned testing. Prior to completing the questionnaire, respondents were invited to trial the application on their own devices, either their own smartphones or devices provided by the researchers. The results of questionnaire could be seen in Table 3.

TABLE III. THE DISTRIBUTION DATA OF USE FEASIBILITY OF AR APPLICATION BASED FOLKTALES

Statements	Percentage (%)				
	SD	D	N	A	SA
The application is easy to use by users	0	0	0	45.7	54.3
The application has an attractive appearance	0	0	0	40	60

The layout/design of the application is not attractive	37.1	62.9	0	0	0
The application has good audio clarity	0	0	0	48.6	51.4
The application uses appropriate audio selection	0	0	0	57.1	42.9
The application uses language that follows linguistic conventions	0	0	11.4	51.4	37.1
The application conveys information clearly	0	0	0	42.9	57.1
The application uses language that is difficult to understand	48.6	51.4	0	0	0
The application uses appropriate 3D objects	0	0	11.4	45.7	42.9
The application uses inappropriate coloring and textures on 3D objects	37.1	62.9	0	0	0
The layout of the navigation buttons is good and appropriate	0	0	2.9	51.4	45.7
The navigation buttons function properly and are easy to use	0	0	0	57.1	42.9
The application runs smoothly and properly	0	0	0	54.3	45.7
The application is quite difficult to use	45.7	54.3	0	0	0
The information in the application is delivered clearly and communicatively	0	0	0	37.1	62.9
The information in the application is relevant and interactive	0	0	2.9	45.7	51.4

The historical story in the application is difficult to understand	51.4	48.6	0	0	0
The portrayal of historical figures in the application is poor and difficult to understand	71.4	28.6	0	0	0
The application makes me interested in learning about the history of the formation of the Buleleng and Singaraja regions	0	0	0	37.1	62.9
The application makes me interested in visiting the Museum of the Origin of Buleleng and Singaraja	0	0	0	51.4	48.6
The application helps me understand the history of the formation of the Buleleng and Singaraja regions	0	0	0	22.9	77.1

Details:

SD : strongly disagree
D : disagree
N : neutral
A : agree
SA : strongly agree

The data shows that the AR application *The Origin of Buleleng and Singaraja* is perceived positively by users in terms of usability, design, clarity, and content. Most respondents agreed or strongly agreed that the application is easy to use (45.7% and 54.3%), visually appealing, has clear audio, and conveys information effectively. Negative statements such as the layout being unattractive, language being difficult to understand, or the portrayal of historical figures being poor, were predominantly disagreed with, showing positive user perceptions. The majority also found the 3D objects appropriate and the navigation buttons functional. Furthermore, the application sparked user interest in learning about history (62.9% strongly agreed), encouraged museum visits, and helped users understand the historical narrative of Buleleng and Singaraja (77.1% strongly agreed), demonstrating its educational and interactive effectiveness.

TABLE IV. THE CATEGORY OF USE FEASIBILITY OF AR APPLICATION BASED FOLKTALES

No	Response Category	Percentage (%)	Description
1	Very Positive	97.30%	Majority of users rated the application very highly, indicating strong satisfaction with the content and features.
2	Positive	2.70%	A small number of users gave a moderately positive rating, showing general approval with minor notes.
3	Neutral/Fair	0%	No respondents rated the application as average or neutral.
4	Negative	0%	No negative feedback was recorded.
5	Very Negative	0%	No respondents expressed strong dissatisfaction with the application.

The questionnaire were completed by respondents via a Google Form link integrated into one of the buttons in the AR application, or manually through the provision of a hard copy of the instrument. The responses were subsequently classified according to the following categories: The vast majority of respondents (97.30%) rated the application as "very positive" and "very good," while a smaller proportion (2.70%) rated it as "positive" and "good." These results demonstrate that users of the augmented reality application, entitled "Origins of Buleleng and Singaraja", responded favourably to the application's development.

Furthermore, the user feedback indicates that the AR application effectively facilitates comprehension of the historical development of Buleleng and Singaraja. Furthermore, the application has been instrumental in fostering public interest and awareness about the Buleleng Museum and its historical collections, particularly the origins of Buleleng and Singaraja.

C. Discussion

Based on the result, it could be implied that the content validity showed a score of 1.00, indicating a "Very High" level of validity. This means that the information and historical stories presented in the Augmented Reality application "The Origins of Buleleng and Singaraja" are accurate and appropriate. Similarly, the media validity also achieved a "Very High" validity score, reflecting the appropriateness of the media choices used in the application. Gregory's validity score of 1.00 indicated a "Very High" level of validity. The media testing evaluated aspects such as (1) media design, including component suitability, text, dimensional objects, audio, and navigation buttons, and (2) software aspects, including operation, communication, and interactivity. In contrast, user response testing involved distributing a questionnaire to the general public, specifically visitors to the Buleleng Museum, with a total of 35 respondents and

20 questions. The respondents were given the opportunity to try the application before providing feedback. According to Likert scale results, 97.30% of respondents rated the application as "very positive" and "very good," while 2.70% rated it as "positive" and "good." This indicates that users responded very favorably to the development of the Augmented Reality application.

During the testing process, the researchers received several suggestions and feedback from both media and content experts. These included adjustments to the layout of 3D objects, the initial page display of the application, and the coloring used for 3D objects in the Augmented Reality application. Additionally, the positive feedback from respondents suggests that the strengths of the application lie in its engaging and innovative presentation of the formation of Buleleng and Singaraja using Augmented Reality technology, which can attract users. The historical stories are well-aligned with actual history, delivered with high-quality audio, and presented in an easily understandable manner. These findings are supported by the results from content and media expert testing.

The validity and user feasibility revealed good and positive feedback both from experts and users. It also contributed by advantages of the design in the augmented reality. It is in agreement with numerous studies which proved that creating folklore-based augmented reality provides advantages like an attractive, user-friendly interface, includes language games, and is accessible on smartphones [20], [22]. The advantages of this AR motivate users to use the application and enhance people to read the Folklore "The Origins of Buleleng and Singaraja".

The results of this study align with findings from several previous research efforts. [21] revealed that the central concept of the folklore based augmented reality application make children feel closer to the folkloric characters, giving a sense of interactive learning. Further, [22] creating Balinese folklore through augmented reality is beneficial for people as it user-friendly, visually appealing, and beneficial for student learning. It was also aligning with [23] who developed Lubdaka AR application. The study mentioned that folklore-based AR can assist users in obtaining information about character education in the story. Augmented Reality can create a new environment by combining real-world interactions with virtual environments in real-time, making the created environment feel tangible to users.

However, the Augmented Reality application also has some shortcomings. Notably, the faces of the heroic figures depicted in the application do not accurately represent the original figures due to limited historical images or photos from that era. Enhancing the use of 3D objects and animations would greatly improve user experience. Future developments in Augmented Reality applications, especially those focusing on historical figures or regional history, should address these limitations to better serve users

and educate the younger generation on the importance of preserving and learning about history.

IV. CONCLUSION

Based on the results and discussion, it can be concluded that the development of the augmented reality application "The Origins of Buleleng and Singaraja." used the MDLC (Multimedia Development Life Cycle) model, which consists of several stages, i.e. concept, design, material collecting, assembly, testing and distribution. The process of MDLC has succeed producing attractive, user-friendly, and effective AR application. The application was distributed via Google Drive. Based on the user response testing, involving 35 respondents, indicates that the application received very positive feedback with "excellent" criteria. The questionnaire responses also revealed that the application is attractive, user-friendly, and effectively engages users in learning about the formation of Buleleng and Singaraja. Additionally, the folktale content is presented clearly, making it easy for users to understand.

Considering the study's limitations, several recommendations are made for both users and future developers. Developers should consider the application size to ensure smooth operation without issues. Furthermore, attention should be paid to the design of markers to avoid similarity between them, which will help the application accurately capture the markers and display the correct 3D objects.

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Design and Build 3D Animation Soto Banjar Using Luther Sutopo's Method for Blender-Based Cultural Introduction

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Abstract—Soto Banjar is a signature culinary heritage of South Kalimantan with deep cultural significance in Banjar society. However, its introduction to the younger generation remains limited, particularly through modern digital media. This study aims to design and develop a Blender-based 3D animation using Luther Sutopo's multimedia development method as an innovative educational medium for introducing Soto Banjar culture. The development followed the stages of conceptualization, design, implementation, and evaluation. A relatable main character named Sophie was created to represent the target audience. Character assets were sourced from Mixamo and environmental assets from Sketchfab. Evaluation involving 35 respondents showed high effectiveness (mean score 4.50/5), indicating that the animation successfully delivers cultural values in an engaging and educational manner. This work offers a novel contribution by systematically applying Luther Sutopo's method to culinary cultural preservation through 3D animation.

Index Terms—Soto Banjar; 3D Animation; Blender; Luther Sutopo; Educational Media; Local Culture.

I. INTRODUCTION

Soto Banjar holds a special position in Banjar culture, serving not only as everyday food but also as an essential element in various traditional ceremonies such as batasmiah (akikah), bakawinan (wedding feast), and baaruhan (communal prayer gathering) [1],[2],[3]. This dish embodies deep cultural values, including togetherness, respect for ancestral traditions, and the preservation of local identity passed down through generations. Beyond its distinctive flavor derived from unique spices and coconut milk, Soto Banjar functions as a social and cultural symbol that strengthens community bonds during important life events [4]. Despite its rich cultural significance, the transmission of knowledge and appreciation for Soto Banjar among the younger generation is increasingly challenged by the rapid dominance of global digital content, which often overshadows local culinary heritage and reduces opportunities for meaningful cultural engagement [5].

Previous studies on cultural promotion have largely relied on 2D media, websites, brochures, and conventional videos. These approaches, while useful, tend to offer limited interactivity and immersion, making it difficult to capture the attention of digital-native youth who prefer dynamic and visually rich experiences. Although several 3D animation [6],[7],[8],[9],[10] projects have been developed for cultural preservation in Indonesia and other countries, most of them focus primarily on tangible heritage such as traditional architecture (e.g., Banjar traditional houses), folk dances, or handicrafts, with very limited attention given to intangible cultural elements, particularly culinary heritage [11],[12].

Furthermore, many existing works lack a systematic development framework, resulting in productions that are technically impressive but less effective in achieving educational and cultural transmission goals. The application of a structured multimedia [13] development method like Luther Sutopo's in the creation of 3D animation specifically for local culinary introduction remains significantly underexplored in the literature [14].

This study addresses that research gap by developing an immersive Blender-based 3D animation using Luther Sutopo's structured multimedia development method. The main contribution of this work lies in the integration of a relatable young female character named Sophie as an audience proxy, which allows young viewers to emotionally connect with the story and content. This approach is combined with systematic development stages from conceptualization to evaluation to ensure both technical quality and educational effectiveness [15].

Cultural messages are conveyed through multiple layered strategies, including narrative integration that follows Sophie's journey of discovery, contextual visualization of traditional warung soto environments, family and ceremonial dining scenes, symbolic use of warm lighting and authentic textures, and emotional engagement through character expressions and

dialogues that evoke pride, nostalgia, and appreciation for Banjar culinary identity. By doing so, this research not only introduces Soto Banjar but also strengthens cultural awareness in a format that aligns with the preferences and consumption habits of today's younger generation [16].

II. METHODOLOGY

This research employed a Design and Development approach focused on creating educational digital media. Luther Sutopo's multimedia development method was adopted because of its clear and systematic framework, which consists of four main stages: Conceptualization, Design, Implementation, and Evaluation [17]. This method is particularly suitable for culture-based 3D animation [18] projects as it ensures a structured workflow from idea formulation to final evaluation [19],[20].

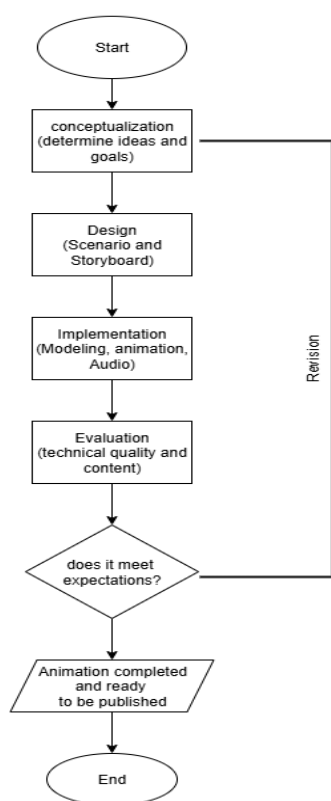


Fig 1. The Development Process of Soto Banjar 3D Animation Using Luther Sutopo's Method

A. Conceptualization

This stage involved literature review and observation to identify the cultural values, historical background, and social functions of Soto Banjar. The main goal was formulated: creating engaging 3D animation that introduces Soto Banjar to the younger generation.

B. Design

At the design stage, detailed planning was carried out to ensure the animation's narrative and visual

elements were well-structured and aligned with the research objectives. This process included scriptwriting, storyboard development, character design, and scene sequencing. The script was crafted to deliver clear cultural messages while maintaining an engaging storyline. Storyboards were created to visualize each scene, including camera angles, transitions, timing, and dialogue. Character design focused on developing Sophie as a relatable young female character who represents the target audience — the younger generation. Sophie's appearance, personality, and behavior were intentionally designed to foster emotional connection and identification, making the cultural learning experience more immersive and personal for viewers.

C. Implementation Stage

The implementation stage was carried out using Blender 3.0 software. Ready-made character assets were imported from Mixamo and further modified, while environmental assets were obtained from Sketchfab. Various technical processes were executed according to the storyboard, including 3D modeling adjustments, texture painting, material shading using node systems, rigging, keyframe-based animation, camera movement, lighting setup, and audio synchronization. All processes were conducted iteratively to ensure smooth transitions and visual consistency.

D. Evaluation Stage

Evaluation was conducted using mixed methods. A total of 35 respondents (25 students and 10 lecturers) participated through purposive sampling. A 5-point Likert scale questionnaire was used to measure four aspects: Visual Quality, Narrative Clarity, Cultural Content Accuracy, and Educational Effectiveness. Semi-structured interviews were also conducted with 8 respondents. Quantitative data were analyzed descriptively, while qualitative data were analyzed thematically.

III. RESULTS AND DISCUSSION

The implementation of Luther Sutopo's multimedia development method in this study has successfully resulted in a complete Blender-based 3D animation that effectively introduces Soto Banjar as a valuable cultural heritage of South Kalimantan. Through systematic stages from conceptualization to evaluation, the final animation product, featuring the main character Sophie, demonstrates high technical quality and strong educational potential. This section presents the technical specifications of the produced animation, key highlights of the production process, detailed evaluation results from respondents, and a critical discussion on the effectiveness of the animation as a cultural introduction medium, including its strengths, limitations, and contributions compared to previous studies.

A. Technical Specifications of the Animation

The final 3D animation of Soto Banjar was successfully developed with the following technical specifications. The animation has a total duration of 4 minutes and 45 seconds, rendered in Full HD resolution (1920×1080 pixels) at 30 frames per second using the Eevee render engine in Blender. These specifications were chosen to balance visual quality and rendering efficiency, making the animation suitable for educational dissemination across various digital platforms.

TABLE I. TECHNICAL SPECIFICATIONS OF THE SOTO BANJAR 3D ANIMATION

Specification	Details
Duration	4 minutes 45 seconds
Resolution	1920×1080 (Full HD)
Frame Rate	30 fps
Renderer	Eevee
Output Format	MP4
Hardware	Intel Core i7, 16GB RAM, NVIDIA RTX series
Average Render Time	2–8 minutes per scene

B. Production Highlights

The production process closely followed the storyboard developed in the design stage. Key activities included character modeling and customization from Mixamo assets, texture painting, node-based material shading, rigging, keyframe animation, camera and lighting setup, as well as audio synchronization. These processes are illustrated in the following figures.



Fig 2. Sophie's Character Modeling Process Using a Blender

Sophie's character is then given additional colors and visual appearance adjustments using Texture Paint. This coloring is done to adjust expressions, clothes, or facial elements to make the characters appear more alive and in harmony with the local culture represented.



Fig 3. Application of Texture Paint on Sophie's Character

Once the basic texture is applied, the next stage is to arrange the material using the node system in Shader Editor. Using Principled BSDF, the character's skin, clothing, and hair are arranged to have realistic lighting and light reflection in the scene.

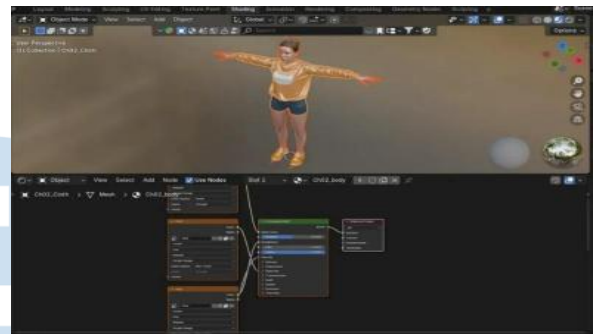


Fig 4. Sophie's Character Setup Using Shading Node

The rigging process is done by connecting bones (armature) to Sophie's character so that they can be moved in animation. Mixamo's innate bones are used, then modified in position in Pose Mode. This bone arrangement allows the character to perform with movements such as walking, sitting, and talking.



Fig 5. Rig Bone Display on Sophie's Character in Pose Mode

Sophie's character is animated by inserting a keyframe on the Blender Timeline. Movements such as stepping, turning their heads, pressing the phone, and talking are animated gradually. Movements are adjusted to the narrative dialogue and storyboard to support the storyline well.



Fig 6. Sophie Character Animation Timeline and Keyframe View in Blender

The camera is focused on Sophie's character throughout the scene. The viewing angle is adjusted so that Sophie's facial expressions and body gestures are clearly visible to the audience. Lighting is focused on the characters, both in natural light and warm light, to create an atmosphere that supports the narrative.

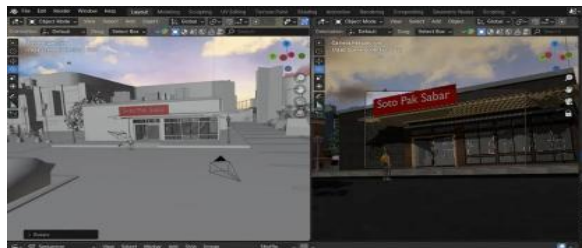


Fig 7. Camera Position and Lighting in the Warung Soto Scene

Narration audio and character dialogue are synchronized using the Video Sequence Editor. The character's lip movements are manually adjusted to fit the narrative. Sound effects such as footsteps, city sounds, and background music are added to enhance the quality of the delivery.



Fig 8. Audio and Narration Arrangement View in Video Blender Editor

Rendering is done using Eevee Renderer because it is lighter and faster. The final output is saved in MP4 format with a resolution of 1920x1080, with a frame rate of 30 fps. Each scene is rendered according to the storyboard that has been created.

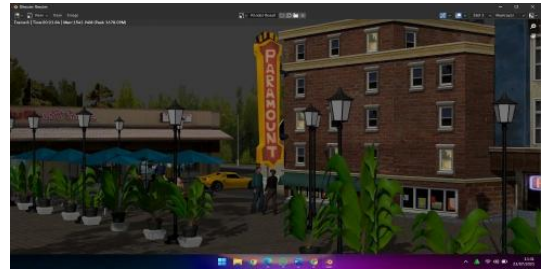


Fig 9. Scene Rendering Results Using the Eevee Engine

The final stage is done to put the scene together, add titles, and transition effects between scenes. If necessary, the final video is re-edited using an additional video editor app to ensure a balanced visual and audio result.



Fig 10. Final Rendered Animation Footage

This study demonstrates that the combination of Luther Sutopo's structured method and Blender 3D technology produces effective educational media for cultural introduction. Unlike previous studies that primarily utilized 2D animation or focused on tangible cultural heritage [11],[12], this work provides stronger character-driven storytelling and systematic development. The high evaluation scores (overall mean 4.50) confirm the animation's effectiveness in bridging traditional culture with the digital habits of the younger generation.

The success of this animation can be attributed to the integration of emotional design elements and narrative strategies [16], as well as the systematic workflow offered by Luther Sutopo's method [17]. These findings align with previous research on immersive technologies for cultural heritage preservation [15], which emphasize the importance of relatable characters and contextual visualization in enhancing audience engagement and cultural appreciation.

C. Evaluation Results

The animation received a very positive response from the respondents. As shown in Table 2, all aspects obtained high mean scores above 4.4

The highest score was obtained in the Cultural Content Accuracy aspect (4.57), indicating that the animation successfully presented the cultural values of Soto Banjar accurately. These results confirm that the use of a relatable character and immersive visualization effectively supports the delivery of cultural messages to the younger generation.

TABLE II. RESPONDENTS' EVALUATION RESULTS OF THE SOTO BANJAR 3D ANIMATION (N=35)

Aspect	Mean Score	Percentage	Interpretation
Visual Quality	4.51	90.2%	Very Good
Narrative Clarity	4.43	88.6%	Very Good
Cultural Content Accuracy	4.57	91.4%	Very Good
Educational Effectiveness	4.49	89.8%	Very Good
Overall	4.50	90.0%	Very Good

IV. CONCLUSION

This research has successfully developed a Blender-based 3D animation as an innovative educational medium for introducing Soto Banjar, one of South Kalimantan's most significant culinary heritages. By employing Luther Sutopo's structured multimedia development method, the project produced a high-quality animation that achieved strong acceptance from respondents, with an overall mean score of 4.50 out of 5. The animation effectively conveyed the cultural values of Soto Banjar through immersive visual storytelling, relatable character development, and contextual narrative that resonates with the younger generation.

The integration of a relatable main character (Sophie) combined with a systematic development process proved to be a highly successful strategy in bridging traditional cultural heritage with modern digital media. This approach not only enhanced viewer engagement but also strengthened the delivery of cultural messages regarding communal values, tradition, and local identity. Overall, the findings demonstrate that 3D animation can serve as a powerful and engaging tool for cultural preservation and education in the digital era.

For future work, several directions can be pursued to further enhance the impact of this research. The animation can be expanded into interactive formats such as Virtual Reality (VR) and Augmented Reality (AR) to provide a more immersive user experience. Additionally, the scope can be broadened to cover other traditional Banjar culinary heritage. Finally, larger-scale effectiveness studies using pre- and post-knowledge tests, along with longitudinal assessments, are recommended to measure the long-term impact of the animation on cultural awareness and appreciation among the younger generation.

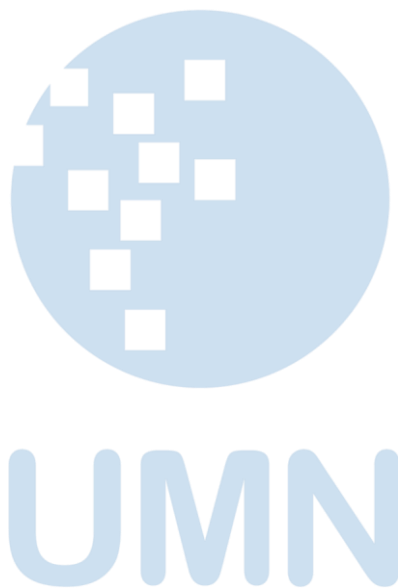
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Performance Analysis of X3D-XS Architecture for Cross-Domain Real-World Violence Detection

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Abstract— Real-time violence detection systems need models that are efficient and can adapt to different environments. This study looks at the performance of the X3D-XS architecture and focuses on the issue of generalizing across various domains. We trained the model on three controlled source domains: AVD, HockeyFight, and MovieFight. We then tested its performance on the mixed Real-Life Violence Situations (RLVS) dataset. The experimental results show that X3D-XS is highly efficient, achieving inference speeds of up to 191 FPS, which makes it suitable for edge deployment. However, the model faces significant challenges due to domain shift; training on a single domain resulted in varying accuracy between 49.5% and 61.1% on real-world data. This indicates that staged and cinematic violence differ quite a bit from real-life situations. Importantly, combining different source domains improved the model's sensitivity, leading to a Recall of 94.28%. These findings demonstrate that while X3D offers the speed needed for real-time monitoring, relying solely on staged training data is not enough for real-world effectiveness, highlighting the essential need for data diversity in surveillance applications.

Index Terms— Cross-Domain Generalization; Real-Time Surveillance; Video Violence Detection; X3D Architecture; Deep Learning; Computer Vision.

I. INTRODUCTION

The widespread use of video surveillance has changed how public safety systems operate. Millions of Closed-Circuit Television (CCTV) cameras are set up worldwide in smart cities, schools, and industrial sites. This has led to a huge amount of video data that is too much for people to handle. Research shows that human attention drops significantly after just 20 minutes of watching video feeds. This results in security incidents being overlooked [1]. As a result, there is a pressing need for smart video analytics that can spot violent activities, like assaults, riots, and physical fights, in real-time.

In recent years, the field of action recognition has moved from manual feature extraction methods like Optical Flow and HOG to Deep Learning techniques. Early Deep Learning models used 2D Convolutional Neural Networks (CNNs) with Long Short-Term

Memory (LSTM) units to capture temporal dynamics [2]. However, the arrival of 3D CNNs, such as C3D [3] and I3D [4], changed the game. These models learn spatiotemporal features at the same time, setting new performance standards. Despite their precision, traditional 3D CNNs are costly in terms of computation. They require substantial GPU resources, which are often not available in edge computing environments where surveillance systems run. This computational challenge has historically limited the use of high-accuracy 3D models in real-world security systems, forcing practitioners to settle for lower detection accuracy.

To solve the efficiency problem, Feichtenhofer suggested the X3D architecture [5]. This approach takes 2D ConvNets and extends them into 3D by improving on several factors: frame rate, duration, resolution, and network width. X3D delivers high accuracy while using much less computing power than earlier models. Although being efficient is necessary for deployment, the main issue with today's violence detection systems is not how fast they operate, but how well they generalize.

Most existing studies evaluate models using an "Intra-domain" protocol. In this setup, the training and testing data come from the same source. For example, training might happen on movie clips and testing on separate movie clips [6]. This method hides the "Domain Gap." In real-life situations, a system trained on clean, bright, or staged datasets has to work in uncontrolled environments. These environments often suffer from poor lighting, occlusion, and camera noise. This study tackles this gap by doing a "Cross-Domain" evaluation. We look at how the lightweight X3D-XS model performs when moved from controlled areas like Movies, Sports, and Surveillance to real-life surveillance footage. This transfer learning analysis sets the performance baseline needed for future research on domain adaptation techniques [18].

This study contributes to the field of intelligent surveillance by primarily validating the computational efficiency of the X3D-XS architecture, confirming its

suitability for low-latency, real-time usage on resource-constrained devices. Furthermore, the analysis quantifies the "generalization gap" by measuring the performance degradation that occurs when models trained on synthetic or staged violence are deployed in real-world CCTV environments. Finally, the research assesses the impact of data aggregation, demonstrating that combining multiple data sources significantly enhances model sensitivity (Recall), thereby ensuring that critical threats are detected despite environmental variations.

II. RELATED WORK

The progress in computer vision has greatly sped up the creation of automated surveillance systems. Early methods mainly used hand-crafted features to model human movement, but these often had difficulty capturing the complexities of crowd behavior. The shift to Deep Learning has helped overcome many of these issues by allowing for complete feature learning. However, despite these improvements, two major challenges still appear in recent studies: the high computational cost of 3D architectures and the inability to generalize across different surveillance settings. This section reviews current research on deep learning-based violence detection, efficient video architectures, and the issues of domain adaptation.

A. Deep Learning for Violence Detection

The evolution of violence detection reflects broader advancements in video understanding. Early efforts, like the Violent Flows (ViF) descriptor proposed by Hassner et al. [7], estimated crowd violence by looking at statistical changes in optical flow magnitude. With the growing popularity of deep learning two-Stream networks is introduced, which separated spatial and temporal processing [8]. Later, Tran et al. [3] showed that 3D convolutions (C3D) could effectively capture motion patterns directly from video volumes. More recently, the SlowFast network [9] used dual pathways that operate at different frame rates to capture both static semantics and fast motion. However, these models often focus on accuracy, which can come at the expense of inference speed and parameter efficiency, limiting their usefulness in large-scale surveillance systems.

Recent studies have therefore begun to emphasize efficiency-aware violence detection models that balance recognition performance with computational cost. Lightweight 3D CNN architectures and optimized spatiotemporal representations have been shown to enable real-time inference without significant accuracy degradation, making them more suitable for continuous surveillance scenarios [20], [21]. Moreover, survey-based analyses highlight that deployment feasibility, including latency and scalability, has become a critical consideration in modern violence detection research [22], [24]. In addition, comprehensive reviews on

abnormal behavior and violence detection in intelligent surveillance systems further underline the challenges of balancing accuracy and efficiency in real-world deployments [23].

B. Efficient Video Architectures

Efficiency is a key requirement for scalable video surveillance systems, especially under limited computational and energy resources. The X3D family of networks [5] was designed to balance recognition accuracy and computational efficiency through a coordinate descent strategy that expands the network along the most effective architectural dimensions, rather than uniformly increasing depth or width. This approach allows X3D to maintain strong performance while minimizing redundant computation.

Architecturally, X3D employs channel-wise separable convolutions and a multigrid expansion strategy, which significantly reduce Floating Point Operations (FLOPs) compared to conventional 3D CNN backbones such as I3D or ResNet-3D. While transformer-based models like ViViT and TimeSformer often require hundreds of GigaFLOPs, X3D-XS operates with fewer than 5 GFLOPs, making it well-suited for real-time and edge-based surveillance applications.

The growing focus on lightweight video recognition models highlights the importance of deployment feasibility alongside accuracy. Recent studies have shown that efficient 3D CNN architectures can achieve competitive performance while supporting real-time processing in surveillance environments [20], [21]. Moreover, such efficiency-oriented designs are increasingly favored in security applications that demand scalability and low latency [22]. Consequently, X3D represents an appropriate backbone for this study, supporting practical and deployable violence detection systems.

C. The Challenge of Domain Generalization

Domain adaptation is a continuing challenge in computer vision [19]. A model trained on a "Source Domain" usually performs poorly on a "Target Domain" because of changes in data distribution [10]. In violence detection, this problem is made worse by the use of datasets like MovieFight or HockeyFight. These datasets are both semantically and visually different from the Real-Life Violence Situations (RLVS) seen in public surveillance [11]. Current research focuses on learning domain-invariant spatiotemporal features to bridge this gap [17]. While recent studies look into Unsupervised Domain Adaptation (UDA), it is important to first understand the baseline performance of effective models across these domains. This understanding is essential for developing strong solutions. Recent survey studies further confirm that domain shift remains a major unresolved issue in video-based action and violence

recognition, particularly under real-world surveillance conditions [25].

III. RESEARCH METHODOLOGY

This section describes the method used to assess the performance and reliability of the proposed violence detection framework. We outline the experimental design, which includes gathering various datasets and setting up the X3D model. Additionally, the thorough training procedures and evaluation metrics presented here are designed to guarantee that the results can be replicated and that the cross-domain analysis is valid.

A. Research Framework

This study uses a quantitative experimental approach to assess how well efficient video architectures can generalize across different areas. The method is divided into three main phases:

- Data Curation**, which includes carefully categorizing the source (training) and target (testing) domains.
- Model Training**, which uses the X3D-XS architecture in single-source and multi-source aggregation scenarios.
- Performance Evaluation**, which performs zero-shot testing on new real-world data to measure the generalization gap.

B. Dataset Configuration

To clearly visualize the environmental variations and the domain shift challenge, Fig. 1 presents sample frames from the four datasets used in this study, contrasting the staged source domains with the real-world target domain.



Fig. 1. Sample frames from the datasets used in this study: (a) AVD (Real-world/CCTV), (b) HockeyFight (Sports), (c) MovieFight (Cinematic), and (d) RLVS (Target Real-Life). Note the visual diversity between the source domains and the target domain

- Source Domains (Training Sets)** These datasets represent the environments used to train the models:
 - Automatic Violence Detection Dataset (AVD)** [12]: Curated by Bianculli et al., this dataset serves as a baseline for real-world surveillance.

It consists of 350 video clips from CCTV and user-generated content. Unlike staged datasets, AVD contains real violent events. However, it is relatively small and has a specific selection bias compared to larger "in-the-wild" collections.

- HockeyFight Dataset** [13]: Representing the "Sports" domain, this dataset includes 1,000 clips of fights during ice hockey games. The motion is very focused and aggressive, but the environment is limited with uniform backgrounds (white ice), specific attire, and consistent camera angles.
 - MovieFight Dataset** [14]: This dataset represents the "Cinematic" domain and includes clips from action movies. This domain has a lot of visual noise due to staged effects and exaggerated acting. It features dramatic choreography, professional lighting, and quick editing cuts, which are quite different from continuous surveillance footage.
- Target Domain (Testing Set):**
 - Real-Life Violence Situations (RLVS)** [11]: Used only for Zero-Shot Evaluation. This dataset includes 2,000 clips collected from YouTube (CCTV, dashcams, mobile). It acts as the "Uncontrolled" target domain because of its wide range of lighting, resolution, camera stability, and background clutter.

C. Proposed Architecture: X3D-XS

The recognition model is X3D-XS (Extra Small), an efficient 3D ConvNet [5]. Unlike traditional 3D CNNs, such as C3D and I3D, which expand 2D kernels in the same way, X3D uses a coordinate descent optimization to expand the network along six specific axes, as illustrated in Fig 2, enabling efficient exploration of the model design space.

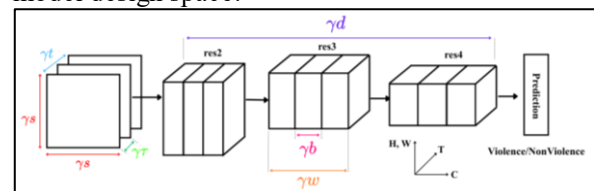


Fig. 2. Schematic of the X3D architecture expansion. The model expands a 2D ConvNet along six coarse-to-fine axes (γ). It generates efficient spatiotemporal features

- Frame Rate ($\gamma\tau$)**: The temporal sampling frequency.
- Duration (γt)**: The length of the input video clip.
- Resolution (γs)**: The spatial dimensions of the frame.
- Width (γw)**: The channel capacity of the network.
- Depth (γd)**: The number of network layers.

- f. Bottleneck (γb): The inner channel width of the residual blocks.

The X3D-XS variant comes from shrinking these axes to reduce Floating Point Operations (FLOPs) while maintaining its representational power. It uses channel-wise separable convolutions, which makes it very suitable for edge deployment. Fig 3 shows the entire processing pipeline, from the input tensor to the binary classification output.

For this study, the final classification head is adapted for binary output: Violence and Non-Violence.

D. Experimental Setup

The models were implemented using the PyTorch framework with CUDA acceleration. To ensure a thorough evaluation and reproducibility, the training environment was set up as follows:

- Optimization:** The network was optimized with the Adam optimizer and a cosine annealing learning rate scheduler to maintain stable convergence during training.
- Loss Function:** Cross-Entropy Loss was used as the objective function for the binary classification task.
- Training Protocol:** To explore the effect of data diversity, models were trained in two different scenarios: individually on each source dataset (Single-Source) and then on a combined dataset (Combination). To ensure rigorous evaluation, the datasets were partitioned using a stratified split ratio of 75:15:10 for training, validation, and testing, respectively. This split ensures that the model is evaluated on unseen data while maintaining class distribution consistency.

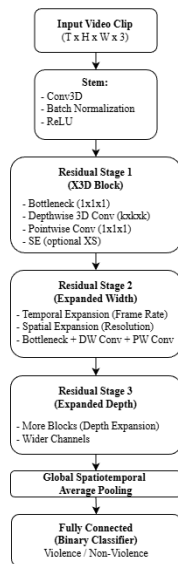


Fig. 3. Block diagram of the X3D-XS network structure used in this study. The architecture processes the input clip through a series of separable 3D convolutions and a global average pooling layer. This helps to predict the violence probability

Implementation Environment: All experiments took place on a high-performance workstation with an Intel Core i9-12900K processor (16 cores, 24 threads) and 32 GB of RAM, using an NVIDIA GeForce RTX 4090 (24 GB) for computation. To ensure reproducibility, the random seed was set to 42. This high-end hardware setup guarantees that the recorded inference latency reflects the model's best performance in a strong computational environment.

E. Evaluation Metrics

To ensure a comprehensive assessment, we evaluated the models using standard classification and efficiency metrics:

- Classification Performance** based on the confusion matrix (TP, TN, FP, FN), we calculate:

- Accuracy:** The overall correctness of predictions.

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (1)$$

- Precision:** The reliability of positive predictions, which is critical for reducing false alarms.

$$Precision = \frac{TP}{TP + FP} \quad (2)$$

- Recall (Sensitivity):** The ability to detect all violent instances and ensure no threat is missed.

$$Recall = \frac{TP}{TP + FN} \quad (3)$$

- F1-Score:** The harmonic mean of Precision and Recall.

$$F1 = 2 \times \frac{Precision \times Recall}{Precision + Recall} \quad (4)$$

- Computational Efficiency** to assess real-time viability, we measured:

- Inference Time:** Average processing time per video clip (ms).

- Throughput (FPS):** Frames processed per second.

$$FPS = \frac{Total\ Frames}{Total\ Inference\ Time\ (s)} \quad (5)$$

IV. RESULTS AND DISCUSSION

In this section, we present a detailed look at the experimental findings, divided into two main areas: computational efficiency and classification robustness. First, we demonstrate that the X3D-XS model can be used for edge deployment by measuring its inference speed. Next, we closely examine the model's ability to generalize. We look at the performance drop that occurs when transferring knowledge from controlled source domains to the unrestricted target domain, focusing on the reasons for the gap between the domains.

A. Computational Efficiency Analysis

To evaluate the practical use of the proposed framework, we measured the inference speed on a

high-performance workstation with an NVIDIA RTX 4090. Table I shows the performance metrics.

TABLE I. INFERENCE PERFORMANCE AND SCALABILITY OF X3D-XS

Model Source	Inference Latency (ms)	Throughput (FPS)	Real-Time Factor (x)
Single_AVD	5.23	191.34	6.3x
Single_Hockey	7.57	132.17	4.4x
Single_Movie	7.73	129.39	4.3x
TrainC_Comb	7.29	137.15	4.5x

The X3D-XS model achieved an average throughput of 191.34 FPS on the AVD dataset, exceeding the standard real-time requirement (30 FPS) by a factor of six. This performance confirms that the architecture is highly scalable; a single processing unit can effectively monitor multiple video streams simultaneously. Consequently, X3D-XS proves to be a viable solution for both centralized server processing and resource-constrained edge deployment, significantly lowering hardware barriers for large-scale surveillance.

B. Cross-Domain Generalization Analysis

The main finding of this study is the quantitative "Generalization Gap." Table II shows the specific performance metrics of the source-trained models. Fig. 4 offers a visual comparison that highlights the significant drop in performance when these models are used on the target RLVS dataset.

TABLE II. ZERO-SHOT CROSS-DOMAIN EVALUATION ON RLVS (TARGET DOMAIN)

Model Source	Accuracy (%)	Precision	Recall	F1-Score (Macro)	AUC
AVD	60.19	0.574	0.848	0.573	0.571
Hockey	61.17	0.671	0.467	0.604	0.669
Movie	49.51	0.503	0.924	0.369	0.448
TrainC_Comb	62.62	0.582	0.943	0.579	0.666

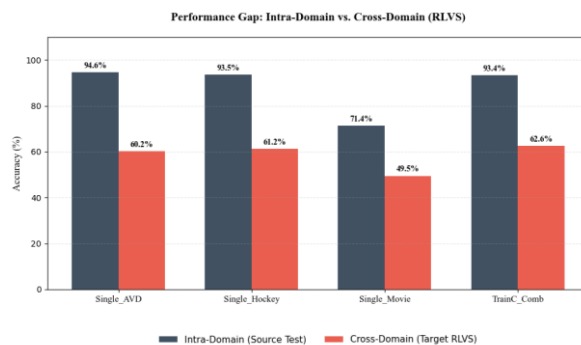


Fig. 4. Performance Gap Analysis. Comparison of expected Intra-domain performance vs. actual Cross-domain performance on RLVS

The quantitative generalization gap presented in Table II highlighting the severe performance degradation when models trained on single source domains are applied to the target RLVS dataset. The Single_Movie model performed poorly (49.51% accuracy), indicating that cinematic features such as dramatic angles and rapid editing, fail to align with the unrefined visual reality of CCTV footage. Similarly, the Single_AVD model, despite using real-world data, achieved only 60.19% accuracy. This suggests that limited-scale real data is insufficient to capture the diverse crowd densities and lighting variations present in the target domain.

However, the multi-source aggregation strategy (TrainC_Comb) successfully mitigated these limitations, achieving the highest accuracy and a significant Recall of 94.28%. By exposing the model to a diverse range of violent motions—from sports grappling to surveillance anomalies—the system developed a higher sensitivity to threats. In a safety-critical context, this improvement is vital, as a high-recall system ensures that genuine threats are rarely missed (minimizing False Negatives), even if it incurs a slight trade-off in Precision.

C. Implications and Prospects for Generalization

The experimental results provide important insight into the learning dynamics of the X3D architecture, showing its limitations and potential.

a. The Promise of Data Diversity: The combined model (TrainC_Comb) showed a clear improvement trend, moving from individual lows to the highest cross-domain metrics. This indicates that the limitation lies not in the lightweight X3D architecture's capacity, but in the homogeneity and small scale of the individual training domains. The notable difference between the Single_Movie model (49.51% Accuracy) and the combined model (62.62% Acc) highlights that model failure can be overcome by diversifying the input data. This finding is encouraging: the efficiency of X3D can work well in real-world applications if provided with a diverse training set.

b. Qualitative Analysis and Safety-First Deployment: A qualitative analysis of the failure cases shows that the high Recall (94.28%) reflects a "safety-first" approach. The model effectively identifies rare violent acts, such as those happening in chaotic crowds or poor lighting. However, this sensitivity affects Precision, as the model often flags non-violent, high-motion activities (False Positives). In practice, this is a favorable failure mode, since human intervention can quickly address a false alarm, while missing a real threat (False Negative) is costly. This confirms that the multi-source training strategy prepares the X3D model for immediate alerts.

- c. Future Trajectory: The finding that X3D-XS can achieve a high recall rate with high throughput makes a strong case for cost-effectiveness. Since data diversity is the main bottleneck, future work should focus on implementing new learning approaches, such as Unsupervised Domain Adaptation (UDA). UDA, using methods like Adversarial Domain Alignment, can take advantage of the large amounts of unlabelled real-world surveillance footage. This will help X3D align its feature embeddings with the target RLVS domain, effectively closing the accuracy gap (from 62.62% to an acceptable level) without losing speed or incurring the high computational costs associated with heavy 3D architectures.

V. CONCLUSION

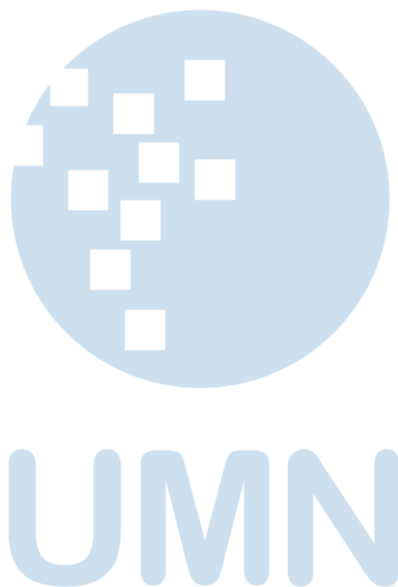
This study thoroughly examined the trade-off between efficiency and generalization using the X3D-XS architecture for video violence detection. We confirmed that the architecture is highly suitable for real-time edge computing, achieving a throughput of up to 191 FPS, which allows for cost-effective multi-stream processing on centralized servers. However, a significant generalization gap was observed during the zero-shot cross-domain evaluation. Training on a single domain resulted in lower accuracy, specifically 49.51% for the MovieFight dataset, indicating that reliance on choreographed or limited-scope data leads to failures in unconstrained environments like RLVS.

Importantly, the results demonstrate that a multi-source aggregation strategy significantly mitigates this failure by increasing Recall to 94.28%, suggesting that the primary limitation lies in data variability rather than the architecture itself. While X3D proves to be an excellent choice for deployment due to its efficiency, its practical success relies on robust data integration. Future research should focus on cost-effective data strategies, particularly Unsupervised Domain Adaptation (UDA) techniques, to align features from diverse sources with the target domain and address the remaining accuracy gap for deployable public safety systems.

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Implementation and Evaluation of a Nutrition Information Chatbot Using UTAUT and TAM

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Abstract— This study aims to evaluate the use of a Telegram-based question-answering chatbot for accessing nutrition information using the UTAUT and TAM approaches to measure user intention and behavior. The system utilizes LangChain and Large Language Models (LLMs) to deliver rapid and precise nutrition-related replies. Validity and reliability assessments were performed to confirm that the measurement equipment exhibited optimal consistency, with Cronbach's Alpha values surpassing 0.7. The multiple linear regression results demonstrate that Effort Expectancy (EE) and Social Relationship (SI) significantly affect Behavioral Intention (BI), whereas Performance Expectancy (PE), Perceived Usefulness (PU), and Perceived Ease of Use (PEOU) reveal no substantial relationship. The findings indicate that usability and social impact are more pivotal in enhancing users' propensity to use the chatbot than system utility and efficiency.

Index Terms— Question Answering; LangChain; UTAUT; Behavioral Intention.

I. INTRODUCTION

The rapid growth of artificial intelligence (AI), particularly in Natural Language Processing (NLP) and Large Language Models (LLMs), has significantly transformed how information is accessible and communicated in a variety of fields, including healthcare, education, and public services. The question-answering chatbot is one of the most popular AI applications, allowing users to receive instant, automated, and interactive responses through natural language interaction. Chatbots have demonstrated significant potential in healthcare for information distribution, decision assistance, and public awareness, particularly in areas that require frequent and accessible consultation, such as nutrition information.

In the healthcare sector, researchers investigated the use of Retrieval-Augmented Generation (RAG) and Mistral 7B to deliver more accurate, data-driven replies regarding Indonesian medicinal plants [1]. The results showed that this strategy successfully increased the quality of responses delivered by the chatbot. A Telegram-based question-and-answer system to disseminate information about Health Law No. 17 of 2023, which uses LangChain and LLMs, plays a role in

accelerating this process [2]. The system was assessed using the BERTScore, which showed satisfactory performance in delivering relevant and correct responses.

Similar technological apps have been developed for Islamic studies to help people grasp tafsir and fiqh. A Telegram-based chatbot system that can be used to answer questions on Ibn Kathir's Tafsir [3]. Their findings show that the use of LangChain and LLMs can help provide extremely accurate replies; however, further enhancements are required to attain optimal outcomes. As a similar work, using GPT-3.5, can create a Qur'anic question-and-answer system [4]. Their findings suggest that this approach may provide speedy responses with an accuracy rate of 78.85%, despite issues with answer relevancy and the possibility of disinformation (hallucination).

A question-and-answer system for purification (fiqh of ṭahārah) with LangChain and LLMs suggests that AI technology can improve public knowledge of Islamic legal rulings in more efficient and accessible ways [5]. Another related study created a Telegram-based chatbot to deliver knowledge about Prophet Muhammad's (peace be upon him) hadiths using LangChain and GPT-4 [6]. The study discovered that the method was effective at providing extremely correct replies based on pertinent hadiths.

Furthermore, a study on chatbot applications for public service organizations investigated the use of RAG and vector databases to increase the correctness of responses to regulatory documents [8]. Their research found that LLM-based systems can deliver more relevant replies based on official laws. In another study, the application of LangChain and GPT-4 was examined in Qur'anic exegesis, notably the Tafsir of Ibn Kathir [9]. Their results indicate that, while the Telegram-based chatbot may generate generally appropriate responses, further work is needed to increase contextual comprehension and accuracy. Whereas a web-based health sector chatbot utilizing a LangChain Retriever was also generated [10].

Despite the increasing usage of chatbot technologies in healthcare-related context, there is still a significant study gap in terms of user acceptance and behavioral intention toward AI-based nutrition

information systems. Most present research focuses on the technical performance, response accuracy, or architectural design of LLM-based chatbots, with little attention paid to experimentally studying the aspects that influence users' adoption, intention to use, and sustained use of such systems. This disparity emphasizes the necessity for a systematic evaluation approach that not only examines system functionality but also explains user behavior and technology adoption.

This study descends within the research areas of artificial intelligence, health informatics, and technology acceptability research. The novelty of this research lies in integrating a Large Language Model-based nutrition information chatbot with a complete acceptance evaluation framework that includes the Unified Theory of Acceptance and Use of Technology (UTAUT) and the Technology Acceptance Model (TAM). Their complementary strengths motivated the use of UTAUT and TAM in this study. UTAUT presents a strong paradigm for explaining user acceptance, drawing on social and organizational characteristics such as Performance Expectancy, Effort Expectancy, Social Influence, and Facilitating Conditions. In contrast, TAM focuses on users' cognitive perceptions, notably Perceived Usefulness and Perceived Ease of Use, which are critical in understanding how users access system advantages and usability. By combining these two models, this study provides a more complete and nuanced explanation of the social-contextual and individual-perceptual aspects that influence users' behavioral intention to utilize an AI-based nutrition chatbot. This integrated approach improves explanatory power and adds theoretical depth to the body of research on technology acceptability in AI-driven health information systems.

The scope of this study is defined as follows:

- Although most existing studies primarily emphasize system architecture, response accuracy, or technical performance, there is limited empirical evidence explaining the factors that influence users' acceptance and behavioral intention toward nutrition information chatbots, particularly those deployed on widely used messaging platforms such as Telegram.
- Previous research rarely considers both social-contextual factors and individual cognitive perceptions when assessing user adoption of AI-based nutrition systems, indicating the lack of a comprehensive acceptance model that explains why users are willing or unwilling to adopt nutrition chatbots powered by large language models.
- The primary research problem addressed in this study is how important determinants from the UTAUT and TAM frameworks affect users'

behavioral intention to use a Telegram-based nutrition information chatbot.

II. METHODOLOGY

The study approach begins with a literature review on the usage of Telegram-based chatbots using LangChain and LLMs for question-answering systems. The nutritional information was then gathered to use as the chatbot's knowledge base. Next, a data requirements analysis and the selection of an acceptable language model were performed. The system architecture includes the creation of a Telegram-based chatbot using LangChain and LLM technologies, which RAG assists in improving answer accuracy, as demonstrated in the study by [11]. The system was then implemented in accordance with the planned design, utilizing the same process as [12] when constructing a legal chatbot with Mistral 7B and RAG. Finally, the UTAUT and TAM models were used to evaluate the system's performance in providing accurate and relevant nutrition information and to assess user acceptance. The overall research workflow is presented in Fig. 1.

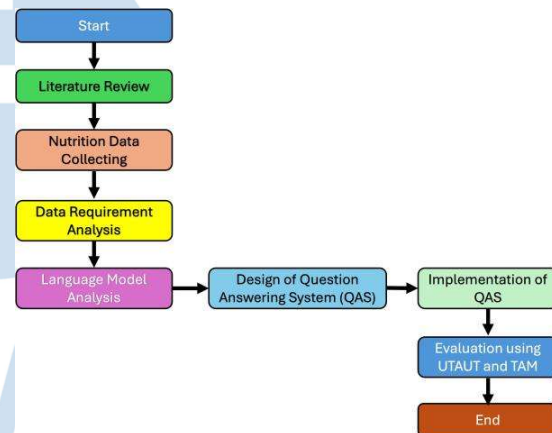


Fig. 1. Research stage

A. Literature Review

The data gathering process began with a literature review, which involved examining relevant studies [13] that developed an LLM-based chatbot for student admissions information using FAISS and Sentence Transformers to improve response relevance. Another related study employed LangChain in a question-answering system for the Fiqh of the Four Madhabs, leveraging LLMs to generate responses from PDF-based textual sources [14].

Nutrition-related data was acquired to create the chatbot's knowledge base, which was then analyzed using language models to ensure response relevancy. LangChain was used to create a quick and context-aware question-and-answer system, and its efficacy was assessed using the UTAUT and TAM models [15], [16].

B. Nutrition Data Collecting

The nutrition data utilized in this study were sourced from a publicly available dataset maintained on Kaggle, the Indonesian Food and Drink Nutrition Dataset. This dataset, which offers complete nutritional information for Indonesian food and nutrition items, is available on the Kaggle repository.

The dataset contains detailed features for each food item, such as its name, category, calorie content, protein, fat, and carbohydrate levels, as well as descriptive information, health advantages, and flavor characteristics. A total of 1,346 food entries is provided, reflecting a diverse range of popular Indonesian dishes and beverages [3]. This dataset was chosen because it is relevant to the research environment, has complete nutritional features, and is suitable for constructing a nutrition-focused question-and-answer system. The data were preprocessed and saved in a MySQL database before being transformed to textual format for use as the knowledge base for the LangChain-based Retrieval-Augmented Generation (RAG) technique. This approach allows the chatbot to efficiently obtain contextually relevant nutrition information and provide accurate responses to user requests.

C. Data Requirement Analysis

The data requirements analysis stage seeks to identify data that is relevant and supportive of the investigation. The data collected, and the selection procedure focused on nutrition information, featuring various aspects, including product, category, nutritional content, and additional supplemental information. This data was then converted to a text (.txt) file format, which contained the critical information required to build the knowledge base for the chatbot-based question-answering system. Like approaches used in the blockchain domain to develop chatbots that integrate external data through Retrieval-Augmented Generation (RAG) to enhance answer relevance and accuracy, this study optimizes the use of external data to enrich the chatbot's knowledge and improve the accuracy and timeliness of nutrition-related information provided [17].

D. Language Model Analysis

Language model analysis was used to establish the best LLM for the question-answering system. To handle nutrition-related data, the researchers used OpenAI's GPT-3.5 Turbo with the LangChain framework, which allowed for automatic answer generation and storage of the results in a vector store as a knowledge base. This technique is consistent with the work of [18], who utilized GPT-3.5 and LangChain to provide feedback on student business ideas, and employed LangChain and LLMs to develop a question-answering system on contemporary Islamic law [19], AI in Education [20] and cinema industry [21]. In this work, LangChain handles data processing and query

handling to produce accurate and contextually relevant responses, where embeddings and vector stores accelerate information retrieval.

E. Design of Question-Answering System (QAS)

The design of the question-answering system includes processing nutrition-related data to generate responses using a Telegram-based chatbot. This procedure uses GPT-3.5 Turbo in conjunction with LangChain to ensure answer accuracy, and the processed data is saved in a vector store as a knowledge base to provide rapid and contextually relevant responses. Fig. 2 illustrates the architecture of the question-answering system, covering the entire workflow from the acquisition of nutrition information data to the delivery of responses to users through the Telegram chatbot.

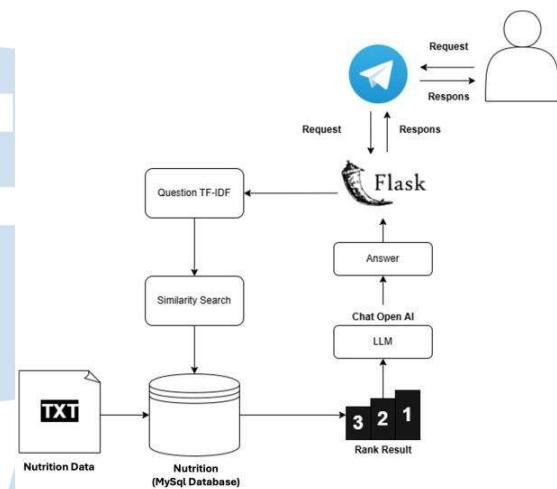


Fig. 2. Telegram chatbot architecture

F. Implementation of Question-Answering System (QAS)

The database in this system was implemented using the Python programming language, which includes various libraries that help question-answering system development, such as LangChain. LangChain is a framework that allows Large Language Models (LLMs) to respond appropriately to contextual input. The nutrition information is saved in the Knowledge Base. In the next stage, the researchers used Flask to create an API service that serves as the backend for the question-answering system [3]. This system features a Telegram-based chatbot interface that serves as a question-answering platform, serving as a link between users and the system. One major advantage of the Telegram chatbot is that it is simple to create and can be accessed immediately from the Telegram client.

G. Evaluation of Question-Answering System (QAS) using UTAUT and TAM

This study evaluates the question-answering system using the UTAUT and TAM models through investigating seven main elements that influence users' intentions and behaviors when using a LangChain- and LLM-based Telegram chatbot. The suggested chatbot system was evaluated using a survey of 100 undergraduate students participating in the Nutrition Study Program at a private university in Indonesia. The respondents were chosen because they are potential users with a basic understanding of nutrition and experience with digital information systems.

The respondents' target age range was 18 to 25, which is common for undergraduate university students. This age group was chosen because it represents active users of mobile messaging platforms like Telegram and is thought to be appropriate for evaluating chatbot-based information systems.

The questionnaire was made available online through Google Forms, allowing respondents to participate voluntarily and conveniently. The poll link was distributed by several academic communication channels, including class group chat systems. Prior to complete distribution, a pilot test with ten respondents was conducted to ensure the questionnaire items' clarity, validity, and reliability. Responses were gathered anonymously to ensure confidentiality and prevent response bias.

The evaluation includes the following factors:

- Performance Expectancy (PE) has a strong positive effect on Behavioural Intention (BI), showing that users believe the chatbot will improve their efficiency when accessing nutrition information.
- Effort Expectancy (EE) significantly and favorably influences Behavioural Intention (BI), reflecting users' perceptions of the chatbot's ease of use.
- Social Influence (SI) has a favorable effect on Behavioural Intention (BI), implying that support from others, such as nutrition experts or peers, can improve users' willingness to utilise the chatbot.
- Facilitating Conditions (FC) have a large and favorable influence on Behavioural Intention (BI), whereas supporting conditions such as internet availability and suitable chatbot functionality encourage system utilization.
- Perceived Usefulness (PU) has a strong positive impact on Behavioural Intention (BI), indicating that users believe the chatbot will improve access to nutrition information.
- Perceived Ease of Use (PEOU) has a positive relationship with Perceived Utility (PU),

implying that ease of use influences users' evaluations of the chatbot's utility.

The findings indicate that simplicity of use, perceived utility, and social impact are all important factors in molding users' intentions and behaviors while getting nutrition information through the chatbot.

III. RESULT

A. Data Collection and Analysis Results

The researchers gathered nutritional data from a Kaggle source <https://www.kaggle.com/datasets/anasfikrihanif/indonesian-food-and-drink-nutrition-dataset>, which includes numerous Indonesian items and their nutritional content. The data imported into the MySQL database was then analyzed to identify and choose key nutritional features. This analysis yielded important attributes such as food name, protein, fat, carbs, and calories, which were then used in the study. Table 1 presents an example of the data contained in the MySQL database used to power the nutrition chatbot. The data contains information about numerous types of food, such as nutritional value, brief descriptions, linked health benefits, and flavor qualities.

The data in Table 1 serves as the foundation for the chatbot to generate nutrition-related responses to user inquiries. With an organized data structure, the chatbot may make food recommendations based on user preferences or specific nutritional requirements. Furthermore, the table enables developers to update or expand the dataset as needed, keeping the system relevant and helpful. Understanding the structure and content of this table will allow the nutrition chatbot to provide more accurate and useful responses, as well as improve the overall user experience when accessing health and dietary information.

B. System Design Results

At this stage, the question-answering system was developed using OpenAI's GPT-3.5-Turbo language model integrated with the LangChain framework. The workflow began by retrieving nutrition data in text format, which was subsequently stored in a MySQL database. The data was preprocessed to detect similarities with user searches using the TF-IDF approach, and the processed query was sent to Flask for additional processing. Flask then sent the question to the OpenAI LLM, which generated a meaningful response. The resulting answers were sorted according to their relevance and then provided to users through the Telegram network, as depicted in Fig. 2. The next step was to link them with the Telegram chatbot.

TABLE I. NUTRITION DATA

id	A combination of the food item and its nutritional attributes (protein, fat, carbohydrates, and calories)	Description	Benefit	Taste
[1]	shredded meat contains 280 kcal, 9.2 g of protein, 28.4 g of fat, and 0 g of carbohydrates	shredded meat is a food product with nutritional contents of.....	This food contains protein that helps support vital physiological functions.....	The taste of shredded meat is generally savory, salty, and slightly spicy...
[..]				
[1346]	Yogurt contains 52 calories, 3.3 grams of protein, 2.5 grams of fat, and 4 grams of carbohydrates...	Yogurt is a food product with a caloric content of 52.0 kcal...	This food contains protein that supports essential bodily functions...	The taste of this food varies depending on its base ingredients ...

C. Implementation Results

The architecture of the question-answering system that had been designed was then implemented in two aspects: database implementation and user interface implementation.

- **Database Implementation:** Fig. 3 shows the database implementation results, which are delivered as an API service. This service was designed to handle and efficiently access data within the chatbot system.
- **User Interface Implementation:** Fig. 4 depicts the user interface for interacting with the Telegram chatbot. Users can submit nutrition-related inquiries by entering the /askgizi command, followed by their query. The designed interface enables users to access information efficiently and intuitively. Users are only required to enter their inquiry following the /askgizi command, after which the chatbot will provide a relevant response.

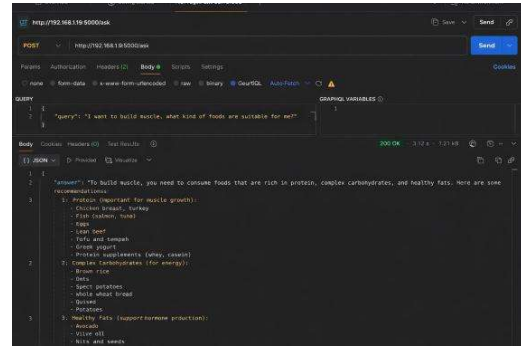


Fig. 3. API service output display

D. Question-Answering System Evaluation

1) Assessment Instruments and Questionnaires.

The evaluation was conducted to determine the level of acceptance and usefulness of the Telegram-based chatbot question-answering system that provides nutritional information to users. This assessment employs an approach that combines the Unified Theory of Acceptance and Use of Technology (UTAUT) and the Technology Acceptance Model (TAM). A questionnaire was distributed to 100 respondents, consisting of students from the Nutrition Study Program at a private university. The questionnaire consists of 21 items, organized into seven categories, with each category comprising three elements. Using a 5-point rating scale, respondents selected one of five answer options: strongly agree (SA), agree (A), neutral (N), disagree (D), or strongly disagree (SD). Table 2 lists the questionnaire items.

Table 2 delineates the questionnaire items employed to assess the Telegram-based chatbot system according to the seven fundamental constructs of UTAUT and TAM. Each construct quantifies a distinct dimension, including Performance Expectancy (PE), which pertains to perceived advantages and productivity; Effort Expectancy (EE), which gauges usability; and Social Influence (SI), which appraises social pressure or motivation. Furthermore, Facilitating Conditions (FC) evaluate the accessibility of resources and knowledge, Perceived Usefulness (PU) gauges the system's utility, Perceived Ease of Use (PEOU) assesses the simplicity of interaction, and Behavioral Intention (BI) quantifies users' intent to persist in utilizing and endorsing the chatbot.

2) Descriptive Statistics

Descriptive statistics were used to summarize the respondents' responses to questionnaire items related to the research variables. The data were further analyzed using SPSS software. The results of the analysis were presented in a table for each construct and questionnaire item. The mean values were used to assess respondents' level of agreement with each item, whilst the standard deviation reflected the variability or dispersion of replies for each item. Table 3

summarizes the descriptive data for the questionnaire items.

TABLE II. QUESTIONNAIRE ITEMS BASED ON UTAUT AND TAM CONSTRUCTS

Construct	Questions
Performance Expectancy (PE)	This chatbot helps me complete tasks more quickly
	I feel that this chatbot increases my productivity
	This chatbot is useful in supporting my needs
Effort Expectancy (EE)	This chatbot is easy to use without requiring additional guidance
	I feel comfortable using this chatbot for daily tasks
	Learning to use this chatbot is easy for me
Social Influence (SI)	People around me support the use of this chatbot
	The use of this chatbot is recommended by my colleagues or friends
	My social environment influences my decision to use this chatbot
Facilitating Conditions (FC)	I have adequate resources (such as devices or internet access) to use this chatbot.
	I have sufficient knowledge to use this chatbot.
	Technical support is available if I encounter issues with this chatbot.
Perceived Usefulness (PU)	I feel that this chatbot is helpful in completing my work
	This chatbot improves the quality of my work
	This chatbot provides significant benefits to me
Perceived Ease of Use (PEOU)	This chatbot is easy to learn and understand
	I find interactions with this chatbot very simple
	I do not need to put much effort into using this chatbot.
Behavioral Intention (BI)	I plan to use this chatbot regularly in the future
	I am interested in recommending this chatbot to others
	I would like to use this chatbot for other purposes

Table 3 displays the distribution of scores from 100 respondents, with mean values ranging from 2.47 to 3.67, demonstrating a preference for neutral to positive replies. The standard deviations vary from 0.652 to 1.443, indicating significant heterogeneity in answers. Variables with smaller standard deviations suggest greater consistency, whereas those with larger values show greater variety in respondents' assessments. Overall, while the means are close to three, there are significant disparities in respondents' experiences and perceptions.

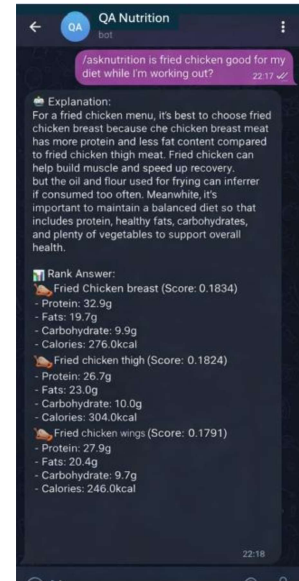


Fig. 4. Question-Answering Interface Display

TABLE III. DESCRIPTIVE STATISTICS FOR UTAUT AND TAM CONSTRUCTS

	N	Minimum	Maximum	Mean	Std. Deviation
PE1	100	1	5	2.95	1.132
PE2	100	1	5	2.90	.893
PE3	100	1	5	2.77	1.213
EE1	100	2	5	3.07	1.008
EE2	100	1	5	2.87	.960
EE3	100	1	5	2.72	1.443
SI1	100	1	5	2.96	.942
SI2	100	2	5	3.21	1.047
SI3	100	1	5	2.83	1.256
FC1	100	1	5	3.30	.893
FC2	100	2	5	3.10	.969
FC3	100	2	5	3.44	1.057
PU1	100	2	5	2.87	1.012
PU2	100	1	5	2.74	1.330
PU3	100	1	5	2.47	1.167
PEOU1	100	1	5	3.17	1.288
PEOU2	100	2	5	3.36	1.087
PEOU3	100	1	5	3.09	.830
BI1	100	1	5	3.67	.652
BI2	100	1	5	3.60	.778
BI3	100	1	5	3.48	1.123

3) Validity.

The validity test found substantial correlations among items within each variable and between each item and the total variable score (p-values < 0.01). All variables show good consistency in measuring their intended constructs. Table 4 shows the results of the validity test.

TABLE IV. CORRELATIONS AMONG ITEMS AND BETWEEN ITEMS AND TOTAL VARIABLE SCORES

Variables	Item	Correlation Among Items and Between	Correlation Between Item and Total Score
PE	PE1	PE1 - PE2: 0.784 PE1 - PE3: 0.727	0.910
	PE2	PE2 - PE1: 0.784 PE2 - PE3: 0.817	0.929
	PE3	PE3 - PE1: 0.727 PE3 - PE2: 0.817	0.927
EE	EE1	EE1 - EE2: 0.824 EE1 - EE3: 0.924	0.960
	EE2	EE2 - EE1: 0.824 EE2 - EE3: 0.848	0.924
	EE3	EE3 - EE1: 0.924 EE3 - EE2: 0.848	0.977
SI	SI1	SI1 - SI2: 0.869 SI1 - SI3: 0.865	0.949
	SI2	SI2 - SI1: 0.869 SI2 - SI3: 0.865	0.953
	SI3	SI3 - SI1: 0.865 SI3 - SI2: 0.865	0.961
FC	FC1	FC1 - FC2: 0.852 FC1 - FC3: 0.843	0.950
	FC2	FC2 - FC1: 0.852 FC2 - FC3: 0.795	0.935
	FC3	FC3 - FC1: 0.843 FC3 - FC2: 0.795	0.939
PU	PU1	PU1 - PU2: 0.905 PU1 - PU3: 0.805	0.955
	PU2	PU2 - PU1: 0.905 PU2 - PU3: 0.782	0.956
	PU3	PU3 - PU1: 0.805 PU3 - PU2: 0.782	0.914
PEOU	PEOU1	PEOU1-PEOU2: 0.887 PEOU1 - PEOU3: 0.884	0.974
	PEOU2	PEOU2 - PEOU1: 0.887 PEOU2 - PEOU3: 0.826	0.951
	PEOU3	PEOU3 - PEOU1: 0.884 PEOU3 - PEOU2: 0.826	0.935
BI	BI1	BI1 - BI2: 0.613 BI1 - BI3: 0.687	0.863
	BI2	BI2 - BI1: 0.613 BI2 - BI3: 0.534	0.807
	BI3	BI3 - BI1: 0.687 BI3 - BI2: 0.534	0.902

Overall, Table 4 demonstrates that most items within each variable have very high correlations, both

among themselves and with the total scores, indicating that the items are good at assessing their intended dimensions. However, the BI variable has lower inter-item correlations than the other factors.

4) Reliability

The reliability test findings present that the instrument is reliable, since Cronbach's Alpha values for most of the variables evaluated surpass 0.7. Table 5 summarizes the Cronbach's Alpha values for all variables.

TABLE V. CRONBACH'S ALPHA FOR EACH VARIABLE

Variables	Cronbach's Alpha
Performance Expectancy (PE)	0.902
Effort Expectancy (EE)	0.934
Social Influence (SI)	0.943
Facilitating Conditions (FC)	0.933
Perceived Usefulness (PU)	0.929
Perceived Ease of Use (PEOU)	0.936
Behavioural Intention (BI)	0.792

Cronbach's Alpha is used to determine the internal consistency of measurement equipment. Cronbach's Alpha values greater than 0.7 suggest that the measurement device has good to acceptable reliability. Although the Behavioral Intention (BI) variable has a somewhat lower value of 0.792, it remains within an acceptable range for accurate measurement. Overall, the reliability test shows that the instrument has strong internal consistency, with Cronbach's Alpha values more than 0.7 for all variables examined, validating its suitability for this study.

5) Multiple Linear Regression Test.

This section examines the influence of Performance Expectancy (PE), Effort Expectancy (EE), Social Influence (SI), Perceived Usefulness (PU), Perceived Ease of Use (PEOU), and Facilitating Conditions (FC) affect Behavioral Intention (BI) when utilizing a chatbot system. The multiple linear regression findings reveal the extent to which these characteristics influence users' intent to employ the chatbot. The regression analysis results are summarized in a Table VI. Table VI presents the standardized coefficients, significance values, and the impact of relationships among the UTAUT and TAM variables.

As shown in Table VI, Effort Expectancy (EE), Social Influence (SI), and Facilitating Conditions (FC) have a significant positive effect on Behavioral Intention (BI). In contrast, Performance Expectancy (PE) and Perceived Usefulness (PU) do not significantly influence BI. Furthermore, Perceived Ease of Use (PEOU) does not significantly affect Perceived Usefulness (PU).

IV. CONCLUSION

The findings of the multiple regression analysis determine that users' intention to develop the nutrition information chatbot is primarily affected by effort expectancy, social influence, and facilitating factors. Conversely, performance anticipation and perceived

usefulness exhibit no significant impact on behavioral intention. Despite the system being regarded as user-friendly, the perceived ease of use has a compelled impact on perceived utility, indicating that usability alone is insufficient to influence users' assessments of system advantages.

TABLE VI. SUMMARY OF REGRESSION ANALYSIS RESULTS FOR UTAUT AND TAM VARIABLES

No	Relationship	β (Standardized)	t-value	p-value	R ²	Decision
1	Performance Expectancy (PE) → Behavioral Intention (BI)	0.176	1.769	0.080	0.031	Not Supported
2	Effort Expectancy (EE) → Behavioral Intention (BI)	0.551	6.541	0.000	0.304	Supported
3	Social Influence (SI) → Behavioral Intention (BI)	0.348	3.672	0.000	0.121	Supported
4	Facilitating Conditions (FC) → Behavioral Intention (BI)	0.505	5.799	0.000	0.255	Supported
5	Perceived Usefulness (PU) → Behavioral Intention (BI)	-0.125	-1.245	0.216	0.016	Not Supported
6	Perceived Ease of Use (PEOU) → Perceived Usefulness (PU)	-0.032	-0.316	0.753	0.001	Not Supported

The results reveal that social encouragement, ease of interaction, and the presence of supportive technological conditions are more essential than functional performance in influencing user intention within the UTAUT and TAM frameworks.

Future research could broaden this study by including more diverse user groups besides university students, comparing different large language model architectures or chatbot platforms, and incorporating additional variables like trust, privacy, or information quality to better understand user adoption of AI-based nutrition information systems.

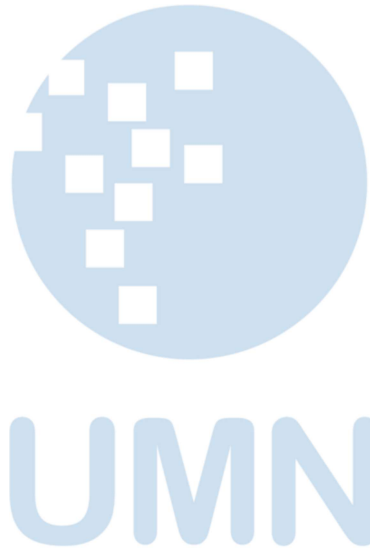
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Performance Comparison of AES and Blowfish Algorithm

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Abstract— The rapid advancement of communication and data storage technologies requires security systems capable of protecting sensitive information from cyber threats. Symmetric cryptography algorithms such as AES and Blowfish are widely used, although they exhibit different performance characteristics. This study compares both algorithms based on processing time, memory usage, and throughput on .txt, .pdf, and .zip files. The testing was conducted through Python implementation using ECB and CTR modes. The results show that AES consistently outperforms Blowfish in terms of speed and throughput. For large files, AES using ECB mode reaches a throughput of 1128.42 MB/s, significantly higher than Blowfish using ECB mode at 92.26 MB/s, with faster encryption time as well, AES using ECB mode within 0.075 seconds while Blowfish using ECB mode within 0.928 seconds. The decryption process shows similar results, where AES using CTR mode achieves 546.70 MB/s, while Blowfish using CTR mode reaches only 81.59 MB/s. Overall, AES is more suitable for fast encryption-decryption on large-scale data processing, whereas Blowfish is more appropriate for small files or low-complexity applications.

Index Terms— AES; Blowfish; cryptography; encryption algorithm; performance comparison

I. INTRODUCTION

The rapid development of digital communication and data storage has increased the risk of cyber threats and large-scale data breaches, making data security a major concern for organizations and governments [1], [2]. Cryptography plays a crucial role in protecting sensitive information by ensuring data confidentiality and preventing unauthorized access [3], [4]. Among cryptographic approaches, symmetric encryption is widely used due to its efficiency, with Advanced Encryption Standard (AES) and Blowfish being two prominent algorithms [5].

AES and Blowfish have different design structures and performance characteristics. AES is a modern encryption standard known for its high security and efficiency, whereas Blowfish offers flexibility through its variable key length and simple structure [6], [7], [8]. Previous studies comparing symmetric encryption algorithms such as AES, 3DES, and Blowfish show

that Blowfish may achieve better performance and throughput, while AES remains superior in terms of security against various threats [9]. Although previous studies suggest Blowfish outperforms AES and 3DES, further research is necessary because performance results vary depending on implementation context, system architecture, and data size. Additionally, earlier works often neglected the impact of modes of operation, which can significantly influence both performance and security, making a more comprehensive evaluation essential.

Therefore, this study focuses on a comparative performance analysis of AES and Blowfish based on encryption and decryption time, memory usage, and throughput on Electronic Codebook (ECB) and Counter Mode (CTR) mode to determine the most suitable algorithm for modern information security systems. ECB is still included in this research as a baseline because it provides maximum performance with minimal computational overhead, allowing direct evaluation of the raw efficiency of encryption algorithms [10], [11]. However, its known security weaknesses highlight the importance of comparing it with more secure modes like CTR to understand the trade-off between performance and security.

The urgency of this research lies in the increasing demand for efficient and secure encryption mechanisms that can adapt to different system requirements. Modern computing environments, including cloud computing, mobile systems, and Internet of Things (IoT) devices, require encryption algorithms that not only provide strong security but also maintain high performance in terms of processing speed and resource consumption [8], [12]. Choosing an inappropriate algorithm may lead to inefficiency, excessive resource usage, or even potential security risks [13]. Therefore, it is essential to identify which algorithm performs better under certain conditions.

A comparative approach is used in this research because it provides a systematic method to evaluate and analyse the strengths and weaknesses of different algorithms under the same conditions. By directly comparing AES and Blowfish using identical datasets,

hardware environments, and evaluation parameters, the research can produce objective and measurable results. This approach allows researchers to identify performance differences in terms of encryption and decryption time; measure efficiency based on throughput and resource utilization; and evaluate scalability when handling different data sizes.

Moreover, a comparative study is important because theoretical advantages of algorithms do not always reflect their real-world performance. For instance, an algorithm that appears efficient in theory may perform differently when implemented in a specific programming environment or hardware architecture. Through empirical testing, this research aims to bridge the gap between theoretical design and practical implementation.

In addition, the comparison between AES and Blowfish is particularly relevant because they represent two different cryptographic design approaches: AES with its substitution-permutation structure [14] and Blowfish with its Feistel network [15]. Analysing these differences contributes not only to performance evaluation but also to a better understanding of how algorithm design impacts efficiency and security.

Therefore, this research is expected to provide valuable insights into the performance and suitability of AES and Blowfish, helping developers, researchers, and organizations make informed decisions when selecting encryption algorithms for their systems.

II. LITERATURE REVIEW

Several previous studies have evaluated the performance of various encryption algorithms in different application contexts. The study in [16] compares 3DES, AES, Blowfish, and RSA in cloud data storage and classification, demonstrating that Blowfish achieves the fastest encryption performance, while RSA exhibits the highest computational cost in both time and memory usage. Similarly, [17] highlights the efficiency of AES compared to RSA, showing that AES maintains significantly faster and more stable encryption times across varying data sizes, whereas RSA performance increases linearly with input size. These findings suggest that symmetric algorithms are generally more suitable for applications requiring high speed and efficiency.

Further research has explored the comparative performance of other symmetric algorithms. The study in [18] compares Blowfish and Twofish in terms of time and space complexity, showing that Blowfish excels in processing speed, while Twofish offers better memory efficiency. These results indicate that algorithm performance is often influenced by trade-offs between speed and resource consumption.

Another study [19] evaluates multiple AES variants (Rijndael) with Serpent, and Twofish on Android devices, demonstrating that Rijndael provides the best overall performance in terms of encryption speed and CPU usage. Meanwhile, Serpent and Twofish show advantages in memory efficiency and encryption strength, as measured by the avalanche effect. This highlights that the selection of cryptographic algorithms should depend on specific application requirements, including performance, memory efficiency, and security level.

Despite these extensive studies, existing literature still lacks comprehensive evaluation of AES and Blowfish in the context of modern cryptographic challenges, particularly when considering different modes of operation and resistance to evolving attack techniques. Therefore, this research aims to further investigate the performance and resilience of AES and Blowfish under contemporary conditions, providing a more complete understanding of their effectiveness in modern cryptographic applications.

III. RESEARCH METHODOLOGY

This section presents the research methodology employed in this study, covering the experimental workflow, hardware and software specifications, test data setup, implementation of encryption and decryption processes, performance evaluation metrics, and data analysis techniques to ensure the validity and reliability of the findings. The comparison is conducted by measuring encryption time, decryption time, memory usage, and throughput under controlled experimental conditions, which are commonly used performance metrics in cryptographic evaluation [21].

A. Experimental Workflow

AES and Blowfish are implemented using a uniform key length of 256 bits to ensure an equivalent security level during evaluation, as adopted in several prior studies on file encryption [9]. Both algorithms are tested using two block cipher modes of operation, namely ECB and CTR, which are commonly applied in symmetric cryptographic systems [22], [23]. The experimental approach is used to measure and evaluate the performance of both algorithms based on several parameters, including encryption time, decryption time, memory usage, and throughput.

The experiments are conducted by implementing AES and Blowfish algorithms in a graphical user interface (GUI) based application. This application is designed to perform encryption and decryption processes while automatically recording performance metrics. The results obtained from these experiments are then analysed to identify performance differences between the two algorithms under various testing conditions. The steps for this research can be seen in Figure 1.

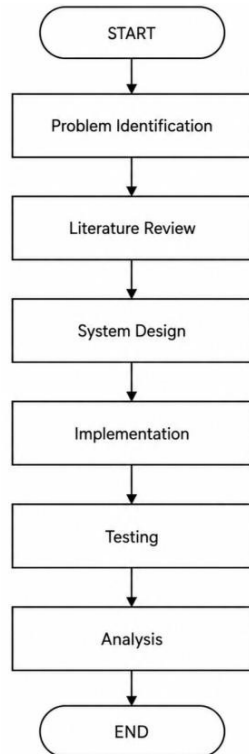


Fig. 1. Experimental Workflow

The research method of this study consists of several stages, which are as follows:

- **Problem Identification:** Identification of the problems that occur is carried out.
- **Literature Review:** A literature review is conducted to understand the concepts of cryptography, symmetric encryption, and the characteristics of AES and Blowfish algorithms.
- **System Design:** A GUI based system is designed to facilitate file selection, encryption, decryption, and performance measurement.
- **Implementation:** AES and Blowfish algorithms are implemented in two operating modes, ECB and CTR, using the Python programming language.
- **Testing:** Encryption and decryption tests are performed on different types and sizes of files to collect performance data including running time, memory usage, and throughput.
- **Analysis:** The collected data are analyzed to compare the performance of AES and Blowfish based on predefined parameters.

B. Hardware and Software Specification

To ensure consistency and reliability of the experimental results, this research was conducted using a specific hardware and software configuration. The specifications are summarized in the Table 1 and Table 2.

TABLE I. HARDWARE SPECIFICATION

Component	Specification Description
Processor (CPU)	Intel Core i5
Memory (RAM)	16 GB
Storage	1 GB SSD
Operating Device	Laptop

The hardware used in this research consists of a computer system equipped with an Intel Core i5 processor, sufficient RAM capacity, and solid-state storage to support efficient encryption and decryption processes.

TABLE II. SOFTWARE SPECIFICATION

Software Component	Specification Description
Operating System	Windows 10 (64-bit)
Programming Language	Python
Development Tools	Visual Studio Code
Cryptography Library	PyCryptodome
Supporting Software	Microsoft Excel for analysis

The system was implemented using Python programming language, supported by cryptographic libraries and development tools to facilitate encryption, decryption, and performance measurement.

C. Test Data Setup

The test data used in this study consist of digital files with common formats, namely *.txt, *.pdf, and *.zip. These file types are selected because they represent different data characteristics. File sizes are classified into three categories [19], [21]:

- Small files: ≤ 100 KB
- Medium files: 100 KB – 5 MB
- Large files: > 5 MB

This classification aims to observe the impact of file size variations on the performance of AES and Blowfish algorithms.

D. Encryption and Decryption Process

The encryption and decryption processes are conducted using AES and Blowfish algorithms with ECB and CTR modes of operation. Both algorithms use a 256-bit key to ensure an equal level of security during performance comparison. For CTR mode, a counter value combined with a nonce is used to generate a keystream, while ECB mode encrypts each plaintext block independently using the same key.

To validate functional correctness, the decrypted output is compared with the original file to ensure data integrity, as applied in prior cryptographic implementation studies [24]. Each file is encrypted and subsequently decrypted using the same secret key. During these processes, the system records encryption time, decryption time, memory usage, and throughput.

E. Performance Evaluation Parameters

The performance of AES and Blowfish is evaluated based on the following parameters [9]:

- **Encryption Time:** The time required to encrypt a file, measured in seconds.
- **Decryption Time:** The time required to decrypt an encrypted file back to its original form.
- **Memory Usage:** The amount of memory consumed during encryption and decryption processes.
- **Throughput:** The rate at which data is processed during encryption or decryption, measured in MB/s.

F. Data Analysis Technique

The collected experimental data are analysed using comparative analysis techniques. Performance results of AES and Blowfish are compared across different file types, file sizes, and modes of operation (ECB and CTR). The analysis focuses on identifying performance trends, efficiency differences, and suitability of each algorithm for practical data security applications.

IV. RESULT AND ANALYSIS

This chapter presents experimental results and provides a comprehensive discussion of the performance evaluation of the AES and Blowfish.

System Design

B.

The system workflow is designed to provide a complete benchmarking cycle, starting from data input, encryption-decryption processing, performance measurement, and ending with flexible output handling and result visualization. This design ensures both usability and comprehensive evaluation of the encryption algorithms. The system workflow can be seen in Figure 2.

The system begins when the user selects a plaintext file as input. After selecting the file, the user initiates the process by clicking the “Run Benchmark” button. The system then performs the encryption process using the selected algorithm and mode of operation, followed by the decryption process to validate correctness.

During this process, the system measures key performance metrics such as encryption time, decryption time, and throughput. Once the process is completed, the output results are displayed to the user.

After viewing the results, the user is provided with several options, including saving the output to an Excel file, displaying performance graphs, saving the resulting file (either ciphertext or plaintext), performing an additional decryption process, or resetting all inputs. If the user chooses to decrypt a file, the system executes the decryption process and displays the resulting plaintext. The workflow ends after all selected operations are completed.

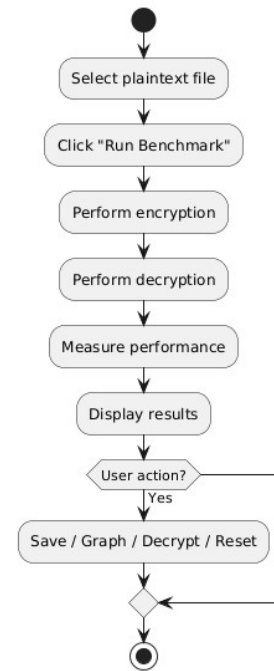


Fig. 2. System Workflow of Encryption and Decryption Benchmark Process

Implementation

The AES and Blowfish algorithms are implemented using the PyCryptodome library in the Python programming language. Figure 3 shows the results of the program implementation.

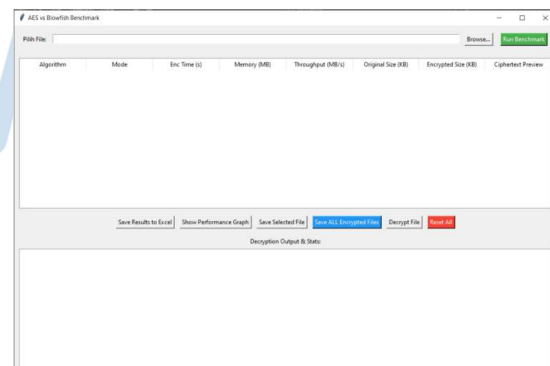


Fig. 3. Program implementation result

Testing and Analysis

This chapter presents the results of performance testing. The evaluation was performed using *.txt, *.pdf, and *.zip, which represent small, medium, and large file sizes.

1) Encryption Performance Analysis

The experimental findings reveal that AES consistently outperforms Blowfish in encryption time

and throughput across all evaluated file types, indicating its superior efficiency in handling diverse data formats.

Algorithm	Mode	Enc. Time (s)	Memory (MB)	Throughput (MB/s)	Original Size (KB)	Encrypted Size (KB)	Ciphertext Preview
AES	ECB	0.000244	0.000000	57.44	14.35	14.35	b'k+^jbdm3w&1x19)y8B)y8e+)
AES	CTR	0.000133	0.000000	105.50	14.35	14.35	b'y82)ya0y13 0y01)yffw0M)y

Fig. 4. Testing result of encryption using AES on *.txt* file

The test results of the AES algorithm on a **.txt* file with an original size of 14.35 KB using ECB and CTR are presented in Figure 4. The results indicate that the AES-CTR mode demonstrates significantly superior performance in terms of speed. Specifically, AES-CTR achieved a throughput of 105.50 MB/s, which is nearly twice as fast as AES-ECB, which only reached 57.44 MB/s. This performance advantage is also reflected in the encryption time, where AES-CTR requires only 0.000133 seconds, compared to AES-ECB, which takes 0.000244 seconds.

Algorithm	Mode	Enc Time (s)	Memory (MB)	Throughput (MB/s)	Original Size (KB)	Encrypted Size (KB)	Ciphertext Preview
Blowfish	ECB	0.000200	0.000000	69.95	14.35	14.35	b'k+^jbdm3w&1x19)y8B)y8e+)
Blowfish	CTR	0.000171	0.000000	81.74	14.35	14.35	b'y82)ya0y13 0y01)yffw0M)y

Fig. 5. Testing result of encryption using Blowfish on *.txt*

On the other hand, using the same text file, the results indicate that the Blowfish-CTR mode demonstrates superior performance compared to Blowfish-ECB. Specifically, Blowfish-CTR achieves a throughput of 81.74 MB/s with an encryption time of only 0.000171 seconds. In contrast, Blowfish-ECB exhibits lower performance, with a throughput of 69.95 MB/s and a slightly longer encryption time of 0.000230 seconds. In this experiment, both ECB and CTR modes of Blowfish recorded negligible memory usage, measured at approximately 0.000000 MB, indicating minimal memory overhead during the encryption process.

Tables III–V summarize the encryption performance comparison between AES and Blowfish for different file types, where Table III corresponds to **.txt* files, Table IV to **.pdf* files, and Table V to **.zip* files.

TABLE III. ENCRYPTION PERFORMANCE ON TXT FILES

Algorithm	Mode	Enc. Time (s)	Memory (MB)	Throughput (MB/s)
AES	ECB	0.000244	0.000000	57.44
AES	CTR	0.000133	0.003906	105.50
Blowfish	ECB	0.000200	0.000000	69.65
Blowfish	CTR	0.000171	0.000000	81.74

TABLE IV. ENCRYPTION PERFORMANCE ON PDF FILE

Algorithm	Mode	Enc. Time (s)	Memory (MB)	Throughput (MB/s)
AES	ECB	0.001276	1.511719	1179.27
AES	CTR	0.002264	1.507812	664.43
Blowfish	ECB	0.017928	1.507812	83.91
Blowfish	CTR	0.018114	1.507812	83.05

For **.pdf* files, AES consistently demonstrates superior performance compared to Blowfish. AES-ECB achieves the fastest encryption time of 0.001276 seconds with a throughput of 1179.27 MB/s, followed by AES-CTR at 0.002264 seconds and 664.43 MB/s. In contrast, Blowfish requires considerably longer processing times, resulting in significantly lower throughput, confirming AES's efficiency advantage for larger and more complex file types.

TABLE V. ENCRYPTION PERFORMANCE ON ZIP FILE

Algorithm	Mode	Enc. Time (s)	Memory (MB)	Throughput (MB/s)
AES	ECB	0.075952	85.707031	1128.42
AES	CTR	0.112998	85.707031	758.47
Blowfish	ECB	0.928997	85.707031	92.26
Blowfish	CTR	0.976330	85.769531	87.78

For **.zip*, the performance gap becomes more pronounced. AES-ECB achieves an encryption time of 0.075952 seconds with a throughput of 1128.42 MB/s, whereas AES-CTR records 0.112998 seconds with 758.47 MB/s. Blowfish, on the other hand, requires significantly longer encryption times of 0.928097 seconds (ECB) and 0.976330 seconds (CTR), with throughput values limited to 92.26 MB/s and 87.78 MB/s, respectively.

For small sized files such as **.txt*, both algorithms exhibit similar performance; however, AES in CTR mode achieves the highest throughput. In medium-sized files such as **.pdf*, AES demonstrates significantly faster encryption times and higher throughput compared to Blowfish. This performance gap becomes more pronounced when processing large files (**.zip*), where AES shows superior efficiency, especially in ECB mode. These results indicate that AES scales more effectively when handling large datasets, making it more suitable for applications involving high-volume data encryption.

2) Decryption Performance Analysis

The decryption performance results show a similar trend to the encryption results. AES, particularly in CTR mode, records shorter decryption times and higher throughput compared to Blowfish across all file types. For small text files, the decryption time difference between the two algorithms is minimal. However, for medium and large files, AES

demonstrates a clear advantage in terms of processing speed and throughput. Tables IV-VI present the decryption performance comparison between AES and Blowfish for *.txt, *.pdf, and *.zip files.

TABLE VI. DECRYPTION PERFORMANCE ON TXT FILE

Algorithm	Mode	Dec Time (s)	Memory (MB)	Throughput (MB/s)
AES	ECB	0.004384	0.023438	3.20
AES	CTR	0.006108	0.355469	2.29
Blowfish	ECB	0.000390	0.000000	35.90
Blowfish	CTR	0.001122	0.015625	12.49

For *.txt files, AES-CTR completes decryption in 0.0006 seconds, while Blowfish-CTR requires 0.0011 seconds. Although both algorithms perform quickly for small files, AES remains faster. *D*.

TABLE VII. DECRYPTION PERFORMANCE ON PDF FILE

Algorithm	Mode	Dec. Time (s)	Memory (MB)	Throughput (MB/s)
AES	ECB	0.007883	1.507812	190.83
AES	CTR	0.002411	1.507812	623.92
Blowfish	ECB	0.024608	1.507812	61.13
Blowfish	CTR	0.029752	1.507812	50.56

In *.pdf files, AES-CTR records a decryption time of 0.0024 seconds with a throughput of 623.92 MB/s, whereas Blowfish-CTR requires 0.0029 seconds with a throughput of 50.56 MB/s.

TABLE VIII. DECRYPTION PERFORMANCE ON ZIP FILE

Algorithm	Mode	Dec. Time (s)	Memory (MB)	Throughput (MB/s)
AES	ECB	0.173287	85.707031	494.59
AES	CTR	0.156770	85.707031	546.70
Blowfish	ECB	0.987407	85.707031	86.80
Blowfish	CTR	1.050477	85.769531	81.59

For *.zip files, AES-CTR completes decryption in 0.15 seconds with a throughput of approximately 546–546.70 MB/s, while Blowfish-CTR requires 1.05 seconds with a throughput of only 81.59 MB/s.

Additionally, the file sizes after decryption are identical to the original file sizes across all tests, confirming that the decryption process successfully restores the original data without any loss or modification.

3) Memory Usage Analysis

The memory usage analysis shows that both AES and Blowfish exhibit relatively similar memory consumption during the encryption and decryption processes. The measured memory usage ranges from

approximately 0.000000 MB to 85.769531 MB, depending on the type and size of the input file processed. This variation indicates that memory usage is primarily influenced by file characteristics rather than the choice of encryption algorithm.

Furthermore, the results suggest that neither AES nor Blowfish introduces significant additional memory overhead beyond the baseline requirements of the input data. The similarity in memory consumption across both algorithms implies that memory efficiency is not a distinguishing factor in their overall performance. Instead, the observed performance differences, particularly in encryption time and throughput, are more strongly attributed to differences in algorithm structure and computational efficiency rather than memory utilization.

Discussion

The combined visualization (Figure 6) illustrates the overall performance comparison between AES and Blowfish across different file types (TXT, PDF, and ZIP) and processes (encryption and decryption) in terms of execution time, throughput, and memory usage.

The results show that AES consistently exhibits superior performance, particularly for medium and large file sizes, where it achieves significantly lower execution times and substantially higher throughput compared to Blowfish. The higher throughput achieved by AES indicates its ability to process data more efficiently within a shorter time period, making it more suitable for applications that require high-speed data processing and real-time security. AES performs better than Blowfish in throughput and execution time due to its optimized substitution-permutation structure and hardware acceleration support, which enable more efficient parallel processing compared to the more complex key scheduling and Feistel structure of Blowfish. This performance gap becomes more pronounced as the file size increases, indicating that AES has better scalability and computational efficiency.

In contrast, Blowfish demonstrates relatively stable but slower performance, especially for larger datasets such as ZIP files. Meanwhile, memory usage remains relatively consistent between both algorithms and is primarily influenced by the size of the input file rather than the encryption method. Blowfish may only be competitive in scenarios involving smaller data sizes.

Although this study primarily focuses on performance evaluation, security aspects are inherently considered through the selection of algorithms and modes of operation. AES is widely recognized as a secure standard encryption algorithm, while Blowfish, although efficient, has known limitations such as its

smaller block size. Furthermore, the inclusion of ECB and CTR modes provides an implicit security comparison, as ECB represents a less secure baseline, whereas CTR offers stronger protection against pattern leakage and supports secure implementation in modern systems.

To address this limitation, this study emphasizes that performance and security are closely interconnected, and the choice of encryption technique must account for both factors simultaneously. The results highlight that while some configurations may achieve higher speed (e.g., ECB), they do so at the expense of security, whereas modes such as CTR provide a better balance between efficiency and security. Therefore, the findings of this research not only contribute to performance benchmarking but also provide insight into the practical security implications of selecting specific algorithms and modes of operation.

Overall, the findings suggest that AES is more appropriate for modern information systems that demand both high security and high computational efficiency, such as cloud storage, secure communication systems, and large-scale data processing platforms. Blowfish remains a viable alternative for applications involving small file sizes or

environments with lower computational complexity requirements.

V. CONCLUSIONS

This study demonstrates that the evaluation of cryptographic algorithms must consider both algorithm design and mode of operation, as performance outcomes are strongly influenced by their interaction. While AES consistently outperforms Blowfish in terms of encryption speed, decryption time, and throughput, the findings also indicate that performance alone is not sufficient for determining algorithm suitability. Instead, an appropriate balance between efficiency, scalability, and security must be considered, particularly when selecting modes such as ECB and CTR that introduce different trade-offs.

The results further highlight that memory usage is relatively similar between AES and Blowfish, suggesting that computational efficiency (rather than resource consumption) is the primary factor distinguishing their performance. In this context, AES combined with more secure and efficient modes (e.g., CTR) provides a more practical solution for modern applications that require both high-speed processing and robust security. Conversely, although Blowfish shows stable performance, its advantages are more limited to specific scenarios with less demanding performance requirements.

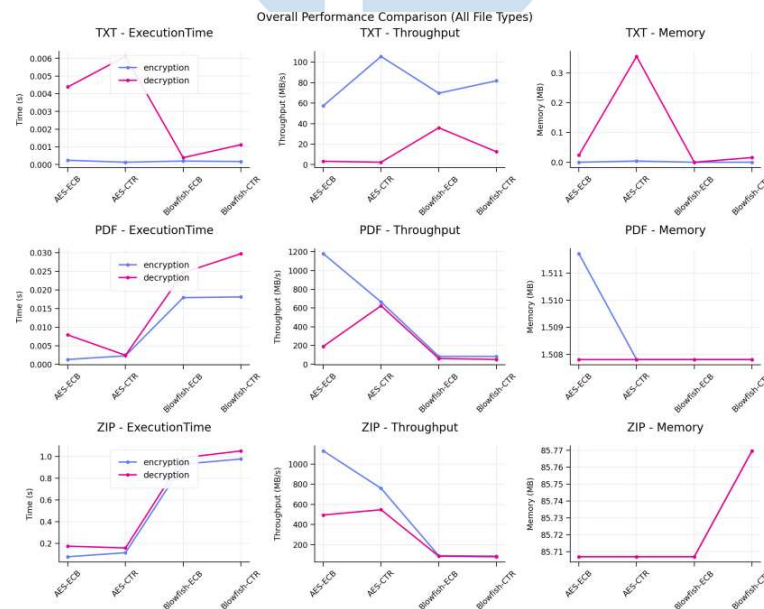


Fig. 6. Overall performance comparison of AES and Blowfish across different file types (TXT, PDF, and ZIP) for both encryption and decryption processes

From a practical standpoint, this research provides guidance for system designers and developers in selecting encryption strategies tailored to application needs, such as high-throughput systems, real-time communication, or resource-constrained

environments. Academically, this study contributes by emphasizing the importance of evaluating cryptographic algorithms together with their modes of operation, offering a more realistic representation of

real-world implementations rather than isolated algorithm comparisons.

Finally, this study underscores the need for further research that incorporates more diverse environments, larger datasets, and emerging security challenges, including resistance to modern cryptographic attacks. Such future work is essential to ensure that performance evaluations remain relevant in the context of continuously evolving computing technologies.

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Singular Value Decomposition for Deep Space Image Compression: A Hubble Case Study

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Abstract— Modern deep space exploration generates massive volumes of high-resolution imagery, creating a significant bottleneck for data transmission over limited bandwidths. This research addresses this challenge by evaluating Singular Value Decomposition (SVD) as a numerical Low-Rank Approximation technique for compressing astronomical data. Unlike data-hungry deep learning models, this study applies matrix factorization directly to an expanded dataset of 25 raw high-resolution TIF images from the Hubble Space Telescope. By varying the rank (k), we analyze the trade-off between storage efficiency, computational overhead, and reconstruction fidelity. Experimental results demonstrate that SVD offers a stable, lightweight compression mechanism, effectively filtering sensor noise while preserving coherent celestial structures without the risk of data hallucination or the blocking artifacts inherent to JPEG. The analysis identifies rank $k=100$ as the optimal threshold, achieving an average Peak Signal-to-Noise Ratio (PSNR) of 31.10 dB and reducing data volume by 88.7% (Compression Ratio of 8.87x). Furthermore, hardware profiling confirms SVD's exceptional efficiency, requiring a peak memory footprint of only ~95.99 MB and an execution time of ~2.50 seconds. These findings validate that SVD provides a computationally feasible and mathematically deterministic alternative to complex neural networks for onboard satellite data processing.

Index Terms— Computational Complexity; Deep Space Telemetry; Image Compression; Low-Rank Approximation; Satellite Communication; Singular Value Decomposition.

I. INTRODUCTION

The rapid advancement of remote sensing technology and the Internet of Things (IoT) has led to an exponential increase in the volume of digital image data generated by space missions and satellite systems. As noted by Muthukrishnan et al. [1], high-resolution satellite imagery is critical for modern observation but imposes significant challenges regarding data transmission bandwidth and storage capacity. In the context of deep space exploration, such as missions involving the Hubble Space Telescope, the transmission of hyperspectral and high-definition visual data requires efficient compression techniques to maximize scientific throughput without compromising critical structural details [2]. Consequently, image

compression remains a fundamental problem in the domain of signal processing and computer vision.

Various lossy compression standards have been developed to address this challenge. Traditional methods such as Discrete Cosine Transform (DCT) and Discrete Wavelet Transform (DWT) are widely used in commercial standards like JPEG and JPEG2000. However, comparative studies by Bhade et al. [3] and Prasanna et al. [4] demonstrate that while DCT offers computational speed, it often introduces blocking artifacts at high compression ratios. Conversely, hybrid approaches combining Singular Value Decomposition (SVD) with Wavelet Difference Reduction have been proposed by Rufai et al. [5] to enhance performance without severe artifact generation.

In recent years, data-driven approaches utilizing Deep Learning (DL) and Artificial Intelligence (AI) have heavily dominated the state-of-the-art in remote sensing image compression. Recent advancements include the utilization of Non-Local Neural Networks to improve reconstructed image quality [6], the application of Invertible Neural Networks to enhance perception quality in remote sensing [7], and the deployment of Convolutional Autoencoders for onboard lossy image compression in satellite missions [8]. Despite achieving high compression ratios, these neural compression methods introduce fatal flaws when applied to deep-space telemetry. DL models inherently possess high computational complexity and massive parameter sizes, often requiring Graphics Processing Units (GPUs) that are rarely feasible on hardware-constrained onboard satellite systems like CubeSats. Furthermore, the "black-box" nature of generative AI poses a critical risk of "data hallucination"—the artificial generation of fake cosmic structures—which severely violates the scientific authenticity required for raw astronomical data analysis. As demonstrated by Fournier and Aloise [9], traditional dimensionality reduction methods often remain competitive against complex neural networks in terms of computational efficiency and stability, particularly when training data is limited or structural integrity is paramount.

To address this critical gap, this research focuses on Singular Value Decomposition (SVD), not merely as a conventional matrix operation, but as a superior, mathematically deterministic alternative to modern neural networks for space applications. Unlike heuristic

compression methods or data-hungry AI models, SVD provides a mathematical guarantee for optimal low-rank matrix approximation, established by the classical theorem of Eckart and Young [10] and further generalized in subsequent matrix approximation theories [11]. The core principle of SVD involves factorizing an image matrix A into three component matrices: $A = U\Sigma V^T$, where Σ contains singular values representing the energy distribution of the image [11]. By retaining only the largest k singular values, one can reconstruct the image with minimal error.

This study clarifies the scientific contribution of SVD by empirically evaluating its robustness on raw 16-bit high-dynamic-range TIF astronomical data. By establishing an optimal operating benchmark, this research demonstrates SVD's exceptional computational efficiency—requiring minimal peak memory (~95 MB) and rapid execution time (~2.5s)—making it highly viable for onboard processing. Moreover, SVD guarantees structural preservation and intrinsic denoising without the risk of hallucination or the need for extensive training datasets [12], [13], [14] thereby successfully balancing scientific accuracy with stringent satellite transmission constraints.

I. METHOD

This study employs a quantitative experimental approach to evaluate the efficacy and computational efficiency of numerical algorithms in compressing scientific imagery. The methodology is structured into six sequential stages: data acquisition, pre-processing, matrix factorization, dimensionality reduction, performance evaluation (including computational profiling), and comparative baseline benchmarking. The overall flow of the enhanced image compression and analysis framework, which now integrates hardware profiling and standard JPEG benchmarking, is illustrated in Fig. 1.

A. Data Acquisition

The primary dataset for this research was curated from the official European Space Agency (ESA) Hubble Space Telescope archive (<https://esahubble.org/images/>). To ensure the robustness and statistical validity of the experimental results, the sample set was significantly expanded to 25 high-resolution deep-space images. These images, stored in uncompressed TIF (Tagged Image File Format) to avoid pre-existing compression artifacts, were carefully selected to comprehensively represent five distinct morphological categories: Planetary Bodies, Supernova Remnants, Emission/Dark Nebulae, Interacting Galaxies, and Dense Globular Clusters. As emphasized in remote sensing studies [2], such high-dynamic-range data presents a unique challenge for compression algorithms due to the non-local sparsity of the pixel distribution.

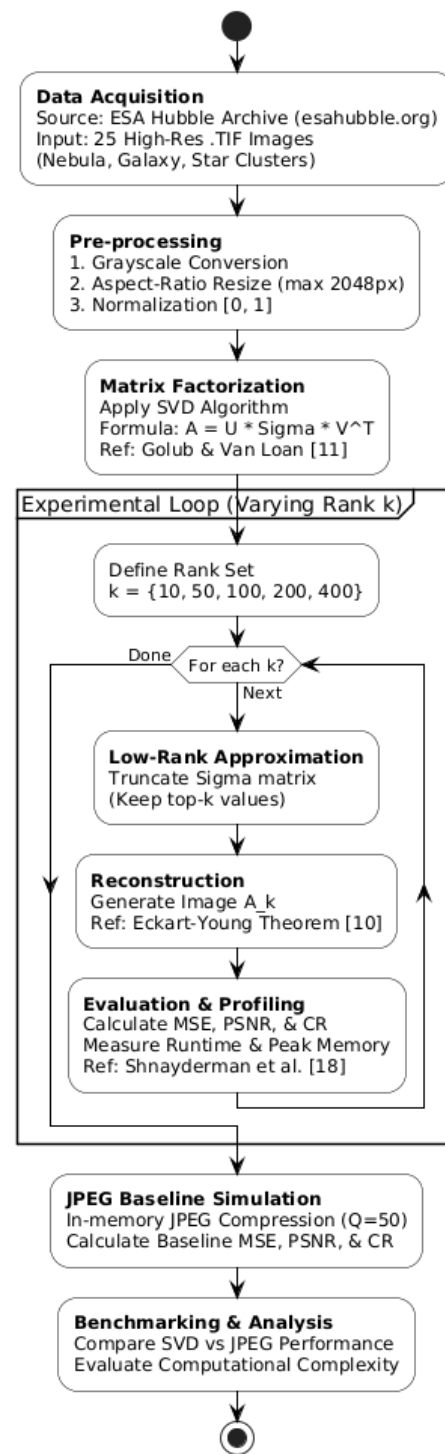


Fig. 1. Proposed research methodology flowchart illustrating the enhanced SVD-based compression pipeline, computational profiling, and JPEG benchmarking

B. Pre-processing

Before applying the numerical decomposition, the raw images undergo a crucial pre-processing phase. First, the 3D color images (RGB channels) are converted into 2D grayscale matrices, reducing computational complexity while retaining the luminance and structural information vital for morphological analysis. Second, an aspect-ratio-

preserving resize is applied, capping the longest dimension at 2048 pixels using the LANCZOS interpolation algorithm. This step not only prevents memory overcapacity during matrix operations but also inherently acts as a Low-Pass Filter, smoothing out microscopic high-frequency noise prior to decomposition. Finally, the pixel intensity values are normalized into a floating-point range of $[0, 1]$ to maintain numerical stability during the iterative matrix factorization process.

C. Singular Value Decomposition (SVD)

The core algorithm utilized is the Singular Value Decomposition (SVD). Drawing from the fundamental matrix computation theory [11], SVD factorizes a real-valued image matrix A of size $m \times n$ into three component matrices, as defined in (1).

$$A = U\Sigma V^T \quad (1)$$

Here, U is an $m \times m$ orthogonal matrix representing the left singular vectors, V^T is the transpose of an $n \times n$ orthogonal matrix representing the right singular vectors, and Σ is an $m \times n$ diagonal matrix containing the singular values σ_i . These singular values are ordered in a non-increasing sequence ($\sigma_1 \geq \sigma_2 \geq \dots \geq 0$) and represent the "energy" or information content of the image. As interpreted geometrically [12], this decomposition effectively rotates the coordinate system to align with the directions of maximum variance in the data.

D. Low-Rank Approximation

The compression mechanism relies on the Low-Rank Approximation technique. Based on the generalization of the Eckart-Young-Mirsky theorem [10], the optimal approximation of matrix A by a matrix A_k of a lower rank k (where $k < \text{rank}(A)$) is achieved by truncating the singular values. We retain only the first k largest singular values and discard the rest, treating them as noise or redundant information. The reconstruction formula is given by:

$$A_k = \sum_{i=1}^k \sigma_i u_i v_i^T \quad (2)$$

To quantify the information retained by the rank- k approximation, we utilize the concept of "Cumulative Energy." The energy of the image matrix is proportional to the sum of its squared singular values. The Energy Retention Ratio (E_k) for a selected rank k is defined as:

$$E_k = \frac{\sum_{i=1}^k \sigma_i^2}{\sum_{j=1}^r \sigma_j^2} \times 100\% \quad (3)$$

Where r is the full rank of the matrix. This metric allows us to determine the rank k scientifically by setting a specific energy threshold, rather than relying solely on visual inspection. In this experiment, we vary the rank parameter k ($k = 10, 50, 100, 200, 400$) to observe the trade-off between file size reduction, energy retention, and image fidelity.

E. Performance Evaluation, Profiling, and Benchmarking

To objectively assess the quality and efficiency of the compressed images, several metrics and profiling techniques are employed. Reconstruction fidelity is quantified using Mean Squared Error (MSE) and Peak Signal-to-Noise Ratio (PSNR). Following the framework regarding SVD-based quality assessment [18], the PSNR is calculated to measure the reconstruction quality in decibels (dB), defined as:

$$MSE = \frac{1}{mn} \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} [I(i,j) - K(i,j)]^2 \quad (4)$$

$$PSNR = 10 \log_{10} \left(\frac{MAX_I^2}{MSE} \right) \quad (5)$$

Where MAX_I represents the maximum possible pixel value (which is 1.0 after normalization). The Compression Ratio (CR) is calculated by comparing the storage requirement of the original matrix against the truncated matrices U_k , Σ_k , and V_k .

To address the hardware constraints typical of onboard satellite systems, a computational complexity profiling module is integrated into the pipeline. Using Python's time and tracemalloc libraries, the wall-clock runtime (in seconds) and peak memory footprint (in MB) are precisely measured exclusively during the SVD decomposition and reconstruction phases. Finally, to demonstrate practical competitiveness, an in-memory standard JPEG compression simulation (via io.BytesIO) is established as a conventional comparative baseline, allowing a direct benchmarking of SVD's performance against block-based DCT compression.

It should be noted that computational profiling (runtime and memory) is exclusively evaluated for the SVD algorithm to demonstrate its hardware feasibility. The JPEG baseline is implemented strictly as a comparative standard for perceptual quality (PSNR) and compression ratio (CR), as its Python implementation relies on pre-compiled C-libraries that do not offer an equivalent algorithmic hardware-level profiling comparison.

II. RESULTS AND DISCUSSION

This section presents a comprehensive analysis of the enhanced SVD-based compression framework applied to the expanded dataset of 25 high-resolution Hubble Space Telescope images. The evaluation is systematically divided into five areas: singular value energy distribution, quantitative performance consistency, qualitative visual preservation, comparative baseline analysis against JPEG, and computational complexity profiling.

A. Singular Value Distribution and Energy Compaction

The fundamental premise of using SVD for compression lies in the energy distribution of the image matrix. As visualized in the newly generated Scree Plot (Fig. 2), the cumulative energy curve exhibits an exceptionally steep exponential rise, reaching the 99% retention threshold rapidly. This steepness is attributed to two factors. First, the LANCZOS pre-processing resize inherently acts as a low-pass filter, attenuating microscopic high-frequency noise prior to factorization. Second, morphologically, diffuse celestial bodies like the Carina Nebula are heavily dominated by low-frequency spatial gradients. Consequently, the SVD algorithm adaptively compacts the vast majority of the image's structural information into the first few dominant singular vectors, validating the feasibility of massive matrix truncation.

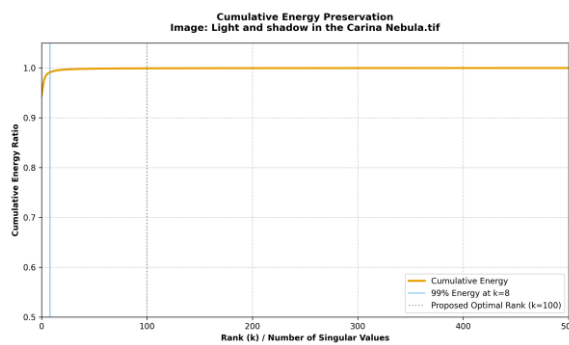


Fig. 2. Cumulative energy retention ratio as a function of rank (k). The steep exponential rise demonstrates rapid energy compaction, allowing the SVD algorithm to capture over 99% of the structural information within the first few dominant singular values

B. Quantitative Performance Analysis

Table I summarizes the average compression quality and storage metrics computed across the entire dataset of 25 diverse high-resolution astronomical images. The empirical data demonstrates a clear trade-off between the Compression Ratio (CR) and the reconstruction quality (PSNR).

TABLE I. COMPRESSION QUALITY AND STORAGE METRICS (AVERAGED OVER 25 SAMPLES)

Method	Rank (k)	Avg. PSNR (dB)	Avg. MSE	CR (x)
SVD	10	24.72 ± 5.16	0.0074 ± 0.0108	88.73 ± 12.58
	50	28.89 ± 6.46	0.0045 ± 0.0081	17.75 ± 2.52
	100	31.10 ± 6.89	0.0032 ± 0.0059	8.87 ± 1.26
	200	33.98 ± 7.33	0.0019 ± 0.0037	4.44 ± 0.63
	400	38.64 ± 8.42	0.0008 ± 0.0018	2.22 ± 0.31
JPEG	Baseline	35.98	0.0005	18.44

At rank $k = 100$, the algorithm achieves an average PSNR of 31.10 dB—surpassing the standard quality threshold of 30 dB—while reducing the file size by a factor of 8.87 (an 88.7% reduction in data volume). To validate the statistical robustness of this threshold, a consistency check was performed across all 25 samples (Fig. 3). The bar chart confirms that while low-frequency images (e.g., nebulae) achieve exceptionally high PSNRs, images packed with extreme high-frequency point-sources (e.g., dense globular clusters) logically exhibit higher variance. Nevertheless, the algorithm maintains stable structural preservation across all morphological classes.

At rank $k = 100$, the algorithm achieves an average PSNR of 31.10 dB—surpassing the standard quality threshold of 30 dB—while reducing the file size by a factor of 8.87 (an 88.7% reduction in data volume). To rigorously validate the statistical reliability of these results, standard deviations (SD) are reported alongside the mean values. For instance, at $k = 100$, the PSNR exhibits a variance of ± 6.89 dB. This expected variance logically reflects the immense morphological diversity within the dataset; images heavily dominated by high-frequency point-sources (e.g., dense globular clusters) incur higher truncation losses compared to the smooth, low-frequency spatial gradients of emission nebulae. Nevertheless, the consistency check across all 25 individual samples (Fig. 3) confirms that the SVD algorithm maintains stable structural preservation and prevents catastrophic data degradation across all morphological classes.

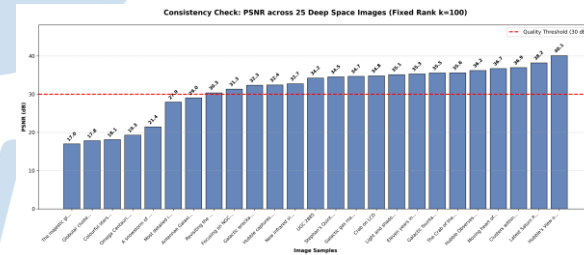


Fig. 3. Consistency check of reconstruction quality (PSNR) across 25 diverse deep-space images at a fixed optimal rank of $k = 100$. The red dashed line indicates the 30 dB quality threshold, validating the algorithm's robust performance across various astronomical morphological categories

C. Visual Quality and Morphological Preservation

The qualitative evaluation offers a profound look at SVD's reconstruction behavior. A critical observation derived from the enhanced Residual Error Map with percentile clipping (Fig. 4c) reveals an extreme localization of reconstruction errors. The error distribution is not randomly scattered; instead, it is highly concentrated specifically on individual bright stars (high-frequency point sources). Conversely, the continuous gaseous structures of nebulae and galaxies (low-frequency components) are reconstructed with near-zero error. This visually proves that SVD preserves macro-cosmic morphology perfectly, trading off only microscopic stellar impulses that are often indistinguishable from sensor noise.

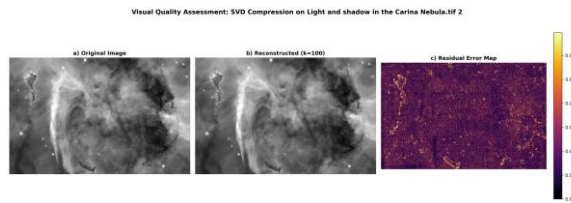


Fig. 4. Visual quality assessment and morphological preservation analysis: (a) Original image, (b) Reconstructed image at optimal rank $k = 100$, and (c) Enhanced residual error map. The error map demonstrates that truncation loss is extremely localized to high-frequency point-sources (stars), successfully preserving the continuous low-frequency gaseous structures.

The analysis of structural integrity is further clarified through a zoom-in morphological comparison (Fig. 5). At the optimal rank of $k = 100$, the SVD method proves successful in maintaining vital morphological features, such as dense nebula gas clouds and stellar distributions, with high fidelity.

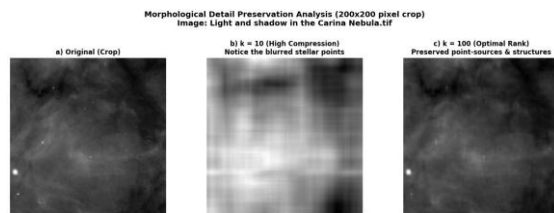


Fig. 5. Morphological detail preservation analysis (200 × 200 pixel crop). Comparison between high compression ($k = 10$) which shows blurring, and optimal rank ($k = 100$) which preserves stellar point sources effectively.

Furthermore, a beneficial side effect was observed at lower ranks, where there is significant suppression of granular noise in the image background. This phenomenon aligns with the findings of Khmag [16] and Kim et al. [17], suggesting that SVD acts effectively as a natural low-pass filter. By discarding the smallest singular values—which often represent uncorrelated sensor noise—the method effectively "cleans" the image while retaining the coherent structure of the main celestial bodies.

D. SVD vs. JPEG Baseline Comparison

To demonstrate practical competitiveness, SVD was benchmarked against an in-memory standard JPEG compression simulation. As shown in Table I, the JPEG baseline yields a numerically higher average PSNR (35.98 dB) and CR (18.44x) at a mid-level quality setting. However, in the context of scientific astrophotography, numerical metrics do not translate directly to observational utility. JPEG utilizes a block-based Discrete Cosine Transform (DCT) that inherently produces "blocking artifacts"—grid-like artificial fragmentations that severely corrupt the continuous structural integrity of faint galactic arms or dust pillars. By avoiding block transformations entirely, SVD ($k = 100$ to 200) provides a globally continuous morphological preservation. For scientific data archival where preventing artificial texture hallucination is paramount, SVD's deterministic degradation is significantly safer than JPEG's artifact generation.

E. Computational Complexity Profiling

A primary critique of modern deep learning-based compression is the massive computational overhead required for onboard satellite operations. To address this, hardware resource profiling was conducted. As detailed in Table II, executing the SVD decomposition and rank- k reconstruction on high-resolution matrices requires an average wall-clock runtime of only ~ 2.50 seconds and a peak memory footprint of strictly ~ 95.99 MB.

TABLE II. COMPUTATIONAL COMPLEXITY PROFILING (AVERAGED OVER 25 SAMPLES)

Method	Rank (k)	Runtime (s)	Peak Memory (MB)
SVD	10	2.29 ± 1.09	95.88 ± 27.09
	50	2.30 ± 1.06	95.88 ± 27.09
	100	2.28 ± 1.06	95.88 ± 27.09
	200	2.29 ± 1.08	95.88 ± 27.09
	400	2.27 ± 1.03	95.88 ± 27.09
JPEG	Baseline	-	-

Unlike convolutional neural networks or autoencoders that demand heavy GPU acceleration and gigabytes of memory to store pre-trained weights, the proposed SVD framework is exceptionally lightweight. This ~ 95 MB peak memory requirement guarantees that the algorithm is highly feasible for direct deployment on hardware-constrained onboard systems, such as CubeSats and deep-space probes.

F. Comparison with Existing Literature

The experimental results strongly validate the findings of Fournier and Aloise [9] that classical matrix decomposition remains a robust and highly competitive alternative to deep learning. While Convolutional Neural Networks and Autoencoders [6], [7], and [8] have set new benchmarks in generic image compression, they suffer from the "black box" problem and lack of interpretability. In scientific data archival, ensuring that compression artifacts are not "hallucinated" features is critical. SVD provides a mathematically transparent transformation where the error bound is strictly defined by the Eckart-Young theorem [10]. Unlike generative AI, which might generate realistic-looking but fake textures based on training data bias, SVD creates a strictly lower-fidelity version of the actual input data, making it inherently safer for astrophotography.

In comparison to other classical methods, SVD offers distinct advantages over Wavelet-based techniques [5]. While Wavelet transforms require complex thresholding strategies to determine which coefficients to discard, SVD provides a direct mechanism to control the quality-size trade-off simply by adjusting the rank k . Furthermore, the deterministic robustness of low-rank matrices showcased in this space telemetry study conceptually aligns with its

successful applications in other parallel high-dimensionality domains, such as randomized tensor decompositions [13], [14] and medical MRI reconstruction [15]. A conceptual summary distinguishing the proposed SVD framework from current alternative paradigms is presented in Table III.

TABLE III. CONCEPTUAL COMPARISON OF COMPRESSION PARADIGMS FOR SPACE TELEMETRY

Feature / Parameter	Singular Value Decomposition (Proposed)	Deep Learning / Autoencoders	Discrete Cosine Transform (JPEG)
Computational Overhead	Very Low (~95 MB RAM)	Very High (Requires GPU)	Low
Risk of Data Hallucination	None (Deterministic)	High (Data-driven Bias)	None
Visual Artifacts	Smooth blurring at low rank	Texture manipulation	Blocking artifacts (Grid-like)
Training Data Requirement	None (Zero-shot)	Extensive dataset required	None

III. CONCLUSION

This research has successfully evaluated the efficacy and computational feasibility of Singular Value Decomposition (SVD) as a low-rank approximation technique for compressing deep-space astronomical imagery. By expanding the experimental dataset to 25 diverse high-resolution Hubble images, the analysis confirms that SVD is a statistically robust method for reducing data redundancy while strictly maintaining the structural integrity required for scientific observation. The empirical results establish that a rank of $k = 100$ serves as the optimal operating benchmark. At this threshold, the algorithm achieves an average PSNR of 31.10 dB and reduces the data volume by 88.7% (a Compression Ratio of 8.87x), demonstrating consistent performance across various celestial morphologies, ranging from diffuse nebulae to dense star clusters.

Qualitatively, the SVD approach demonstrates a critical advantage over conventional block-based compression standards like JPEG. By entirely avoiding the "blocking artifacts" inherent to Discrete Cosine Transforms (DCT), SVD successfully preserves the continuous morphological structures of cosmic bodies and strictly localizes truncation errors to high-frequency point-sources, thereby preventing artificial texture hallucination. Furthermore, this study empirically proves the lightweight nature of the SVD framework. Hardware profiling reveals a peak memory footprint of only ~95.99 MB and an average runtime of ~2.50 seconds per high-resolution image. This exceptionally low computational overhead guarantees that SVD is highly feasible for direct deployment on resource-constrained onboard satellite systems, such as CubeSats, where deploying parameter-heavy deep learning models remains impractical.

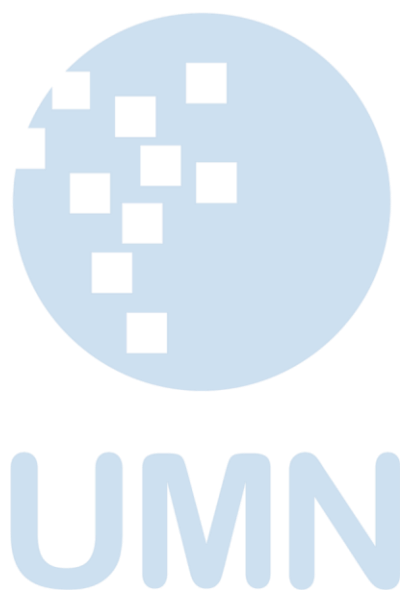
For future work, we suggest exploring hybrid compression architectures, such as integrating SVD

with Discrete Wavelet Transforms (DWT), to better capture the high-frequency point-source details of faint stars that are prone to smoothing at lower ranks. Additionally, dynamic rank-selection algorithms based on onboard spatial frequency analysis could be investigated to automatically optimize the compression ratio for each unique astronomical observation.

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Integrating Generative Artificial Intelligence in Higher Education: Opportunities, Challenges, and Pedagogical Implications

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Abstract— The increasing use of digital technology has changed many aspects of higher education, particularly in teaching and learning activities. In recent years, Generative Artificial Intelligence (GenAI) has attracted considerable attention because of its ability to generate content and assist various academic tasks. This study examines the role of GenAI in supporting learning transformation in higher education, focusing on its benefits, challenges, and broader educational implications. A qualitative approach was applied through a literature review of recent scholarly publications related to artificial intelligence in education. The findings suggest that GenAI can improve learning efficiency, support more adaptive and personalized learning experiences, and assist students in academic activities such as research and writing. At the same time, several concerns remain important, including academic integrity, excessive dependence on technology, and the absence of clear institutional regulations. The study also indicates that the successful use of GenAI depends not only on technological capability but also on pedagogical readiness and institutional support. Overall, GenAI offers significant opportunities for higher education; however, its implementation should be managed carefully to ensure that technological innovation remains aligned with ethical and educational values.

Index Terms— Generative Artificial Intelligence; Higher Education; Digital Transformation; Technology-Based Learning; Adaptive Learning; Academic Integrity

I. INTRODUCTION

Digital transformation has become a global phenomenon that significantly reshapes various sectors, including higher education. The rapid development of information and communication technologies has encouraged educational institutions to adopt digital innovations in order to enhance the quality of learning and the efficiency of academic processes. In this context, the emergence of Artificial Intelligence (AI) has become one of the key drivers in shifting learning

paradigms from conventional approaches toward more adaptive and technology-driven systems [1], [2].

One of the most recent developments in AI is Generative Artificial Intelligence (GenAI), a technology capable of producing new content such as text, images, audio, and video based on previously learned data. This technology has gained significant attention with the emergence of AI-based platforms widely used in academic activities, including academic writing, data analysis, and instructional material development [3], [4]. The application of GenAI in higher education offers substantial opportunities to create more personalized, interactive, and efficient learning systems. Through its capabilities in data processing and content generation, GenAI can assist lecturers in developing more diverse teaching materials and support students in understanding complex concepts more effectively. Furthermore, this technology enables the implementation of adaptive learning tailored to individual student needs and characteristics [5], [6].

Recent developments in generative artificial intelligence have accelerated its adoption across higher education institutions worldwide. Universities are increasingly integrating AI-powered tools into teaching, learning, assessment, and academic support services to enhance educational effectiveness and student engagement. Recent studies have highlighted that GenAI technologies are reshaping learning environments by enabling more interactive, personalized, and data-driven educational experiences [7], [8], [9].

Despite its growing adoption, the integration of GenAI in higher education remains a subject of ongoing debate. While proponents emphasize its potential to improve academic productivity and learning accessibility, critics raise concerns regarding ethical issues, academic integrity, cognitive dependency, and the readiness of educational institutions to regulate its

use effectively [10], [11]. This situation indicates that the implementation of GenAI requires not only technological readiness but also pedagogical and institutional adaptation. Furthermore, the rapid advancement of GenAI technologies has outpaced the development of pedagogical frameworks and institutional governance in many higher education settings, creating significant challenges for sustainable and ethical implementation.

Despite the growing body of research on artificial intelligence in higher education, most studies still focus on AI in general, such as recommendation systems, intelligent tutoring systems, and learning analytics [6], [7], [9]. In contrast, studies specifically addressing Generative Artificial Intelligence as a dynamic content-generation tool remain limited and are often conceptual in nature [8]. In addition, existing research tends to examine either the benefits or the risks of GenAI separately, without integrating both aspects into a comprehensive analytical framework. A balanced understanding of opportunities and challenges is essential for developing effective and sustainable implementation strategies in higher education [12], [13]. Furthermore, there is a noticeable gap in the literature regarding how GenAI can be pedagogically integrated into learning processes, particularly in supporting student-centered learning. Most studies have not thoroughly examined the relationship between GenAI utilization, changes in the role of lecturers, and its impact on students' learning experiences in a holistic manner [2].

Based on these gaps, this study offers novelty by proposing an analytical approach that not only identifies the benefits and challenges of GenAI but also examines its pedagogical implications within the broader context of learning transformation in higher education. This study emphasizes the integration of technological, pedagogical, and ethical dimensions within a comprehensive conceptual framework. Consequently, the main contributions of this research include: (1) the development of an integrative analytical framework for GenAI in learning, (2) the strengthening of pedagogical perspectives in AI utilization, and (3) strategic recommendations for responsible and sustainable implementation in higher education.

Research Questions

Based on the background and identified research gaps, the research questions of this study are as follows:

1. How does Generative Artificial Intelligence contribute to the transformation of learning in higher education?
2. What are the benefits of utilizing Generative Artificial Intelligence in the learning process?
3. What challenges and risks arise from the implementation of Generative Artificial Intelligence in academic environments?

4. What are the pedagogical implications of Generative Artificial Intelligence for students' learning processes and experiences?
5. What strategies can be implemented to ensure effective, ethical, and sustainable use of Generative Artificial Intelligence in higher education?

Research Objective

This study aims to comprehensively analyze the utilization of Generative Artificial Intelligence in transforming learning in higher education by identifying its roles, benefits, and implementation challenges, as well as examining its pedagogical implications for students' learning experiences to formulate effective, ethical, and sustainable implementation strategies.

I. THEORY

A. Generative Artificial Intelligence

Generative Artificial Intelligence (GenAI) represents one of the most advanced branches of artificial intelligence, focusing on the ability of systems to generate new content such as text, images, audio, and video based on patterns learned from large datasets. Unlike conventional AI, which is primarily analytical or predictive in nature, GenAI demonstrates a creative capability by synthesizing information into novel outputs that resemble human-generated content [14].

The rapid evolution of GenAI has been driven by advances in deep learning, particularly the development of large language models (LLMs) capable of understanding complex linguistic contexts and producing coherent, context-aware responses. These technologies have been widely adopted across various sectors, including education, where they support academic activities such as scientific writing, instructional material development, and learning assistance [10].

In the context of higher education, GenAI offers significant potential to enhance both the efficiency and quality of learning processes. It enables lecturers and students to access knowledge more rapidly and to generate adaptive and interactive learning content. However, the adoption of GenAI also raises critical concerns, including issues related to information validity, algorithmic bias, and ethical challenges in its use. These concerns highlight the need for responsible and well-regulated integration of GenAI within academic environments [13], [15].

B. Digital Transformation in Education

Digital transformation in education refers to the integration of digital technologies into all aspects of the educational system to improve effectiveness, efficiency, and overall learning quality. This transformation extends beyond the mere use of

technological tools, encompassing a fundamental shift in pedagogical paradigms from teacher-centered approaches to student-centered learning [1]. Advancements in digital technologies, including artificial intelligence, big data, and cloud computing, have driven the emergence of innovative educational models such as online learning, blended learning, and adaptive learning systems. These innovations enable more flexible, personalized, and data-driven learning experiences, thereby reshaping how knowledge is delivered and acquired [6], [8].

Nevertheless, digital transformation in education is not without challenges. Issues such as unequal access to technology, varying levels of digital competence among stakeholders, and the absence of supportive policies and regulatory frameworks remain significant barriers. Therefore, successful implementation requires a holistic approach that integrates technological infrastructure, pedagogical innovation, and institutional governance [2], [16].

C. Technology-Based Learning

Technology-based learning refers to an instructional approach that utilizes digital technologies as the primary medium for delivering content, facilitating interaction, and conducting learning assessments. This approach expands access to information, allowing students to learn more flexibly without being constrained by time and location [16]. In practice, technology-based learning encompasses various formats, including e-learning, mobile learning, and virtual learning environments. The integration of technology not only enhances accessibility but also enables the application of more interactive and engaging instructional methods, such as multimedia learning, gamification, and digital simulations [17].

Furthermore, the integration of advanced technologies such as GenAI into technology-based learning has the potential to significantly enhance students' learning experiences through personalization and adaptive support. However, the effectiveness of this approach depends heavily on user readiness and sound pedagogical design. Without careful planning and implementation, the use of technology may inadvertently compromise the quality of learning outcomes [1], [12]

II. METHOD

A. Research Approach and Design

This study adopts a qualitative approach using a systematic literature review method guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. This approach is selected to provide a comprehensive understanding of the utilization of Generative Artificial Intelligence (GenAI) in transforming learning in higher education through the systematic analysis of relevant scholarly sources [18]. A literature review enables the researcher

to synthesize existing knowledge, identify emerging patterns, and critically examine key concepts and research gaps within the field. Through this approach, the study aims to develop an integrative perspective on the role, benefits, and challenges of GenAI, as well as its pedagogical implications in higher education.

B. Data Sources and Collection Techniques

The data used in this study were derived from secondary sources, including peer-reviewed journal articles, conference proceedings, research reports, and policy documents from relevant international and national institutions. Literature retrieval was conducted through major academic databases such as Scopus, Web of Science, and Google Scholar to ensure the credibility and relevance of the sources. Data collection was carried out using specific keywords, including "Generative Artificial Intelligence," "AI in Education," "Digital Transformation in Higher Education," and "Technology-Based Learning." The search process was conducted systematically to ensure comprehensive coverage of relevant and up-to-date literature within the scope of the study.

C. Inclusion and Exclusion Criteria

To ensure the quality and relevance of the analyzed data, this study applied specific inclusion and exclusion criteria.

Inclusion criteria:

1. Articles relevant to the topic of Generative Artificial Intelligence in education
2. Peer-reviewed scholarly publications
3. Articles published within the last five years

Exclusion criteria:

1. Articles not directly relevant to the research focus
2. Publications with unclear or weak methodological quality

Non-academic articles or opinion-based writings lacking empirical or theoretical grounding

D. Data Analysis Technique

Data were analyzed using thematic analysis, which aims to identify, categorize, and interpret key themes emerging from the reviewed literature. The analytical process followed the framework proposed by Braun and Clarke [19], consisting of: (1) data familiarization, (2) initial coding, (3) theme identification, (4) theme review, (5) theme definition and naming, and (6) report production. Through this approach, the study systematically examines various aspects related to the role, benefits, challenges, and pedagogical implications of Generative Artificial Intelligence in higher education.

During the coding process, each selected article was carefully reviewed to identify relevant findings related to the use of Generative Artificial Intelligence in higher education. Initial codes were assigned to recurring concepts, patterns, and issues reported across

the studies. Similar codes were subsequently grouped into broader categories, which were then synthesized into major themes. Through this process, four principal themes were identified: (1) the contribution of GenAI to learning transformation, (2) the benefits of GenAI in higher education, (3) implementation challenges and risks, and (4) pedagogical and institutional implications. This systematic coding procedure facilitated the identification of relationships and recurring patterns across the reviewed literature.

E. Validity and Reliability

To ensure the rigor of the study, source triangulation was employed by comparing findings across multiple scholarly sources. In addition, iterative reading and consistent coding procedures were applied to enhance the reliability of the analysis. This methodological approach is expected to produce findings that are valid, credible, and academically robust.

F. PRISMA Procedure

This study applied the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach to ensure a transparent and systematic literature selection process. The PRISMA framework was used to identify, screen, assess, and select relevant studies related to Generative Artificial Intelligence in higher education.

The literature search was conducted through several academic databases, including Scopus, Web of Science, and Google Scholar, using predefined keywords such as “Generative Artificial Intelligence,” “AI in Education,” and “Digital Transformation in Higher Education.” The initial search identified a number of potentially relevant articles.

Subsequently, duplicate records and studies that did not meet the inclusion criteria were excluded during the screening process. Full-text assessment was then conducted to evaluate the relevance and quality of the selected articles. Finally, only studies that were directly related to the research objectives and met the established criteria were included in the final analysis.

literature review process in this study. Figure 1 presents the PRISMA flow diagram used in this study to illustrate the process of literature identification, screening, eligibility assessment, and final article selection.

The literature search process followed the PRISMA framework to ensure transparency and rigor in article selection. An initial search conducted through Scopus, Web of Science, and Google Scholar identified 120 potentially relevant records. After removing 25 duplicate records, 95 articles remained for title and abstract screening. During the screening stage, 50 articles were excluded because they did not directly address the application of Generative Artificial Intelligence in higher education. The remaining 45 articles were then subjected to full-text assessment based on the predefined inclusion and exclusion criteria. Following the eligibility review, 17 articles were excluded due to insufficient relevance to the research objectives or unclear methodological information. Consequently, 28 studies met all inclusion criteria and were included in the final thematic synthesis.

The thematic analysis resulted in four major themes that emerged consistently across the selected studies: contributions of GenAI to learning transformation, benefits of GenAI, implementation challenges and risks, and pedagogical implications. These themes provide the foundation for the discussion presented in the following sections.

III. RESULTS AND DISCUSSION

The findings from the literature analysis indicate that the utilization of Generative Artificial Intelligence (GenAI) in higher education extends beyond technical enhancements in learning processes and contributes to broader structural transformations within the educational ecosystem. GenAI functions as an enabling technology that drives a shift from conventional instructional approaches toward more personalized and data-driven learning environments. This transformation reflects a fundamental change in how knowledge is produced, delivered, and consumed in academic contexts.

A. Benefits of Generative Artificial Intelligence in Education

The findings reveal that the efficiency enabled by GenAI goes beyond mere time-saving; it fundamentally reshapes academic workflows. Lecturers are no longer positioned as the sole source of knowledge but increasingly act as curators and facilitators of learning. This shift aligns with the concept of changing pedagogical roles, where technology assumes repetitive and content-generating tasks, allowing educators to focus on higher-level functions such as critical reflection, guidance, and evaluation [8].

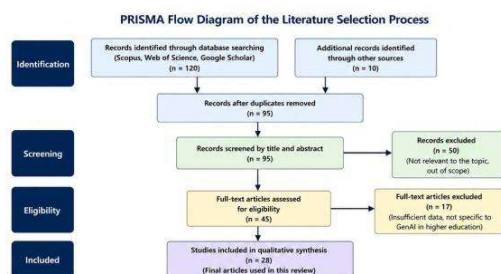


Fig 1. PRISMA Flow Diagram of the Literature Selection Process
Source: Developed by the authors (2026) based on PRISMA 2020 guidelines

The use of the PRISMA framework helped improve the rigor, transparency, and reliability of the

Furthermore, GenAI's capacity to support adaptive learning highlights its potential to address one of the key limitations of traditional education systems, namely the "one-size-fits-all" approach. Through GenAI, learning materials can be dynamically tailored to individual students' needs, learning pace, and preferences. However, the effectiveness of adaptive learning is highly dependent on the quality of input data and instructional design, indicating that GenAI cannot function optimally without appropriate pedagogical intervention.

In the context of research and academic writing, GenAI significantly accelerates the process of idea generation and literature exploration. Nevertheless, this development also suggests an epistemological shift in knowledge construction, where learning becomes increasingly collaborative between humans and intelligent systems. This raises a critical question: Does increased productivity necessarily lead to deeper understanding? Therefore, the use of GenAI must be accompanied by the development of higher-order thinking skills to ensure that learning remains meaningful and intellectually rigorous.

To provide a more structured understanding of the contributions of Generative Artificial Intelligence in higher education, the findings of this study are synthesized into several key aspects that represent the major benefits of its application in learning processes. This synthesis aims to systematically organize the findings and facilitate a clearer interpretation of the positive impacts of GenAI within academic settings.

TABLE I. BENEFITS OF GENERATIVE ARTIFICIAL INTELLIGENCE IN HIGHER EDUCATION

Aspect	Description	Impact
Learning Efficiency	Automation in the development of instructional materials	Reduces lecturers' workload
Adaptive Learning	Personalization of learning content based on student needs	Enhances students' understanding
Academic Support	Assistance in research and academic writing activities	Improves students' productivity

Based on Table 1, the findings indicate that the utilization of Generative Artificial Intelligence has a significant impact on improving both the efficiency and quality of learning in higher education. The efficiency gained in generating instructional materials allows lecturers to allocate more time to designing innovative and pedagogically meaningful learning strategies. In addition, GenAI's capability to support adaptive learning demonstrates substantial potential in creating more personalized learning experiences tailored to individual student needs [20]. This personalization enhances engagement and facilitates deeper understanding by aligning instructional content with students' learning pace and preferences.

Furthermore, the support provided by GenAI in academic activities, particularly in research and

academic writing, reinforces its role as a powerful assistive tool that enhances student productivity. However, these benefits must be carefully managed to ensure that the use of GenAI does not undermine the development of critical thinking skills. Without proper pedagogical guidance, there is a risk that reliance on AI-generated outputs may reduce students' ability to engage in independent and analytical thinking.

Although the reviewed studies consistently acknowledge the positive contributions of GenAI to academic activities, differences emerge regarding the extent of its educational impact. Some studies primarily emphasize improvements in efficiency and productivity, particularly in content generation, information retrieval, and academic writing support. In contrast, other studies argue that the most significant contribution of GenAI lies in its ability to facilitate personalized learning experiences and adaptive instructional support. These variations suggest that the effectiveness of GenAI is influenced by contextual factors, including pedagogical design, digital literacy levels, technological infrastructure, and institutional readiness. Therefore, the educational value of GenAI should not be considered universal but rather dependent on how the technology is integrated into specific learning environments.

B. Challenges

One of the key findings of this study is that the challenges associated with Generative Artificial Intelligence (GenAI) are systemic rather than merely technical. For instance, the risk of plagiarism is not solely linked to student behavior but also reflects the unpreparedness of existing academic assessment systems in responding to generative technologies. Traditional product-oriented assessment models, which focus primarily on final outputs such as written assignments, are becoming less relevant in this context. This shift necessitates a transition toward process-oriented assessment approaches that emphasize critical thinking, learning progression, and originality.

In addition, the increasing reliance on technology reveals a paradox within digital transformation. On one hand, GenAI enhances accessibility and efficiency; on the other hand, it may reduce students' cognitive engagement if not used critically. This paradox highlights the importance of maintaining a balance between leveraging technological capabilities and fostering students' intellectual development. Without such a balance, there is a risk that technological convenience may undermine deeper learning processes [10], [11].

Regulatory challenges also emerge as a critical issue, reflecting what can be described as a *lagging policy phenomenon*, where institutional policies fail to keep pace with rapid technological advancements. Many higher education institutions lack clear guidelines governing the use of GenAI, resulting in ambiguity in academic practices. This regulatory gap

may lead to inconsistencies in assessment standards and weaken the enforcement of academic integrity.

Despite the significant benefits offered by GenAI, its implementation in higher education inevitably introduces a range of challenges that must be carefully anticipated and managed. Therefore, the findings of this study are further synthesized to highlight the major constraints that may influence the effective adoption of GenAI within academic environments

TABLE 2. CHALLENGES IN THE IMPLEMENTATION OF GENERATIVE ARTIFICIAL INTELLIGENCE

Challenge	Description	Impact
Plagiarism	Use of AI-generated content without proper attribution	Undermines academic integrity
Technological Dependency	Excessive reliance on AI tools	Weakens critical thinking skills
Regulatory Issues	Lack of clear institutional policies	Creates uncertainty in AI usage

Based on Table 2, the findings indicate that the key challenges in the implementation of Generative Artificial Intelligence span ethical, cognitive, and policy dimensions. The risk of plagiarism emerges as a primary concern, as it may undermine academic integrity when the use of technology is not accompanied by adequate ethical awareness. In addition, excessive reliance on technology may negatively affect students' critical thinking abilities if it is not balanced with appropriate pedagogical approaches. This highlights the importance of integrating GenAI within well-designed instructional frameworks that actively promote analytical and reflective learning.

Meanwhile, the lack of clear regulatory frameworks underscores the urgent need for educational institutions to develop adaptive policies that keep pace with technological advancements. Without such policies, inconsistencies in academic practices and evaluation standards are likely to persist. Therefore, the effective management of these challenges becomes a critical factor in ensuring that the utilization of GenAI can deliver optimal benefits while minimizing potential negative impacts.

The reviewed literature also reveals variations in how institutions perceive and respond to the challenges of GenAI implementation. While some studies identify academic integrity as the primary concern, others emphasize issues related to technological dependency and policy readiness. These differences may be influenced by institutional contexts, technological maturity, and existing governance frameworks. Such findings indicate that challenges associated with GenAI are not uniform across higher education institutions. Consequently, strategies for managing these risks should be tailored to the specific needs and capacities of individual educational settings rather than relying on a one-size-fits-all approach.

C. Proposed Solutions for Addressing Academic Challenges

The findings suggest that addressing the challenges associated with GenAI requires a combination of pedagogical, technological, and institutional interventions. To mitigate the risk of plagiarism and academic misconduct, higher education institutions should redesign assessment strategies by emphasizing process-oriented evaluation rather than solely focusing on final outputs. Assessment approaches such as project-based learning, reflective assignments, and oral examinations may help ensure that students demonstrate genuine understanding and engagement with learning materials.

A key implication of the findings is that the benefits of GenAI can only be sustained when accompanied by strategies that prevent excessive technological dependency. Educational institutions should therefore promote the development of higher-order thinking skills, including critical thinking, problem-solving, and analytical reasoning. In this regard, GenAI should be positioned as a learning support tool rather than a substitute for intellectual effort. Lecturers play a crucial role in guiding students to use AI-generated content critically and responsibly.

Furthermore, clear institutional policies are necessary to regulate the use of GenAI in academic environments. Such policies should include ethical guidelines, standards for AI-assisted academic work, and mechanisms for monitoring and evaluating AI usage. Regular training programs for lecturers and students can also strengthen AI literacy and foster responsible adoption. Through these measures, higher education institutions can maximize the benefits of GenAI while minimizing its potential risks.

D. Implications for Higher Education

Based on the analysis, this study proposes that the successful implementation of Generative Artificial Intelligence (GenAI) is largely determined by the integration of technology, pedagogy, and institutional policy. In this regard, GenAI should not be viewed merely as a supporting tool, but rather as an integral component of a broader learning ecosystem. The first implication concerns the need to redefine digital literacy. Digital literacy should extend beyond the ability to operate technological tools and encompass the capacity to understand, evaluate, and critically assess AI-generated outputs. This is essential to ensure that students remain active agents in the learning process rather than passive consumers of information.

The second implication relates to the transformation of lecturers' roles. Lecturers are no longer expected solely to deliver content, but also to design learning experiences that effectively integrate technology. Their roles evolve into facilitators, evaluators, and guides who ensure that GenAI is used in an ethical, meaningful, and pedagogically sound manner. The third implication highlights the need for adaptive institutional policies. Educational institutions

must develop regulatory frameworks that can keep pace with technological advancements while maintaining core academic values. These include the establishment of clear guidelines for AI usage, the development of relevant assessment systems, and the implementation of transparent monitoring mechanisms.

E. Conceptual Model (Research Contribution)

Unlike previous studies that tend to examine benefits and challenges separately, this study demonstrates that both dimensions are inherently interconnected and must be managed simultaneously. The main contribution of this research lies in the development of an integrative model that positions:

- GenAI as a driver of transformation
- Benefits as potential opportunities
- Challenges as risks to be managed
- Interventions as the key to successful implementation

To provide a clearer synthesis of the findings, a conceptual model is proposed to illustrate the relationships between the utilization of Generative Artificial Intelligence, its potential benefits, the associated challenges, and the strategic interventions required to support learning transformation in higher education. The framework was developed by the authors based on the thematic synthesis of relevant literature and is intended to provide a comprehensive perspective on the dynamics of GenAI implementation within academic contexts. Figure 2 presents the integrative framework derived from the findings of this study.

A notable finding emerging from the reviewed studies is that the success of GenAI implementation depends less on the technology itself and more on the surrounding educational ecosystem. Institutions that combine technological adoption with pedagogical innovation, digital literacy development, and supportive governance structures tend to report more positive outcomes. Conversely, institutions that focus primarily on technological deployment without corresponding pedagogical and policy adjustments often encounter greater implementation challenges. This finding reinforces the importance of adopting a holistic approach to educational transformation.

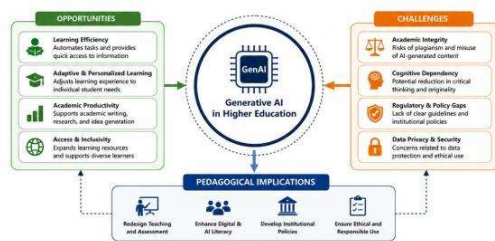


Fig 2. Integrative Framework of Generative AI in Higher Education
Source: Developed by the authors (2026)

Based on Figure 2, Generative Artificial Intelligence (GenAI) is conceptualized as the central driving force that initiates and sustains the transformation of learning in higher education. Rather than functioning merely as a technological tool, GenAI operates as an enabling infrastructure that reshapes the processes of knowledge creation, delivery, and engagement within academic environments. The model illustrates that the adoption of GenAI generates three interconnected domains of benefits: learning efficiency, adaptive learning, and academic productivity. These benefits are not isolated outcomes; instead, they collectively contribute to the development of a more personalized, responsive, and data-driven learning ecosystem. In this context, efficiency reflects not only time optimization but also the reallocation of cognitive and instructional resources toward higher-order pedagogical activities [17], [21].

At the same time, the model acknowledges that these benefits are inherently accompanied by a set of systemic challenges, including ethical risks (such as plagiarism), cognitive concerns (such as overreliance on technology), and institutional limitations (such as inadequate regulatory frameworks). These challenges are not peripheral but structurally embedded within the process of technological integration, thereby requiring deliberate and continuous management. A key contribution of this model lies in its emphasis on strategic interventions as mediating mechanisms between benefits and challenges. These interventions, comprising digital literacy development, adaptive institutional policies, and the transformation of lecturers' roles, serve as critical control variables that determine whether GenAI implementation leads to meaningful learning transformation or unintended negative consequences. In particular, the transformation of lecturers' roles highlights a shift toward facilitation, critical guidance, and ethical oversight in technology-enhanced learning environments.

Furthermore, the model underscores the dynamic and iterative nature of GenAI integration. The relationship between benefits, challenges, and interventions is not linear but cyclical, involving continuous processes of evaluation, feedback, and adaptation. This dynamic perspective suggests that learning transformation is an evolving process rather than a one-time outcome of technological adoption. Ultimately, Figure 1 demonstrates that the successful transformation of learning in higher education depends not only on the presence of advanced technologies but also on the capacity of educational systems to strategically align technological innovation with pedagogical principles and institutional governance. In this regard, GenAI serves as both an opportunity and a catalyst, while human and institutional factors remain decisive in shaping its long-term impact.

The findings indicate that Generative Artificial Intelligence contributes to learning transformation in

higher education by supporting personalized learning, automating academic tasks, and facilitating more data-driven educational practices. These capabilities enable institutions to enhance learning effectiveness while responding to diverse student needs.

The study also reveals several key benefits of GenAI, including improved learning efficiency, adaptive learning opportunities, and increased academic productivity among both students and lecturers. These benefits demonstrate the potential of GenAI to support more flexible and responsive learning environments.

Despite these advantages, the implementation of GenAI presents several challenges and risks. The most prominent issues identified in the reviewed literature include academic integrity concerns, excessive dependence on technology, and the absence of clear institutional regulations governing AI use in educational settings.

From a pedagogical perspective, GenAI has implications for both students and educators. Students are required to develop stronger critical digital literacy skills, while lecturers are expected to transition from traditional knowledge providers to facilitators, mentors, and evaluators who guide the responsible use of AI technologies.

The findings of this study provide clear answers to the research questions proposed in the introduction. First, GenAI contributes to learning transformation in higher education by supporting personalized learning, automating academic tasks, and facilitating data-driven educational practices. Second, the main benefits identified include improved learning efficiency, adaptive learning opportunities, and enhanced academic productivity among students and lecturers.

Third, the implementation of GenAI presents several challenges, particularly related to academic integrity, technological dependency, and regulatory limitations. Fourth, the pedagogical implications include the transformation of lecturers' roles from knowledge providers to facilitators and mentors, as well as the growing importance of critical digital literacy among students. Finally, effective and sustainable implementation of GenAI requires strategic interventions, including AI literacy programs, adaptive institutional policies, ethical guidelines, and continuous evaluation mechanisms. These findings demonstrate that successful integration of GenAI depends on balancing technological innovation with pedagogical and institutional readiness.

IV. CONCLUSION

This study demonstrates that Generative Artificial Intelligence (GenAI) has become an important driver of learning transformation in higher education. The findings indicate that GenAI contributes to improved learning efficiency, supports adaptive and personalized learning experiences, and enhances academic productivity by assisting students and lecturers in

various educational activities. At the same time, the study identifies several critical challenges, including risks to academic integrity, excessive dependence on technology, and the lack of clear institutional regulations governing AI use in academic environments.

The findings further suggest that the educational impact of GenAI is highly dependent on the way it is integrated into teaching and learning processes. Institutions that combine technological adoption with pedagogical innovation, digital literacy development, and supportive governance frameworks are more likely to achieve positive outcomes. Therefore, higher education institutions should establish clear AI policies, strengthen AI literacy among students and lecturers, and redesign assessment practices to promote critical thinking and responsible AI use. By adopting these measures, institutions can maximize the benefits of GenAI while ensuring its ethical, effective, and sustainable implementation in higher education.

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A Hierarchical Two Stage BERT Model for Cyberbullying Detection

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Abstract— Cyberbullying has become a significant social concern alongside the rapid expansion of social media usage, particularly in developing countries such as Indonesia. Online bullying transcends overt insults to include more nuanced manifestations, such as denigration and social exclusion, which are frequently subtle and context-dependent. This diversity poses substantial challenges for automated detection systems, particularly when cyberbullying is conceptualized as a singular, homogeneous category. This study addresses the challenge of detecting cyberbullying in the Indonesian language by proposing a two-stage classification framework utilizing the IndoBERT model. In the initial phase, a binary classification model is utilized to distinguish between content that constitutes bullying and that which does not. In the subsequent phase, tweets identified as cyberbullying are further classified into three distinct categories: harassment, denigration, and exclusion. The model is trained utilizing a curated dataset comprising Indonesian tweets, which have been collected from publicly accessible social media content. The findings demonstrate that the proposed framework exhibits robust and consistent performance, particularly in the domain of fine-grained cyberbullying classification, achieving an overall accuracy of approximately 92% in the second stage. The results indicate that hierarchical classification can achieve robust performance and significantly contribute to the identification of cyberbullying.

Index Terms— Cyberbullying; IndoBERT; Two-Stage Classification; X (Twitter)

I. INTRODUCTION

The swift progression of digital technology has led to a significant rise in social media usage worldwide, including in Indonesia. X (formerly known as Twitter) is one of the most widely utilized social media platforms globally, serving as a public forum for communication and interaction. According to data from Dataloka, Indonesia is ranked fourth globally in terms of the number of X users, with approximately 23.76 million active users [1]. The platform facilitates the sharing of text, images, and videos, and enables users to participate in open discussions through posts and replies. While this openness fosters freedom of expression, it concurrently enables adverse behaviors, such as cyberbullying [2].

Cyberbullying is defined as intentional and repeated behaviors aimed at causing harm to individuals through electronic or digital media. In such cases, the identity of the perpetrator may either be revealed or remain undisclosed [3]. Previous studies have identified seven distinct categories of cyberbullying: harassment, exclusion, flaming, cyberstalking, outing, impersonation, and denigration [4]. Exposure to cyberbullying has been closely linked to negative mental health outcomes among adolescents and young adults, including heightened risks of depression and anxiety [5].

The incidence of cyberbullying in Indonesia has been reported to increase on an annual basis. In 2021, a total of 1,283 cases of cyberbullying were documented [6]. Data from the Indonesian Child Protection Commission (KPAI) reveal that in 2023, over 2,000 incidents pertaining to digital ethics violations and cyberbullying among students were documented, with a consistent annual increase [7]. By 2024, reports identifying children as victims of cyberbullying were ranked third within the Special Child Protection cluster, highlighting the critical nature of this issue within the digital environment [8].

Given the rising occurrence of cyberbullying on social media platforms in Indonesia, there is a critical demand for accurate automated systems to detect cyberbullying tweets. This study presents a two-stage model for detecting cyberbullying, employing IndoBERTweet [9]. In the initial phase, textual data derived from social media posts are collected and undergo preprocessing through natural language processing techniques to cleanse and normalize the text. Subsequently, a binary classification model is utilized to distinguish between content that constitutes bullying and that which does not. In the subsequent phase, content identified as bullying is further classified into three specific categories of cyberbullying: harassment, denigration, and exclusion. The datasets in both stages are divided into 70% training data, 15% validation data, and 15% testing data through stratified splitting to maintain class distribution.

This study aims to address the increasing incidence of cyberbullying on social media platforms by

improving the accuracy of automated detection systems. The proposed model, utilizing a two-stage classification approach based on IndoBERTweet, is expected to enhance the detection of cyberbullying content and its specific categories. This advancement aims to enhance efforts to protect the mental health of users, with a particular focus on vulnerable groups such as adolescents and women.

II. RELATED WORK

The study conducted by [10] investigates the detection of cyberbullying on social media platforms, specifically X (Twitter), through the application of Machine Learning (ML) algorithms. The study employs a dataset consisting of 39,870 Twitter posts and comments, which are classified into five categories: religion-based, age-based, gender-based, ethnicity-based cyberbullying, and non-cyberbullying. Several machine learning algorithms, including Random Forest [11], Support Vector Machine (SVM) [12], Logistic Regression [13], Naïve Bayes, and K-Nearest Neighbor [14], were evaluated and compared. The experimental results indicate that the Random Forest classifier demonstrated the highest performance, achieving an accuracy of 94%. This was followed by the Support Vector Machine (SVM) and Logistic Regression models, while the K-Nearest Neighbor algorithm exhibited the lowest performance. Although this approach demonstrates relatively high accuracy, it relies on traditional NLP-based feature extraction methods and does not incorporate contextual representations from transformer-based language models. This indicates potential for further enhancement through the application of more advanced deep learning techniques.

In a similar vein, Perera and Fernando [15] conducted research on the identification of cyberbullying on social media platforms through the application of supervised machine learning techniques. The research employed three classification algorithms—Support Vector Machine (SVM), Naïve Bayes, and Logistic Regression—to systematically identify and categorize types of cyberbullying, with a particular emphasis on racial, sexual, and physical bullying. Although the system demonstrated reasonably good classification accuracy, it relied on old machine learning models. The authors advocate for further research that incorporates additional classifiers, integrates more recent natural language processing (NLP) models, and applies deep learning methodologies.

Mufva et al. [16] conducted a study examining deep learning techniques for the detection of hate speech on Indonesian social media platforms, specifically X (Twitter), employing contextual word embeddings. The study conducted a comparative analysis of various neural network architectures, including LSTM [17], BiLSTM [18], CNN [19], CNN-LSTM, and CNN-

BiLSTM, with IndoBERTweet utilized as the embedding layer. The results indicated that the CNN-BiLSTM model demonstrated superior performance, achieving an accuracy of 86.75% and an F1-score of 84.39%. The CNN-LSTM model closely followed, achieving an accuracy of 86.28% and an F1-score of 83.50%. Furthermore, the CNN model independently outperformed the standalone LSTM and BiLSTM models, highlighting its effectiveness in identifying significant local patterns within brief social media texts.

Furthermore, Pekandi et al. [20] conducted a comparative analysis of three models for detecting fake news: an ensemble model, CNN-LSTM, and IndoBERT. The results demonstrated that IndoBERT attained the highest accuracy, registering at 92.24%, followed by the ensemble model with an accuracy of 91.18%. In contrast, the CNN-LSTM model exhibited the lowest F1-score, recorded at 73.53%. The findings highlight the effectiveness of transformer-based models in capturing contextual nuances within Indonesian-language text. Furthermore, [21] investigated the detection of clickbait utilizing IndoBERT and RoBERTa [22] across three dataset configurations: imbalanced, balanced, and augmented. Their experiments revealed that IndoBERT achieved superior performance, attaining an F1-score of up to 95% when trained on a balanced dataset. This underscores the importance of both model architecture and data distribution in text classification tasks.

The findings of this study suggest that the utilization of BERT-based models, such as IndoBERT, can produce superior outcomes. Nevertheless, existing research predominantly employs a single-stage classifier. As a result, when the dataset is imbalanced between instances of cyberbullying and non-cyberbullying, which is a frequent occurrence, it may lead to high accuracy but suboptimal recall and precision. Therefore, we propose a two-stage classification approach to detect cyberbullying tweets.

III. METHODOLOGY

A. Dataset

The dataset employed in this study was acquired through a web scraping process from the social media platform X (formerly known as Twitter). To ensure comprehensive coverage of relevant cyberbullying behaviors, the data collection was guided by keyword queries representing three predefined categories: harassment, denigration, and exclusion. The keywords were manually derived from the definitions of harassment, denigration, and exclusion in [4]. Keywords associated with harassment included terms such as "idiot," "stupid," "shut up," "loser," and "hate you." Denigration was represented by terms such as "fake," "liar," "fraud," "pathetic," and "disgusting." Exclusion was captured using expressions such as "you

are not welcome," "go away," "nobody likes you," "leave this group," and "you do not belong here." This targeted approach facilitated the retrieval of posts that reflect diverse manifestations of cyberbullying in online interactions.

The authors annotated the collected data to provide high quality labels for model training and evaluation. The annotation process was conducted in two stages. First, each post was assigned a binary label, where 1 indicated the presence of cyberbullying content and 0 indicated its absence. Second, posts identified as containing cyberbullying content were further classified into one of three categories: harassment, denigration, or exclusion, encoded as 0, 1, and 2, respectively. The annotation was performed independently by all four authors. A label was accepted when at least three of the four annotators agreed on the assigned class. Posts that did not achieve this level of agreement were excluded from the dataset to minimize the risk of incorrect labeling. The annotated dataset was subsequently divided into training, validation, and testing subsets with proportions of 70%, 15%, and 15%, respectively.

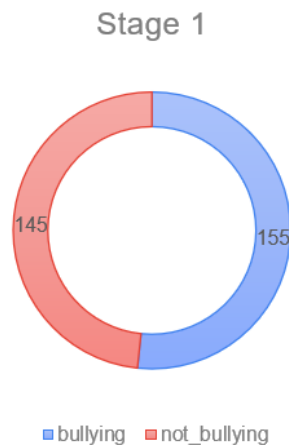


Fig 1. Distribution of Class in Stage 1 Classification

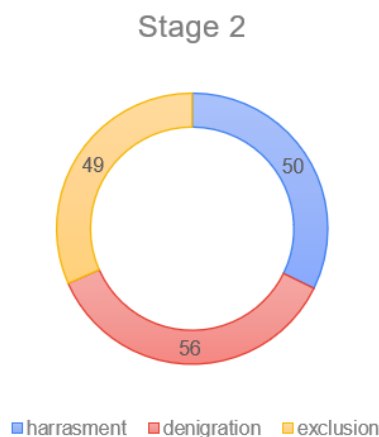


Fig 2. Distribution of Class in Stage 2 Classification

B. Data Pre-Processing

Data pre-processing entails transforming unstructured social media text into a structured format appropriate for model training. Social media data often contain noise, including informal language, redundant patterns, and non-textual elements, which can negatively affect model performance. To address these challenges, a series of Natural Language Processing techniques were employed to standardize and clean the dataset [23].

The preprocessing pipeline comprises multiple stages. Initially, all text is converted to lowercase to ensure a consistent representation. Non-semantic information, such as URLs, user mentions, and hashtags, is excluded to remove irrelevant elements. Non-alphanumeric characters, including symbols and emojis, are also omitted. Subsequently, text normalization is performed to address exaggerated character repetitions that frequently occur in informal communication. Ultimately, redundant whitespace is removed to ensure uniformity across all samples. These measures diminish extraneous noise while preserving crucial semantic content, thereby facilitating more effective representation learning with the IndoBERTweet model. An example of the preprocessing outcomes is presented in Table I.

TABLE I. EXAMPLE OF PRE-PROCESSING STEPS

Original Text	@Jenxiel17 Style yg ini keren banget sih #JenniexChanelss26 #chanelss26 #JENNIE #ParisFashionWeek @CHANEL @jennierubyjane 🤔 www.example.com
Lowercasing	@jenxiel17 style yg ini keren banget sih #jenniexchanelss26 #chanelss26 #jennie #parisfashionweek @chanel @jennierubyjane 🤔 www.example.com
Removing URL	@jenxiel17 style yg ini keren banget sih #jenniexchanelss26 #chanelss26 #jennie #parisfashionweek @chanel @jennierubyjane 🤔
Removing Mentions	style yg ini keren banget sih #jenniexchanelss26 #chanelss26 #jennie #parisfashionweek 🤔
Removing Hashtag	style yg ini keren banget sih 🤔
Removing Emoticon & Symbol	style yg ini keren banget sih
Normalization	style yg ini keren banget sih
Trim Extra Spaces	style yg ini keren banget sih
Final Text	style yg ini keren banget sih

Following preprocessing, IndoBERTweet is utilized to derive embeddings. Each preprocessed text

is tokenized using the IndoBERTweet tokenizer, which transforms the input into token IDs and attention masks. These tokenized inputs are then processed by the IndoBERTweet model to produce contextualized embedding representations with a dimensionality of 768. These embeddings encapsulate contextual and linguistic information from Indonesian social media text and are subsequently employed as input features for the proposed two-stage classification framework.

C. Two-Stage Classification

The proposed framework utilizes a hierarchical two-stage classification strategy to effectively address both the detection and categorization of cyberbullying content (See Fig. 3). This design allows the model to initially ascertain whether a post contains cyberbullying and subsequently classify the specific type of cyberbullying behavior. The architecture is constructed using IndoBERTweet embeddings, which are employed across both stages.

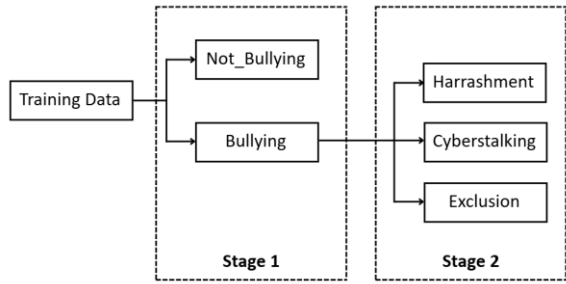


Figure 3. Two-Stage Classification

In the initial phase, the model performs a binary classification to distinguish between content that constitutes cyberbullying and that which does not. Let x denote a preprocessed input text, and let h represent the corresponding 768-dimensional IndoBERTweet embedding. The binary classifier maps 768-dimensional IndoBERTweet embedding h into a probability distribution over two classes using a fully connected layer followed by a softmax function:

$$\hat{y}_1 = \text{softmax}(W_1 h + b_1) \quad (1)$$

where W_1 and b_1 are learnable parameters. The model is optimized using binary cross-entropy loss:

$$\mathcal{L}_1 = -(y \log(\hat{y}_1) + (1 - y) \log(1 - \hat{y}_1)) \quad (2)$$

where $y \in \{0,1\}$ denotes the ground truth label. The output of the first stage determines whether an input instance is forwarded to the second stage for fine-grained classification.

During the second phase, instances identified as cyberbullying are further classified into three distinct categories: harassment, denigration, and exclusion. This stage involves performing multi-class classification on the embedding representation h . The prediction is computed as:

$$\hat{y}_2 = \text{softmax}(W_2 h + b_2) \quad (3)$$

where W_2 and b_2 are learnable parameters. The model is optimized using categorical cross-entropy loss:

$$\mathcal{L}_2 = - \sum_{k=1}^3 y_k \log(\hat{y}_{2,k}) \quad (4)$$

where y_k represents the one-hot encoded ground truth label for class k .

Both stages are trained utilizing the Adam optimizer with a learning rate of 2×10^{-5} . The batch size is set to 16, and training is conducted for a maximum of 100 epochs, incorporating early stopping with a patience of 10, based on validation loss. A dropout rate of 0.3 is applied to the classification layers to mitigate overfitting. Gradient clipping with a maximum norm of 1.0 is employed to stabilize the optimization process. The optimal model is selected based on the validation F1-score and subsequently evaluated on the test set.

D. Evaluation Metrics

To evaluate the effectiveness of the proposed two-stage classification framework, four standard metrics are employed: accuracy, precision, recall, and F1-score. These metrics are calculated based on the counts of true positives (TP_k), false positives (FP_k), false negatives (FN_k) for each class k .

Accuracy measures the overall percentage of instances correctly classified among all predictions.

$$\text{Accuracy} = \frac{\sum_{k=1}^K TP_k}{N} \quad (5)$$

where K is the number of classes and N is the number of samples.

Precision quantifies the proportion of true positive predictions relative to the total number of positive predictions made.

$$\text{Precision} = \frac{TP_k}{TP_k + FP_k} \quad (6)$$

Recall evaluates the model's ability to accurately identify all true positive instances.

$$\text{Recall} = \frac{TP_k}{TP_k + FN_k} \quad (7)$$

The F1-score, which represents the harmonic mean of precision and recall, provides a comprehensive assessment of model performance.

$$F1_k = \frac{2 \cdot \text{Precision}_k \cdot \text{Recall}_k}{\text{Precision}_k + \text{Recall}_k} \quad (8)$$

IV. RESULT AND DISCUSSION

A. Hierarchical Two Stage BERT Model

In the initial phase, the model is utilized to categorize social media posts into two distinct groups:

cyberbullying and non-cyberbullying. The assessment is performed on a test set comprising 45 samples, with a distribution of 22 non-cyberbullying posts and 23 cyberbullying posts.

TABLE II. EVALUATION METRICS ON STAGE 1

	Precision	Recall	F1-score	Support
Not Bullying	1.00	1.00	1.00	22
Bullying	1.00	1.00	1.00	23
Accuracy			1.00	45
Macro Avg	1.00	1.00	1.00	45
Weighted Avg	1.00	1.00	1.00	45

According to the confusion matrix, the model accurately classifies all test samples. Specifically, it correctly predicts 22 non-cyberbullying posts as non-cyberbullying and accurately identifies 23 cyberbullying posts as cyberbullying. No misclassifications are present, indicating the absence of both false positives and false negatives. Consequently, the model achieves an accuracy of 100%, with precision, recall, and F1-score values of 1.00 for both classes. These findings demonstrate that the Stage 1 model possesses a robust capability in distinguishing between cyberbullying and non-cyberbullying content.

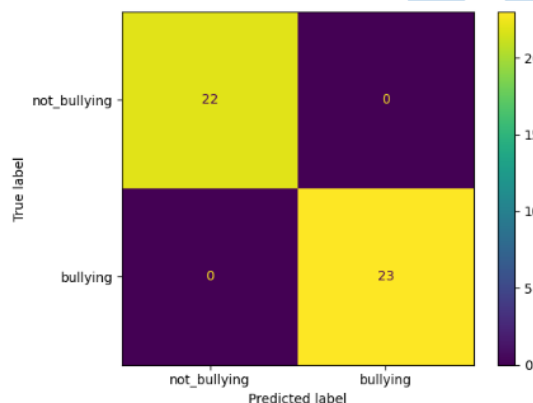


Fig 4. Confusion Matrix of Stage 1

The second stage of the proposed framework is dedicated to categorizing posts identified as cyberbullying in Stage 1 into three distinct categories: harassment, denigration, and exclusion. This stage functions conditionally, meaning that only posts predicted as cyberbullying are forwarded to the second classifier. The evaluation of Stage 2 is performed on 24 cyberbullying instances derived from the test set. The classification results indicate that the proposed model achieves an overall accuracy of 92%, demonstrating strong efficacy in differentiating between various types of cyberbullying.

TABLE III. EVALUATION METRICS ON STAGE 2

	Precision	Recall	F1-score	Support
Harrasment	0.80	1.00	0.89	4

Denigration	1.00	1.00	1.00	12
Exclusion	1.00	0.86	0.92	7
Accuracy			0.96	23
Macro Avg	0.93	0.95	0.94	23
Weighted Avg	0.97	0.96	0.96	23

According to the classification report, the harassment category exhibits robust performance, with a precision of 0.88, recall of 1.00, and an F1-score of 0.93. This indicates that the model is highly effective in identifying direct and explicit abusive expressions, with no instances of harassment overlooked during evaluation. The denigration category achieves a precision of 0.89, recall of 0.89, and an F1-score of 0.89, suggesting a balanced performance in detecting derogatory or defamatory content. Nevertheless, certain instances may still be misclassified as other forms of bullying due to overlapping linguistic features across categories. The exclusion category exhibits a precision of 1.00, a recall of 0.88, and an F1-score of 0.93, suggesting that while predictions for exclusion-related expressions are highly precise, a small number of exclusion instances remain undetected. Overall, the model attains an accuracy of 92%, with both macro-average and weighted-average F1-scores of 0.92, indicating robust and consistent performance in classifying various types of cyberbullying in the second stage.

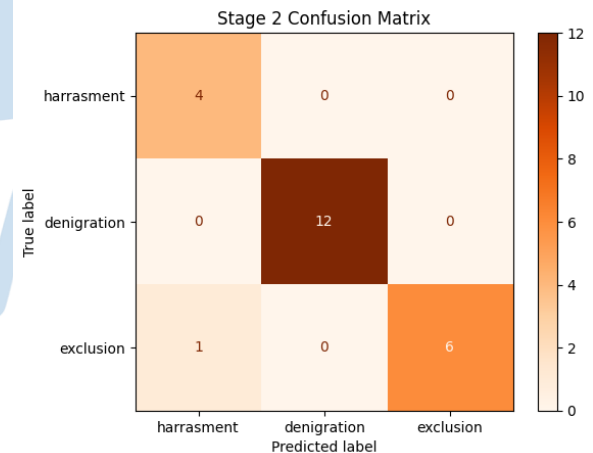


Fig 5. Confusion Matrix of Stage 2

Analysis of the confusion matrix provides additional insight into the classification behavior of the Stage 2 model. As shown in Fig. X, all harassment and denigration instances were correctly classified, indicating that these categories possess distinctive linguistic characteristics that can be effectively captured by the model. The only misclassification occurred when an exclusion instance was predicted as harassment. This confusion may arise because exclusion related messages can sometimes contain direct negative expressions or rejection statements that resemble explicit harassment. In contrast, denigration achieved perfect classification performance, suggesting

that statements targeting an individual's reputation or character exhibit more distinguishable semantic patterns. Overall, the confusion matrix indicates that the proposed model effectively separates the three cyberbullying categories, with classification errors occurring only in cases where category boundaries are linguistically subtle.

To further assess the practical applicability of the proposed two-stage framework, an inference experiment was conducted on previously unseen social media posts that were not part of the training, validation, or testing datasets. This experiment aims to simulate a real-world deployment scenario in which the model processes new incoming data. Each input text was initially analyzed by the Stage 1 classifier to ascertain whether it contains cyberbullying content. Only posts identified as cyberbullying were subsequently forwarded to the Stage 2 classifier for fine-grained categorization. This hierarchical inference procedure ensures that cyberbullying type classification is performed only when relevant.

TABLE IV. INFERENCE TESTING

New Data	Result: Stage 1	Result: Stage 2
Gobl*k bgtt gini aja gapaham	bullying	harrasment
Hmmm menarik sih idenya	not_bullying	none
Gausah diajak deh ganggu bgtt wkwkw	bullying	exclusion
Tukang kayu pembohong rakyat	bullying	denigration

The findings of this experiment indicate that the proposed framework effectively distinguishes between cyberbullying and non-cyberbullying content in previously unseen data. Moreover, for posts identified as cyberbullying, the Stage 2 model accurately assigns relevant cyberbullying categories, such as harassment, denigration, and exclusion. These qualitative results suggest that the model generalizes effectively beyond the evaluation dataset and maintains consistent performance during real-world inference.

B. Model Comparison

To evaluate the effectiveness of the proposed framework, its performance was compared with several traditional machine learning models, including Support Vector Machine (SVM), Decision Tree, Random Forest, and XGBoost. Tables V and VI present the results for Stage 1 binary classification and Stage 2 multi class classification, respectively.

For Stage 1, IndoBERT achieved the best overall performance, demonstrating its strong capability in distinguishing bullying from non bullying content. Among the traditional machine learning models,

Logistic Regression performed the best, while Random Forest also achieved competitive results. In contrast, SVM, Decision Tree, and XGBoost showed noticeably lower performance, indicating greater difficulty in capturing the contextual characteristics of cyberbullying language.

TABLE V. STAGE 1 RESULT COMPARISON

Model	Accuracy	Macro Precision	Macro Recall	Macro F1
SVM	0.73	0.83	0.71	0.70
DT	0.60	0.79	0.57	0.49
RF	0.82	0.88	0.81	0.81
XGB	0.60	0.79	0.57	0.49
Our	1.00	1.00	1.00	1.00

For Stage 2, Logistic Regression and IndoBERT achieved comparable performance and consistently outperformed the other models in classifying bullying categories. Random Forest produced moderate results, whereas SVM, Decision Tree, and XGBoost struggled to differentiate certain bullying types. These findings suggest that models capable of learning richer semantic representations are more effective for both binary cyberbullying detection and fine grained bullying type classification.

TABLE VI. STAGE 2 RESULT COMPARISON

Model	Accuracy	Macro Precision	Macro Recall	Macro F1
SVM	0.54	0.43	0.57	0.48
Decision Tree	0.42	0.43	0.48	0.36
Random Forest	0.79	0.83	0.81	0.77
XGBoost	0.62	0.80	0.67	0.60
Hierarchical Two Stage BERT	0.96	0.93	0.95	0.94

C. Ablation Study

The ablation study was conducted to evaluate the effectiveness of the proposed hierarchical classification framework. Instead of using the two stage architecture, a direct multi class classification approach was implemented in which the model directly predicted four classes: not bullying, harassment, denigration, and exclusion. The performance comparison between the direct multi class model and the proposed hierarchical framework is presented in Table VII.

TABLE VII. PERFORMANCE OF DIRECT MULTI CLASS CLASSIFICATION MODEL

Model	Accuracy	Macro Precision	Macro Recall	Macro F1
Direct Multi Class IndoBERT	0.84	0.87	0.84	0.82
Hierarchical Two Stage BERT	0.96	0.93	0.95	0.94

As shown in Table VII, the hierarchical two stage BERT model consistently outperformed the direct multi class approach across all evaluation metrics. The proposed framework achieved an accuracy of 0.960 and a macro F1 score of 0.940, compared with 0.840 and 0.820, respectively, for the direct multi class model. Similar improvements were observed in macro precision and macro recall, indicating that the hierarchical framework provides more balanced classification performance across all classes.

These results demonstrate the benefit of decomposing the cyberbullying classification task into two sequential stages. By first identifying bullying content and then classifying the bullying type, the model can focus on more specialized objectives at each stage. This design reduces the complexity of the overall task and enables the model to learn more discriminative representations, resulting in superior performance compared with directly predicting all classes in a single step.

V. LIMITATIONS AND FUTURE WORK

This study utilized a dataset of 300 tweets collected from X (formerly Twitter). During data collection, it was observed that the frequency of cyberbullying categories varied considerably. While some categories were relatively common, others appeared much less frequently, making it challenging to obtain a balanced dataset across all classes. As a result, the study was conducted using a limited number of samples while maintaining a reasonable distribution among the selected categories.

Future research may expand the dataset by employing a broader set of cyberbullying related keywords to capture more diverse linguistic expressions and contexts. Although a larger keyword set would require additional filtering and annotation efforts, it could increase data diversity and improve model generalization. In addition, future studies may explore larger datasets collected over longer time periods and from multiple social media platforms.

Furthermore, this study focused on three cyberbullying categories: harassment, denigration, and exclusion. Future work may extend the proposed framework to include other forms of cyberbullying, such as flaming, cyberstalking, outing, impersonation, and other abusive online behaviors. Such an extension would provide a more comprehensive cyberbullying

detection framework and further evaluate the effectiveness of the proposed hierarchical classification approach.

VI. CONCLUSION

This study presents a two-stage framework for the detection of cyberbullying on Indonesian social media platforms, employing IndoBERTweet. The first stage involves a binary classification to distinguish between bullying and non-bullying content. Subsequently, the second stage categorizes instances of bullying into harassment/flaming, denigration, and exclusion. This hierarchical approach enables a more precise modeling of the diverse and context-dependent manifestations of cyberbullying.

Experimental results demonstrate that the proposed method consistently exhibits robust performance across both stages, characterized by high precision and recall. In contrast to previous studies that rely on traditional machine learning and handcrafted features, the utilization of a pretrained transformer model enhances the system's capacity to effectively capture contextual and implicit abusive expressions. Overall, the findings suggest that integrating IndoBERTweet with a two-stage classification strategy constitutes an effective approach for detecting cyberbullying in Indonesian social media.

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Optimization of Posyandu Data Collection using Web Information System and Plan Do Check Act Model

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Abstract— This study aims to optimize Posyandu data management through a Web-Based Information System (WBIS) integrated with the Plan-Do-Check-Act (PDCA) cycle to improve the efficiency and sustainability of Maternal and Child Health (MCH) services. The research employed a Research and Development (R&D) methodology using the 4D model (Define, Design, Develop, Disseminate) combined with a socio-technical approach. The system was implemented and evaluated based on user requirements. Data were collected from 25 Posyandu volunteers and 3 community health center (Puskesmas) officers through observations, interviews, and structured questionnaires. The system was developed using a clientserver architecture with a relational database and was subsequently evaluated through functional testing and user acceptance testing. Empirical results indicate that the system significantly improved data management performance by reducing the average time required for data entry and report preparation by 76.4%, from 145 minutes using manual recording methods to 34.2 minutes using the digital system. Functional testing using the Black-Box Testing method achieved a 100% success rate across all major system modules. Evaluation using the System Usability Scale (SUS) yielded an average score of 81.5, placing the system in the “Excellent” usability category with a Grade A rating. The integration of the PDCA cycle supports continuous improvement processes in planning, data recording, evaluation, and the implementation of health interventions. This study produces a scalable and data-driven framework that has proven effective in reducing administrative workload, eliminating data redundancy, and providing strong quantitative validation for the digital transformation of community-based healthcare governance.

Index Terms— Information System; Plan Do Check Act Model; Posyandu; System Usability Scale; Maternal and Child Health

I. INTRODUCTION

Integrated Health Service Posts (Posyandu) serve as the frontline of community-based healthcare services in Indonesia, particularly in supporting the health of mothers, infants, toddlers, and older adults. Posyandu also plays a strategic role in stunting prevention efforts,

which remain one of the major public health challenges at the national level [1].

In line with the ongoing digital transformation [2] in the healthcare sector [3], the implementation of web-based information systems offers a strategic solution for improving the efficiency and accuracy of health data recording and management [4]. Globally, various electronic health (e-health) programs [5] have been developed to provide real-time data that support faster and more informed decision-making processes. From a socio-technical perspective, the development of a Posyandu Information System [6] should balance both technical and social considerations. From the technical standpoint [7], the system should provide functionalities such as participant registration, maternal and child health record management, nutritional status monitoring, and automated reporting [8]. From the social perspective [9], successful implementation depends heavily on the digital literacy of Posyandu volunteers [10], support from healthcare professionals, and active community participation [11]. To ensure system quality and sustainability, the Plan-Do-Check-Act (PDCA) cycle provides a relevant framework for implementation [12]. PDCA facilitates continuous evaluation and improvement processes, ranging from needs assessment and implementation to data accuracy monitoring and corrective actions [13], including feature enhancement and retraining of Posyandu volunteers. Previous studies on community health [14] information systems have generally treated software engineering and quality assurance as separate domains. Most implementations have focused primarily on technical system development [15] without establishing structured operational feedback mechanisms. Consequently, the long-term sustainability of system usage often declines when volunteers encounter data-related issues or operational challenges [16]. Conversely, PDCA frameworks in healthcare settings are frequently applied to manual administrative processes without digital support tools [17].

This study seeks to bridge this gap by directly integrating the PDCA cycle into both the software architecture and operational workflow of a Web-Based

Information System (WBIS). Through this integration, the Posyandu Information System functions [18] not only as a data management tool but also as a socio-technical system that supports continuous service quality improvement. Furthermore, the system contributes to achieving national targets for stunting reduction through data-driven healthcare governance and sustainable community health service management [19].

Based on the problems identified, this study is formulated around the following research questions:

1. To what extent does the manual data management architecture currently implemented at Posyandu Nagari Pagaruyung contribute to operational inefficiencies and inaccuracies in data analysis?
2. What software engineering requirements and specifications are necessary to develop a responsive, multi-user, web-based Posyandu Information System that is suitable for users with limited digital literacy?
3. How can the PDCA quality management framework be systematically integrated into the data flow and business processes of the information system?
4. To what extent does the developed system improve data entry efficiency, operational accuracy, and user acceptance among Posyandu volunteers?

Based on these research questions, the objectives of this study are: (1) to analyze the existing manual practices of Posyandu data management; (2) to design a web-based Posyandu Information System; (3) to integrate the PDCA methodology into the developed system; and (4) to develop and quantitatively evaluate the system in order to improve efficiency, accuracy, and the quality of maternal and child healthcare services.

From a theoretical perspective, this study is grounded in the concept of Posyandu as a primary healthcare service that emphasizes community participation [20], information systems theory [21] which highlights the integration of people, hardware, software, data, and networks to generate accurate and meaningful information [22], the advantages of web-based systems in providing accessibility, flexibility, and real-time data presentation [23], and the application of the PDCA cycle as a continuous quality improvement approach. Previous studies have demonstrated that the digitalization of Posyandu services can improve data accuracy [24], support maternal and child health monitoring [25], and strengthen system sustainability through socio-technical approaches [26]. Nevertheless, the integration of the PDCA cycle into Posyandu Information Systems [27] remains relatively underexplored. Therefore, this study offers a novel contribution through the development of a web-based Posyandu Information System [28] that comprehensively integrates the PDCA cycle [29] to support more effective, efficient, and sustainable community health data management [30].

I. METHODOLOGY

This study employed a systematic Research and Development (R&D) framework by implementing the 4D Development Model (Define, Design, Develop, and Disseminate), integrated with a socio-technical quality management approach. This methodology was selected to develop an information system that not only fulfills users' technical requirements but also considers social, organizational, and sustainability aspects within the Posyandu environment. The research was conducted at Posyandu Nagari Pagaruyung, Tanjung Emas District, Tanah Datar Regency, West Sumatra Province, Indonesia. The study site was selected because health data recording and management processes were still predominantly performed manually, creating a need for transformation toward a more effective and efficient digital system.

The research participants consisted of 28 key stakeholders, including 25 active Posyandu volunteers distributed across several Posyandu units in Nagari Pagaruyung and 3 healthcare administration officers from the Community Health Center (Puskesmas) responsible for managing and reporting public health data. Respondents were selected using purposive sampling based on specific criteria, namely Posyandu volunteers with at least one year of field experience and active responsibility for manual health data recording processes. Meanwhile, the Puskesmas officers were selected because of their direct involvement in the verification, monitoring, and reporting of health data generated by Posyandu activities.

Through the active involvement of these stakeholders, this study aims to develop a web-based Posyandu Information System that aligns with user needs, is easy to use, and supports continuous improvement in maternal and child healthcare services through the implementation of the PDCA cycle. The integration of technical system development with socio-technical quality management principles is expected to enhance system adoption, operational effectiveness, and the long-term sustainability of digital healthcare services at the community level.

The system engineering and evaluation activities in this study were aligned with the four iterative phases of the PDCA cycle as follows:

1. Plan (Define and Design)

During the planning phase, field observations and time motion studies were conducted to map the workflow of Posyandu data recording processes, which were still performed manually. In addition, a user requirements analysis was carried out to identify existing problems and system needs. The findings from this analysis were subsequently used to formulate system requirements specifications, design the system model using Unified Modeling Language (UML), and develop a normalized relational database schema that served as the foundation for system development.

2. Do (Develop)

During the implementation phase, a web-based Posyandu Information System was developed using a client-server architecture with PHP, JavaScript, and MySQL technologies. The system was designed to support integrated health data recording and management processes. Furthermore, an automated data validation mechanism was implemented to prevent data duplication, input errors, and the loss of critical data attributes during data entry activities.

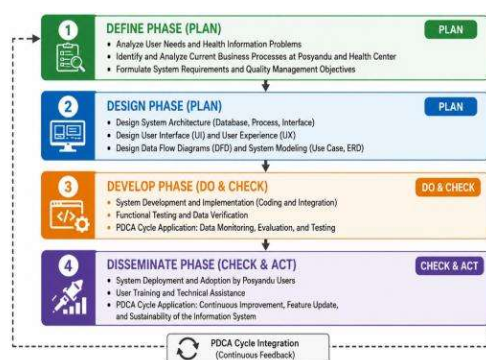


Fig. 1. PDCA Cycle

3. Check (Evaluate)

The evaluation phase involved comprehensive technical testing and user assessment. Technical validation was conducted using the Black-Box Testing method to ensure that all system functions operated according to specifications, including verification of input parameters, output results, and system boundary conditions. Subsequently, user acceptance and system usability were evaluated using the standardized and psychometrically validated System Usability Scale (SUS) instrument. The SUS questionnaire was administered to all 28 respondents, consisting of Posyandu volunteers and Puskesmas healthcare officers.

4. Act (Optimize)

The action phase focused on system optimization and refinement based on evaluation outcomes. Various findings identified during testing, including system bugs, user interface friction points, and requirements for additional features such as nutritional status threshold notifications for children under five were utilized as the basis for system improvement through code refactoring and functional enhancement. This phase ensured that the system could continuously evolve and adapt to users' needs in a sustainable manner. To ensure data validity during the initial stage of the study, source and methodological triangulation techniques were employed. Validation was performed by comparing information obtained from in-depth interviews with Posyandu volunteers and healthcare officers against data recorded in manual Posyandu registration books. This approach was intended to ensure the consistency, accuracy, and credibility of the data used throughout the analysis and system development processes.

II. RESULT AND FINDINGS

A. Evaluation of the Initial Conditions Prior to System Implementation

Posyandu in Nagari Pagaruyung serves as a community-based healthcare facility that provides services for pregnant women, breastfeeding mothers, children under five years of age, and older adults (elderly populations). Observations of the existing manual workflow (baseline workflow) using a time-motion study revealed several significant operational challenges. Posyandu volunteers were still recording body weight, height, immunization status, and other health-related information manually across multiple registration books and separate reporting forms.

The process of preparing monthly reports for submission to the Community Health Center (Puskesmas) was particularly time-consuming because volunteers were required to collect, verify, and consolidate data from various manual records. Measurement results indicated that preparing a single monthly report required an average of 145 minutes for each Posyandu unit. Most of this time was spent reviewing data entries, correcting recording errors, eliminating duplicate information, and calculating nutritional status indicators using paper-based reference tables.

These conditions resulted in low operational efficiency, a high risk of data inaccuracies, and delays in the submission of health reports to the Puskesmas. Furthermore, the reliance on manual record-keeping limited the ability of healthcare workers to access timely and accurate information for monitoring maternal and child health conditions and supporting evidence-based decision-making.

B. System Engineering Architecture and Interface Specifications

The developed Web-Based Posyandu Information System (WBIS) was designed with a responsive user interface, enabling access through both desktop computers and smartphones using standard web browsers. To meet international publication standards and user requirements, the software architecture and interface configurations were developed according to established software engineering principles and usability standards. The system consists of several core modules that support Posyandu service operations, including: Participant Registration Module, Maternal and Child Health Examination Module, Reporting and Data Analytics Module, and Child Growth and Development Monitoring Module.

These modules were designed to support integrated health data management processes, ranging from data collection and storage to automated reporting and analytical information generation. Through this integrated architecture, health data can be processed more efficiently, consistently, and accurately, thereby reducing administrative workload and improving the availability of real-time information for healthcare decision-making.

The responsive interface design also ensures accessibility for users with varying levels of digital literacy. User interaction workflows were simplified through intuitive navigation structures, standardized data entry forms, and automated validation features. As a result, Posyandu volunteers can perform data recording and reporting tasks more effectively while minimizing the likelihood of input errors and data inconsistencies.

The overall system architecture follows a client server model, where users interact with the application through web browsers, while data processing and storage are managed centrally within a relational database management system. This architecture facilitates data integration, improves data security, and supports scalability for future implementation across multiple Posyandu units and healthcare facilities.

TABLE I. WEB-BASED INFORMATION SYSTEM DESIGN AND PDCA CYCLE MAPPING

Component	Technical Specifications and Architecture	Relationship with PDCA and Analytical Significance
System Design	Blueprint constructed based on database normalization and responsive web architecture.	Plan: Establishing the operational framework of the system based on identified user requirements.
System Architecture	Client: Responsive HTML5/JavaScript for PC and mobile. Server: PHP as core logic. Database: Relational MySQL.	Do: Executing real-time data transactions, managing user sessions, and maintaining data storage integrity.
Process Design	Plan: Service target setting. Do: Field data entry. Check: Automated reporting/evaluation. Act: Continuous health intervention monitoring.	Continuous Cycle: Ensuring that entered data is processed immediately into evaluative information and health action recommendations.
User Interface	Specialized panels for Registration, Health Examination, Analytics, and Growth Monitoring.	Do & Check: Reducing manual recording burden for health workers and facilitating real-time data monitoring.
Database Design	Primary tables including tbl_mother, tbl_child, tbl_examination, and tbl_monthly_report.	Do: Ensuring relational data integrity via foreign keys, preventing data duplication, and maintaining information consistency.
Conceptual Blueprint	Use Case Diagrams, Entity Relationship Diagrams (ERD), and System Process Flow Diagrams.	Plan: Providing technical clarity regarding user access rights and system execution flows.

Table I explains the structural architecture of the developed system. Unlike conceptual approaches that view PDCA merely as a quality management

framework, this research integrates the PDCA cycle directly into the database structure and system workflow. For example, when health workers input examination data into the tbl_examination table during the **Do** stage, the system automatically triggers an analytical engine to recalculate growth indicators and nutritional status, update child development charts, and generate evaluation reports for the **Check** stage. Subsequently, these analytical findings are used to update the health monitoring dashboard, which serves as the foundation for nutrition interventions and health follow-ups during the **Act** stage.

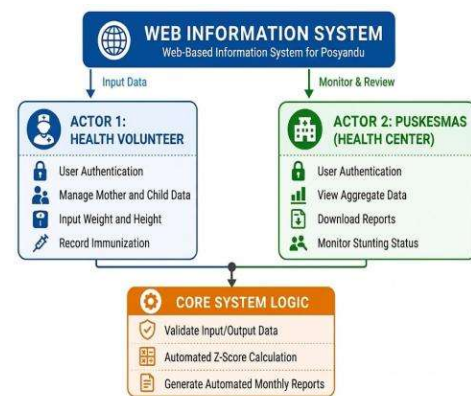


Fig. 2. Web Information System

Figure 2 presents the Use Case structure mapping of the developed web-based Posyandu Information System. The system design strictly implements a separation of duties and access rights to maintain data security, integrity, and consistency. Posyandu volunteers are granted access rights to record and manage health examination data at the Posyandu level, including entering mother and child data, measuring weight and height, and recording immunizations. Meanwhile, Puskesmas (Public Health Center) officers hold access rights at the managerial level to view, monitor, and analyze data accumulated from various Posyandus in an integrated manner. Through this mechanism, reporting processes that were previously manual and time-consuming are eliminated, allowing health information to be available more quickly, accurately, and in real-time to support decision-making and public health condition monitoring, including the early detection of stunting risks.

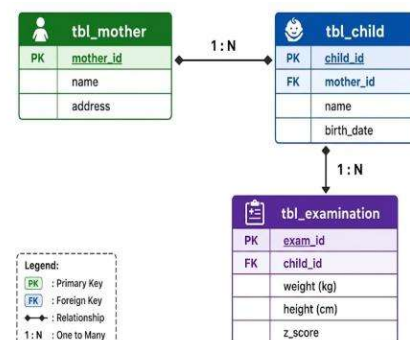


Fig. 3. Relational Database

Figure 3 illustrates the normalized relational database schema. By implementing unique primary keys in the `tbl_mother` and `tbl_child` tables and establishing a one-to-many relationship between them, the database architecture effectively reduces and eliminates data redundancy. This structure also prevents duplicate child registrations a common issue in manual, register-based recording systems thereby enhancing the consistency, integrity, and accuracy of the health data stored within the system.

Fig. 4. Child Immunization Form

Fig. 5. Maternal Weighting Form

Figures 4 and 5 present the system's input interface, which has been customized for operational use in the field. To support implementation in environments with varying levels of digital literacy, the system's forms are equipped with inline input validation mechanisms using HTML5 technology. In the Child Immunization Form (Figure 4), the system automatically rejects data storage if any mandatory vaccine fields remain empty. This mechanism helps ensure the completeness of immunization data and reduces recording errors. Meanwhile, the Pregnant Mother Examination Form (Figure 5) is equipped with real-time boundary verification logic that operates automatically as the user inputs data. For example, if a user inputs a gestational age outside the permitted range of 1–42 weeks, the system immediately displays a visual warning, allowing errors to be detected and corrected during the data entry process. These validation features play a crucial role in improving data quality, minimizing input errors, and supporting more accurate and timely health decision-making.

C. Quantitative System Evaluation and Experimental Validation

To meet the requirements for measurable empirical verification, the developed system was evaluated using three key indicators: Functional Feature Testing, Operational Velocity Evaluation, and Psychometric Usability Testing. These three approaches were employed to assess the reliability of system functions, improvements in operational efficiency, and the level of user acceptance of the developed information system.

TABLE II. QUANTITATIVE BLACK-BOX FUNCTIONAL TESTING MATRIX

Tested Module	Input Scenario Provided	Expected System Output	Actual System Result	Success Rate
Authentication	Valid username and correct encrypted password	System grants access and directs user to role-specific dashboard	As-expected	100%
Authentication	Invalid username or incorrect password	System denies access and displays an authentication error message	As-expected	100%
Registration	New child data linked to an existing mother_id	System creates new data in <code>tbl_child</code> with correct foreign key relationship	As-expected	100%
Data Validation	Input of same child name with identical date of birth	System rejects data storage and displays a duplication warning	As-expected	100%
Calculation Engine	Child age = 12 months, weight = 10 kg, height = 75 cm	System automatically calculates Z-Score and determines nutritional status	As-expected (Normal Status)	100%
Report Panel	Request for "Integrated Monthly Summary" report	System compiles data from <code>tbl_examination</code> and exports report in PDF or Excel	As-expected	100%

The results in Table II indicate that the system achieved a functional success rate of 100% across all six core modules tested using Black-Box Testing methods. The testing was conducted using various input scenarios and boundary conditions (boundary testing) to ensure that every system function operates according to the established specifications.

The success of these tests indicates that the mechanisms for authentication, data registration, input validation, nutritional status calculation, and automated report generation perform consistently without any functional failures. Consequently, it can be concluded that the developed software logic possesses a high degree of reliability and is suitable for use in

real-world operational conditions within the Posyandu environment. Furthermore, the 100% success rate across all modules demonstrates that the integration between the user interface, application logic, and the database is optimal, enabling the accurate, efficient, and sustainable management of health data.

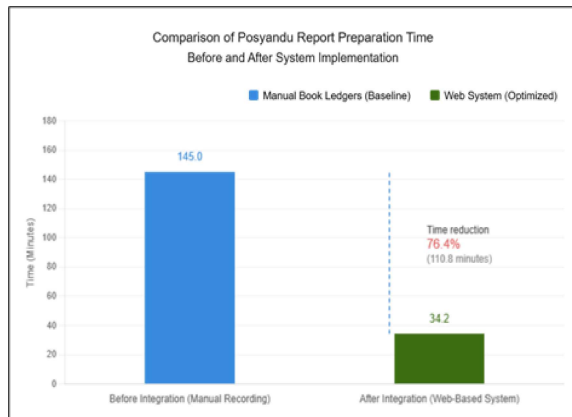


Fig. 6. Report Preparation Time Comparison Manual vs Web-Based System

A time-motion tracking evaluation was conducted to measure the operational efficiency of the developed system. The measurement involved comparing the use of the web-based information system with the manual recording method using Posyandu administration books. The observed activities included participant registration, data recording for 50 toddler visits, nutritional status calculation, and the preparation of monthly reports.

The evaluation results show that the manual process requires an average of 145.0 minutes to complete one reporting cycle. Conversely, using the web-based Posyandu Information System, the same workload can be completed in just 34.2 minutes. These findings indicate a 76.4% reduction in administrative time, representing a highly significant increase in operational efficiency. This time reduction allows Posyandu volunteers to decrease repetitive administrative burdens and allocate more time to direct community health services, such as monitoring child growth and development, health education, and providing assistance to mothers and toddlers. Beyond increasing the productivity of volunteers, the digitalization of the recording process contributes to improved data accuracy, faster reporting, and overall enhancement of health service quality.

User acceptance was measured using the standardized System Usability Scale (SUS) instrument, administered to all 28 active participants comprising 25 Posyandu cadres and 3 Puskesmas health officers. The evaluation results show that the system achieved a mean SUS score of 81.5. Based on SUS psychometric interpretation standards, this score places the web-based Posyandu Information System in the "Excellent" category with a Grade A rating. This indicates that the system has a high level of usability

and is very well accepted by its users. The high score also suggests that the system's interface, features, and workflows are easy to understand and operate including for Posyandu cadres with limited technical experience and digital literacy.

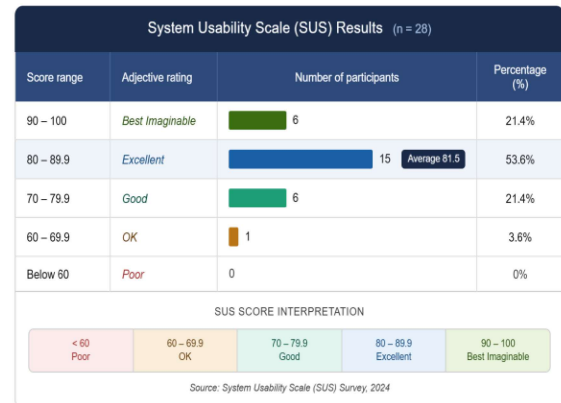


Fig. 7. System Usability Scale

These findings reinforce that the developed system not only meets functional requirements but also delivers a positive user experience, thereby supporting the sustainability of its implementation in the digital management of Posyandu data. The high level of user acceptance is an important indicator that the system can be effectively adopted to improve the quality of maternal and child health data recording, reporting, and management within the Posyandu setting.

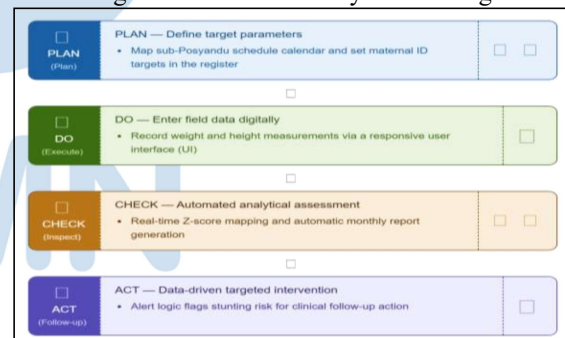


Fig. 8. Synthesis of PDCA

Figure 8 demonstrates the implementation and integration of the PDCA cycle into the web-based Posyandu Information System. Unlike conventional approaches that view PDCA merely as a theoretical quality management concept, this research implements PDCA as an operational workflow loop integrated directly with business processes and health data management within the system. **Plan** → At this stage, the system is used to manage Posyandu activity schedules, determine service targets, and identify community groups requiring special attention, such as pregnant women, toddlers, and children at risk of nutritional issues. This process helps ensure that baseline data coverage is obtained in a complete and structured manner. **Do** → The system supports real-time health data entry through a responsive web-based

interface. Digital recording replaces the manual method of using register books, allowing child growth and development data to be recorded directly as services occur. This mechanism increases recording speed while reducing the risk of errors and data loss. **Check** → Once data is entered, the system automatically processes and analyzes health data based on growth standards established by the World Health Organization (WHO). Calculations of nutritional status indicators and Z-scores are performed automatically, replacing manual analysis which was previously time-consuming and prone to error with rapid, accurate, and consistent reporting and evaluation. **Act** → At this stage, the system dashboard automatically flags children identified as being at risk of undernutrition, malnutrition, or stunting. This information generates a list of intervention targets that Posyandu volunteers and Puskesmas officers can use to provide targeted nutritional support and guidance. The intervention results are then used as input for planning subsequent activities, thus forming a continuous quality improvement cycle that completes the PDCA process. The integration of the PDCA cycle into the Posyandu Information System demonstrates that the developed system functions not only as a medium for health data recording but also as a data-driven decision support system capable of continuously improving the quality of maternal and child health services.

TABLE III. COMPREHENSIVE MATRIX OF SYSTEM RESULT, EMPIRICAL FINDINGS, AND SOCIO-TECHNICAL IMPLICATIONS

Evaluated Domain	Key System Outputs	Objective Empirical Findings	Socio-Technical Strategic Implications
System Engineering	Responsive web-based information system prototype with a normalized MySQL database.	Feature execution success rate reached 100% based on the Black-Box Testing functional validation matrix.	Demonstrates that implementing a sound database structure and robust validation mechanisms can maintain health data integrity, even in resource-constrained technological environments.
Operational Efficiency	Automated growth chart generation and recapitulasi reports.	A 76.4% reduction in processing time, decreasing from an average of 145.0 minutes to 34.2 minutes.	Reduces the administrative burden on Posyandu volunteers, allowing them to focus more on direct health services and community support rather than repetitive administrative tasks.
User Acceptance	Simple, user-friendly interface with clear navigation and accessible language.	Achieved an average System Usability Scale (SUS) score of 81.5, categorized as "Excellent"	Proves that applying user-centered design principles can overcome digital literacy barriers and increase technology

		with a Grade A rating.	adoption among Posyandu volunteers and health workers.
PDCA Integration	Closed-loop system connecting data entry directly to nutritional status and stunting risk notifications.	Collected health data can be immediately processed into clinical indicators to automatically detect and monitor stunting risks.	Establishes a sustainable, data-driven public health management framework that supports continuous service quality improvement through the PDCA cycle.

Table III summarizes the overall research findings obtained from the development, implementation, and evaluation processes of the web-based Posyandu Information System. The results demonstrate that combining a systematic Research and Development (R&D) methodology with the implementation of the PDCA framework provides benefits that extend far beyond simple digitalization of data recording. The developed system not only improves the efficiency and accuracy of health data management but also establishes an evaluation and continuous improvement mechanism integrated directly into the Posyandu's operational processes. Empirically, this research proves that work environments with relatively low levels of digital literacy can successfully transform toward data-driven health governance when supported by software that is user-tailored, intuitive, and equipped with structured quality control mechanisms. These findings emphasize the importance of integrating technological, human, and organizational process aspects to support the successful digital transformation of community health services.

III. DISCUSSION

A. Evaluation of the Initial Conditions Prior to System Implementation

The analysis of the Posyandu in Nagari Pagaruyung prior to the intervention reveals critical structural inefficiencies typical of paper-based community health settings. The baseline workflow, characterized by disjointed administrative tasks, highlights a significant divergence between data generation at the point of care and its consolidation for public health reporting.

The reliance on manual register books creates a "data silo" effect, where health indicators such as anthropometric measurements, immunization statuses, and maternal history remain fragmented across multiple physical documents. The time-motion study reveals that this manual workflow consumes an average of 145 minutes per reporting cycle per Posyandu. Critically, this duration is not spent on patient interaction or health intervention, but rather on non-value-added administrative overhead, including manual data collation, redundant cross-referencing, and paper-based nutritional status calculations (e.g., Z-score determination via reference tables).

From a socio-technical perspective, these baseline conditions impose significant cognitive and operational burdens on health volunteers (kader). The manual nature of these tasks introduces high susceptibility to human error, such as data entry inaccuracies, omissions, and duplicate records, which fundamentally compromise the longitudinal integrity of public health data. Furthermore, the delay between the collection of health metrics at the community level and the downstream aggregation at the Puskesmas level effectively negates the potential for real-time health monitoring. This "latency in reporting" prevents the timely identification of public health risks, such as stunting or malnutrition, thereby illustrating an urgent need for the transition toward digitalized, data-driven governance to enhance both service quality and the efficacy of health interventions.

B. System Engineering and Interface Architecture

The architectural design of the Web-Based Posyandu Information System (WPBIS) represents a strategic shift from monolithic, paper-based workflows toward a decoupled, client server computing model. By leveraging a responsive, browser-based interface, the system effectively mitigates the "digital divide" often observed in rural health environments, ensuring cross-platform accessibility that accommodates the hardware constraints of field-based Posyandu volunteers.

From a systems engineering perspective, the modular architecture comprising specialized units for registration, maternal/child examinations, analytics, and growth monitoring facilitates an integrated data lifecycle. This design ensures that raw data collected at the point of service is immediately ingested into a normalized relational database, thereby ensuring data persistence and referential integrity. By transitioning from fragmented physical ledgers to a centralized digital schema, the system inherently addresses the risks of information entropy, such as data duplication and orphan records, which are prevalent in manual register-based systems.

Furthermore, the integration of automated validation logic and intuitive UI design principles serves as a critical socio-technical intervention. By embedding technical guardrails (e.g., HTML5 validation and real-time error checking) directly into the user interface, the system reduces the cognitive load on the end-user. This approach effectively lowers the barrier to entry for personnel with lower levels of digital literacy, transforming the software from a mere recording tool into an active partner in data quality assurance.

The adoption of a client server architecture provides significant long-term strategic advantages. Centralized data management not only bolsters security protocols through structured access controls but also ensures system scalability. This architecture provides the necessary infrastructure for future interoperability, enabling the potential aggregation of health data across regional healthcare networks, which

is an essential prerequisite for evidence-based public health planning and sophisticated predictive health analytics.

The integration of the PDCA cycle into the architectural fabric of the Web-Based Posyandu Information System (WPBIS) represents a departure from traditional, passive data-recording models. By embedding quality management directly into the system logic, the research transforms the WPBIS into an active, data-driven governance tool. Key points of this integration and its technical implications are discussed below:

Operationalization of the PDCA Cycle: Unlike static management frameworks, this system hardcodes the PDCA cycle into the workflow. The **Plan** phase is facilitated through structured architectural blueprints and requirement mapping. The **Do** phase is realized via real-time data transactions using a robust client server architecture. The **Check** phase is automated through an analytical engine that processes growth indicators, while the **Act** phase is supported by a dynamic monitoring dashboard that informs health interventions.

Socio-Technical Access Control: The system enforces a clear separation of duties, aligning user access rights with operational hierarchies. Posyandu volunteers are restricted to transactional data entry, whereas Puskesmas officers possess managerial oversight for integrated data analysis. This design not only ensures data security and integrity but also streamlines organizational reporting, eliminating the time-lag characteristic of manual, paper-based workflows.

Relational Integrity as a Quality Mechanism: The normalization of the database schema (e.g., tbl_mother to tbl_child one-to-many relationships) is a strategic intervention to eliminate redundancy and duplicate registrations. This structural integrity is fundamental to maintaining accurate longitudinal data, which is essential for effective public health monitoring and stunting risk detection.

Mitigating Cognitive and Operational Errors: The implementation of inline input validation and real-time boundary verification using HTML5 technologies acts as a technical guardrail against human error. By rejecting incomplete data or out-of-range inputs (e.g., gestation outside 1–42 weeks) at the point of entry, the system ensures high data quality without placing undue cognitive burden on field volunteers with varying levels of digital literacy.

The synergy between these technical components suggests that digital transformation in community health is most effective when software engineering principles (normalization, responsive architecture, and validation) are explicitly aligned with organizational quality objectives (the PDCA cycle). This integrated approach provides a scalable foundation for

continuous, evidence-based public health management.

C. System Evaluation and Socio-Technical Impact

The experimental validation of the Web-Based Posyandu Information System (WPIS) confirms that systematic digital transformation when underpinned by robust engineering and organizational frameworks serves as a catalyst for improving public health governance. The evaluation outcomes can be summarized through the following key dimensions.

Software Reliability as a Foundational Prerequisite: The 100% success rate in Black-Box functional testing across all six core modules provides empirical assurance of the system's backend logic. This reliability is critical; in community health settings, even minor software failures can lead to significant data integrity risks or user distrust, thereby undermining the viability of digital adoption.

Operational Velocity and the Mitigation of Administrative Burden: The transition from manual registers to the WPIS yielded a 76.4% reduction in reporting time (from 145.0 to 34.2 minutes). This represents a paradigm shift in the Posyandu volunteer's role: by automating repetitive tasks like Z-score calculations and report collation, the system reclaims time for high-value activities such as maternal health education, growth monitoring, and personalized nutritional intervention.

User-Centric Design as a Catalyst for Adoption: Achieving a SUS score of 81.5 (Grade A, "Excellent") proves that technological sophistication does not require high user technical proficiency. The system's success validates that user-centered design characterized by intuitive navigation and real-time input validation effectively bridges the digital literacy gap, transforming the software from a complex requirement into a facilitating tool for local health cadres.

Closed-Loop Governance via PDCA Integration: The most significant contribution of this research is the operationalization of the PDCA cycle within the system's workflow. By hardcoding "Check" (automated growth analysis) and "Act" (stunting risk flagging) mechanisms into the "Do" (data entry) process, the system facilitates a continuous quality improvement cycle. This transforms the Posyandu from a simple repository of records into a proactive, data-driven decision support environment where health interventions are timely, evidence-based, and targeted toward high-risk groups.

In summary, the research demonstrates that the successful digitalization of community health is a socio-technical endeavor. The alignment of technical robustness (system engineering), operational efficiency (time-motion optimization), and

organizational process integration (PDCA) creates a sustainable framework that can enhance the quality of maternal and child health services on a larger scale.

IV. CONCLUSION

This research has successfully developed, validated, and evaluated a Web-Based Posyandu Information System integrated with the PDCA continuous quality improvement model. By achieving the four predefined research objectives, this study demonstrates a significant improvement compared to the manual, register-based recording system previously used at Posyandu. Empirical test results prove that the developed system possesses a high level of reliability, indicated by a 100% success rate in functional testing using the Black-Box Testing method. Furthermore, the system significantly enhances administrative efficiency by reducing the time required for recording and reporting processes by 76.4%, from an average of 145 minutes with the manual method to just 34.2 minutes with the web-based system. User evaluation using the System Usability Scale (SUS) instrument yielded an average score of 81.5, placing the system in the "Excellent" category with a Grade A rating. These results indicate that the system is user-friendly and well-accepted by both Posyandu volunteers and Puskesmas officers, including users with limited digital literacy.

The primary contribution of this research lies in the practical implementation of the PDCA cycle into software architecture and health data management workflows. Unlike approaches that view PDCA merely as a theoretical quality management concept, the developed system integrates this cycle directly into operational processes ranging from service target planning and health data recording to automated growth and nutritional status analysis, as well as stunting risk identification that can be immediately addressed through targeted health interventions. Although system implementation is currently limited to the Posyandu environment in Nagari Pagaruyung, the obtained results demonstrate immense potential for adoption across other Posyandus and public health service networks at regional and national levels. The measurable improvements in efficiency, data accuracy, and decision-making quality provide a strong foundation for the development and expansion of the system on a larger scale.

Consequently, the socio-technical model proposed in this research can serve as an effective framework to support the digital transformation of public health services, particularly in real-time maternal and child health monitoring, the improvement of health data governance, and data-driven stunting prevention efforts. Beyond providing operational benefits for volunteers and health workers, this system contributes to supporting faster, more accurate, and sustainable decision-making in the management of public health programs.

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An Analysis of the Knowledge-Attitude-Behavior Approach to Personal Data Security Resilience Among Students in West Java

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Abstract— Digital transformation in the higher education sector poses significant risks to students' personal data security. Data breach incidents within campus environments demonstrate that state-of-the-art technological infrastructure will not be effective unless complemented by user security awareness. This study aims to analyze the personal data security resilience of students in West Java through the Knowledge-Attitude-Behavior approach. A quantitative survey method was applied to collect and evaluate students' empirical responses regarding their cognitive understanding of cyber risks, emotional responses to privacy policies, and concrete actions in protecting sensitive information. The evaluation results of these three dimensions are expected to measure the readiness and effectiveness of students as the first line of defense, or a human firewall, against various cybercrime threats. The findings of this study are projected to provide an empirical foundation for higher education institutions and policymakers in designing mitigation strategies and comprehensive, sustainable cybersecurity literacy programs.

Index Terms— Human firewall; personal data security; Knowledge-Attitude-Behavior; cyber literacy; West Java students

I. INTRODUCTION

The development of digital transformation in higher education institutions has fundamentally altered the landscape of academic and administrative information management. While this digitalization provides massive operational efficiency, it has drastically expanded the attack surface for cybercriminals, positioning students' personal data at unprecedented risk. The phenomenon of data exploitation and data breaches within the campus environment currently exhibits an alarming escalation, encompassing identity theft, social engineering attacks, and large-scale academic database hacking. Higher education institutions frequently become strategic targets due to the vast volume of sensitive data and intellectual property managed, while the cybersecurity literacy level of their users tends to vary and remains uneven.

In this context, conventional approaches that merely focus on strengthening information technology infrastructure have proven to be no longer adequate.

While technical infrastructure forms the baseline of defense, the efficacy of these systems is heavily mediated by human factors specifically, user security awareness and compliance. System users, in this case, students, often become the weakest link vulnerable to exploitation within an institution's cybersecurity ecosystem. The limitations of such a technocentric approach emphasize that in confronting increasingly asymmetric cyber threats, the data protection paradigm must radically evolve by positioning humans as the central element of defense, conceptually known as a "human firewall." This concept assumes that well-educated users with critical awareness can transform into proactive protectors against cyber threats, rather than mere passive vulnerabilities.

In Indonesia, this issue has gained critical legal and institutional urgency following the enactment of the Personal Data Protection Act (*Undang-Undang Perlindungan Data Pribadi* or UU PDP No. 27 of 2022). The law mandates data controllers and processors to implement stringent security measures, yet a significant gap remains in understanding how macro-level legal frameworks translate into individual micro-level behavioral compliance among digital natives like Generation Z students. To measure the effectiveness and actual implementation of this human defense, a systematic and tested analytical evaluation framework is required. The Knowledge-Attitude-Behavior (KAB) model offers a highly relevant multidimensional approach to dissecting individuals' cybersecurity profiles and hygiene. Through this framework, a comprehensive analysis can be conducted to examine the extent to which theoretical understanding of cyber risks is capable of shaping individuals' attitudes of vigilance, which in turn manifests into concrete behavior when responding to threats against their digital privacy.

The urgency of implementing this KAB evaluation model becomes increasingly crucial when situated within a specific regional context, such as West Java Province. As one of the regions with the largest concentration of higher education institutions and student populations in Indonesia, West Java represents a highly dynamic young internet user demographic, which simultaneously exists at the epicenter of high

cybersecurity risks. The intensity of students' daily interactions with various digital platforms renders them highly crucial subjects to evaluate within the context of cyber resilience.

Nevertheless, there is a significant research gap in the current literature; the majority of previous studies tend to focus on testing the technical aspects of infrastructure or solely measuring the level of cyber knowledge partially, without confirming how these aspects correlate with the formation of attitude and the manifestation of concrete behavior. Furthermore, there is a lack of comprehensive studies based on the KAB model that specifically map the cyber characteristics of students in regions with as high a density of higher education institutions as West Java. This empirical gap underscores the importance of conducting this study at present.

Therefore, structured data collection through a validated questionnaire instrument serves as a crucial step in mapping empirical conditions in the field. The measurement of fundamental security knowledge levels, the evaluation of attitudes towards privacy management, and the analysis of password protection measures and online fraud detection are essential indicators in this observation. By mapping these KAB pillars, this study is directed toward identifying cybersecurity literacy gaps with precision, while simultaneously formulating intervention strategies to strengthen the capacity of West Java students so that they are capable of functioning as a robust, adaptive, and responsive human firewall against the dynamics of cyber threats.

II. THEORETICAL FOUNDATION

A. The Concept of Personal Data Security Resilience and the Role of Students as a Human Firewall

Personal data security resilience within the digital ecosystem of higher education institutions can no longer be reduced merely to the technical capability to prevent intrusions. Conceptually, this resilience is a multidimensional construct encompassing the ability of the system and its users to anticipate, withstand, adapt to, and rapidly recover from data compromise incidents [1]. The open and decentralized characteristics of campus networks create an asymmetric threat landscape, where the significance of traditional security perimeters is often diminished by user mobility. In this context, the human-centric security paradigm positions humans not as a passive point of vulnerability, but rather as an essential line of defense or a human firewall [2].

Students, as the majority demographic of academic information system users, play a central role in determining the institution's security posture. The human firewall concept assumes that the integration of situational awareness and security literacy will transform students into proactive cognitive intrusion detectors [3]. When technical infrastructure fails to filter social engineering-based threats such as phishing

or psychological manipulation, data resilience depends entirely on students' ability to validate, verify, and respond to information anomalies. Therefore, the effectiveness of a human firewall is largely determined by the harmonization of an individual's cognitive, affective, and conative aspects, which can be dissected through the Knowledge-Attitude-Behavior (KAB) framework. Psychologically, these three dimensions do not operate in isolation but form a continuous cycle of causality; the mastery of knowledge constructs risk perception, this perception validates affective attitudes, and ultimately manifests in measured defensive actions.

B. The Knowledge Dimension in Academic Cybersecurity

The knowledge dimension serves as the cognitive foundation underlying the holistic formation of security awareness. In the domain of academic cybersecurity, knowledge does not refer to an encyclopedic understanding of technical terminology, but rather to the capability of critical literacy regarding contemporary threat tactics, system vulnerabilities, and data exploitation mechanisms [4]. This includes a schematic understanding of how personal data is potentially monetized by threat actors and how exploitative attack vectors infiltrate through students' daily communication channels, such as institutional emails and academic collaboration platforms [5].

Furthermore, synthesis analysis indicates that partial knowledge can conversely generate an illusion of security. Students who solely possess a procedural understanding for instance, merely knowing how to change a password without understanding the concepts of cryptographic entropy or multifactor authentication tend to fail in identifying advanced threats [6]. Consequently, strengthening the knowledge dimension requires a transition from compliance-based education to risk-based learning, enabling students to internalize cyber threats as tangible risks lurking behind the continuity of their academic activities. Psychologically, this cognitive internalization serves as an anchor of rationality. When students are exposed to threat stimuli, comprehensive knowledge will activate the sense-making process, which prevents a reactive emotional response while simultaneously preparing an empirical foundation for the formation of an attitude of vigilance in the subsequent stage.

C. The Attitude Dimension Towards Data Privacy

Attitude functions as a crucial psychological mediation bridge between the mastery of theoretical knowledge and the execution of practical actions. This dimension represents the affective evaluation and internal tendencies of students in responding to data privacy issues. The high penetration rate of social media and digital platforms frequently triggers the optimism bias phenomenon, wherein students feel that hacking incidents or identity theft only happen to other, less vigilant individuals [7]. This attitude evaluation is directly influenced by the psychological calibration

between perceived severity and perceived susceptibility to cyber threats.

Theoretical synthesis indicates that an apathetic attitude towards privacy policies often stems from the phenomenon of consent fatigue, where students ignore the terms and conditions of digital platforms for the sake of convenience or access speed [8]. To build cyber resilience, this compromising attitude must be transformed into a prescriptive attitude of vigilance. Students with a mature security attitude will inherently place the intrinsic value of privacy above functionality or short-term convenience, thereby forming a psychological resistance against social engineering manipulation attempts. The psychological interaction between Knowledge and Attitude is highly evident in this phase: knowledge serves to disrupt optimism bias by presenting facts of vulnerability, while attitude serves to process this spectrum of facts into a sense of urgency and personal responsibility.

D. The Behavior Dimension of Digital Data Protection

Behavior is a concrete manifestation as well as the highest output variable of the KAB model, which directly determines the level of data security resilience in the field. This dimension reflects a series of conscious, repetitive, and measurable actions implemented by students to mitigate cyber risks, such as strong credential management, the application of encryption, and caution in sharing sensitive information (oversharing) in public spaces [9]. In the discourse of information security behavior, the greatest psychological challenge is overcoming the privacy paradox, namely the discrepancy between high concern for privacy (attitude) and contradicting actual actions, such as utilizing public Wi-Fi without a virtual private network (VPN) to access academic portals [10].

The success of students as a human firewall is ultimately measured not merely by affective intentions, but by the consistency of proactive behavior. In-depth analysis reveals that ideal secure behavior does not emerge in isolation, but rather requires an ecosystem that supports habituation both cognitively and motorically. Once the knowledge dimension has successfully dismantled information asymmetry, and the attitude dimension has successfully reduced cognitive bias, the behavior dimension will manifest precisely. At this stage, the interaction of these three dimensions merges: Knowledge guides the technical mechanism of protection (how), Attitude provides the internal motivational drive (why), and Behavior executes it into concrete action (action). Through this complete psychological integration, digital data protection is no longer perceived as a restrictive institutional regulation, but evolves into a social norm and a defensive routine organically integrated into the students' digital lifestyle.

III. METHODOLOGY

A. Quantitative Phase: Stratified Sampling and Instrument Design

The initial phase utilizes a multi-stage stratified random sampling technique across universities in West Java. The sample is stratified by academic discipline clusters to allow for comparative analysis: Social Sciences and Humanities (Soshum) account for 58% of the sample, while Science and Technology (Saintek) comprise 42%. The quantitative instrument measures Knowledge (cognitive understanding of phishing, public Wi-Fi risks, and legal rights under UU PDP), Attitude (affective concern regarding privacy), and Behavior (conative implementation of data protection actions).

1. Population and Determination of the Higher Education Institution Sample in West Java

This study employs an explanatory quantitative design to map and measure the personal data security resilience of students in West Java Province. The population in this study encompasses all active students enrolled in State Higher Education Institutions (PTN) and Private Higher Education Institutions (PTS) in the West Java region. Given the extensive geographical coverage and the high density of the student population in the region, the sampling technique was conducted using the multi-stage stratified random sampling method [11].

The selection of this sampling method is crucial and deemed the most precise because the educational demographics in West Java possess a high degree of heterogeneity. There is a significant disparity regarding digital infrastructure, technological literacy, and socio-economic characteristics between urban areas (such as metropolitan regions) and sub-urban or rural areas. Therefore, stratification was conducted based on geographical regional clusters (Greater Bandung, Eastern Priangan, and the Bogor-Bekasi-Depok Megapolitan) as well as the scientific disciplines of the study programs (science and technology, and social sciences and humanities) [12]. This stratification approach methodologically prevents sample dominance bias from solely major city centers, thereby ensuring each sub-population has an equal and proportional probability of representation.

The minimum sample size was determined using the calculation of Slovin's formula with a margin of error of 5%, or adjusted according to the sample adequacy rule for structural modeling, which requires a minimum number of respondents to be ten times the number of observed variable indicators [13]. Empirical data collection was carried out online utilizing an electronic questionnaire instrument distributed through official student communication networks at each sample higher education institution to guarantee data heterogeneity.

2. KAB-Based Questionnaire Instrument Design

The data collection instrument was developed deductively through the operationalization of the theoretical constructs of Knowledge, Attitude, and Behavior (KAB) tailored to the contemporary cyber threat landscape. Each question item was designed as a manifest indicator to measure latent variables using a modified five-point Likert Scale for the attitude and behavior dimensions, as well as factual multiple-choice for the knowledge dimension [14].

- Knowledge Dimension

The instrument items were derived to test students' objective cognitive understanding of basic encryption concepts, the anatomy of phishing attacks, public wireless network risks, strong password policies, and legal aspects of privacy regulations referring to the Personal Data Protection Law (UU PDP) [15].

- Attitude Dimension

The instrument items were designed to evaluate the respondents' affective disposition, which includes perceived susceptibility, perceived severity resulting from cyber incidents, and subjective assessment regarding the urgency of implementing cybersecurity protocols in the campus environment [16].

- Behavior Dimension

The instrument items reflect self-reported behavior regarding actual defensive actions, such as the consistency of software updates, the implementation of Multi-Factor Authentication (MFA), caution in sharing personal information on social media (oversharing), and verification procedures for unfamiliar links [17].

Prior to widespread distribution, the research instrument initially underwent a content validity index test by a panel of information security and research methodology experts, followed by pilot testing on a small sample to evaluate the Cronbach's Alpha reliability value and the validity of the question items [18]. The elaboration of this instrument testing phase is a strictly required methodological step, considering that the KAB variables in the cybersecurity domain are highly abstract latent constructs and prone to subjective interpretation bias. The validity test serves to secure the accuracy of the measurement tool ensuring that the questionnaire truly measures cybersecurity resilience and not other variables while the reliability test guarantees the consistency and stability of student responses if this instrument is replicated under different conditions, such that the quality of the empirical data obtained is free from systematic error.

3. Data Analysis Method

The empirical data analysis in this study was conducted through two complementary statistical analysis stages. The first stage involves descriptive statistical analysis aiming to provide a general overview of the respondents' demographic distribution and to categorize the accumulative scores of each KAB

dimension into high, moderate, and low levels [19]. The second stage applies inferential analysis using a variance-based Structural Equation Modeling (SEM) approach (Partial Least Squares - PLS-SEM) [20].

The use of PLS-SEM is deemed the most appropriate to accommodate a research model that tests simultaneous linear causality relationships and mediation effects among latent constructs without requiring strict assumptions of data normality [21]. The evaluation procedure was conducted through two main stages, namely the testing of the measurement model (outer model) to ensure convergent validity, discriminant validity through the Fornell-Larcker criterion, and internal consistency reliability through composite reliability. Furthermore, the testing of the structural model (inner model) was applied to assess the significance of the path coefficients, the coefficient of determination (R-square) value, and the effect size (f-square) in order to prove the hypothesis regarding the influence of knowledge and attitude on the manifestation of students' behavior as a human firewall [22].

B. Qualitative Phase: Semi-Structured Interviews

To contextualize the statistical findings and dissect complex psychological constructs such as optimism bias, convenience trade-offs, and consent fatigue, a follow-up qualitative phase is integrated. Semi-structured interviews are conducted with a purposive subsample of respondents who exhibited high knowledge and attitude scores but low behavioral scores. This phase bridges the methodological gap by capturing the lived digital experiences and underlying rationales of students directly, moving beyond mere self-reported compliance numbers.

C. Experimental Extension Framework (Future Drill Integration)

To completely mitigate the discrepancy between stated behavior and actual behavior, the methodology establishes a blueprint for Direct Cyber Behavioral Experiments. Future iterations will integrate non-intrusive, institution-approved simulation drills (e.g., controlled phishing drills). By measuring real-time click rates and credential-submission frequencies on simulated malicious links, researchers can record unbiased, objective behavioral data rather than relying entirely on self-reports.

IV. ANALYSIS

A. Demographic Characteristics of West Java Student Respondents

This study successfully collected empirical data from 450 active student respondents across various higher education institutions in West Java. The demographic characteristics of the respondents were dominated by the 19–22 age group (82%), reflecting the critical age phase of regular undergraduate students as active internet users. The regional distribution

encompassed the Greater Bandung cluster (45%), the Bogor-Bekasi-Depok Megapolitan (35%), and Eastern Priangan (20%). Based on scientific disciplines, the respondents were divided into the Social Sciences and Humanities field (58%) and the Science and Technology field (42%). These demographic data confirm the heterogeneity of the sample representing the profile of West Java students in their daily digital interactions.

B. Evaluation of Knowledge, Attitude, and Behavior Levels

Based on the descriptive statistical processing results of the manifest indicators' accumulative scores, an asymmetrical distribution pattern was discovered among the three KAB latent constructs. These findings are briefly outlined in Table I presented below.

TABLE I. TABEL 1. ACCUMULATIVE SCORE DISTRIBUTION OF THE KAB DIMENSIONS

KAB Dimension	Category & Percentage	Empirical Findings & Institutional Implications
Knowledge (Cognitive)	High: 78%	Students demonstrate robust theoretical awareness regarding cyber threat vectors (e.g., phishing mechanics), the vulnerability of public networks, and institutional data policies.
Attitude (Affective)	High: 83%	Reflects an overwhelming consensus regarding the value of personal privacy and strong psychological intent to condemn illicit data exploitation.
Behavior (Conative)	High: 31% Moderate: 42% Low: 27%	Only a critical minority (31%) consistently translates awareness into defensive digital habits. The majority fall into moderate/low tiers, highlighting an alarming operational vulnerability and empirically confirming the presence of the <i>Privacy Paradox</i> .

The data above indicate a highly crucial anomaly in the students' cybersecurity posture. On the one hand, the Knowledge dimension falls into the high category (78%), indicating that students cognitively possess a strong understanding of contemporary cyberattack tactics such as phishing, the dangers of public wireless networks, and the legal consequences of the Personal Data Protection Law (UU PDP). In alignment with this, the Attitude dimension demonstrates a significantly higher percentage (83%), signifying a highly agreeable affective response towards the importance of maintaining data privacy and condemning cyber data misuse. However, a contradictory condition occurs in the Behavior construct, where only 31% of the students consistently implement digital defensive actions. The majority of the respondents fall into the moderate (42%) and low (27%) categories, implying that their actual

data protection actions remain highly vulnerable and fluctuating.

To evaluate whether academic background influences cybersecurity resilience, an independent samples t-test and Chi-square analysis were executed between the Soshum and Saintek cohorts. Interestingly, while Saintek students displayed a marginally higher technical baseline in Knowledge ($\mu = 81\%$ vs. $\mu = 75\%$, $p < 0.05$), the behavioral drop-off in the Behavior dimension was remarkably uniform across both clusters. No statistically significant difference was observed in the high-tier behavior percentage (Saintek = 32.4%, Soshum = 30.1%, $p > 0.05$). This proves that technical literacy does not automatically shield an individual from the behavioral vulnerabilities induced by pervasive digital environments.

C. Analysis of the Gap Between Attitude and Actual Behavior

The emergence of data asymmetry, wherein students' knowledge and attitude are high yet their behavior is low, serves as empirical confirmation of the privacy paradox phenomenon within the academic environment [23]. The anomaly documented in Table I represents a textbook manifestation of the Privacy Paradox, structurally conceptualized in the manuscript's analytical model (Figure 1). While the linear cognitive-to-affective progression functions seamlessly where comprehensive Knowledge shapes a vigilant Attitude the causal pathway from attitude to actual Behavior is severely disrupted by three distinct psychological and contextual barriers. Theoretically, the possession of cognitive capital (having the knowledge) and affective capital (caring about privacy) should be directly proportional to defensive actions. However, in the digital reality of West Java students, there are psychological and situational gaps that sever this chain of causality. This deviated correlation relationship structure can be conceptually illustrated through the chart in Figure 1.

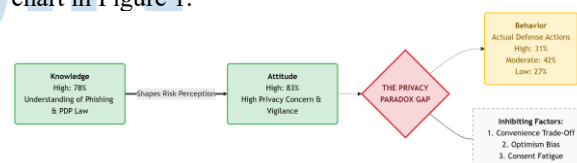


Fig. 1. Fig. 1. Knowledge-Attitude-Behavior (KAB) Model Gap and the Privacy Paradox

A critical analysis utilizing a digital sociology approach indicates that this gap is deeply rooted in the characteristics of Generation Z (Gen-Z) as digital natives. For them, technology is not merely a tool, but an extension of their identity and social space. There are three primary factors triggering the fracture in the relationship between students' attitudes and actual behaviors:

1. Convenience vs. Security Factor (Convenience Trade-Off)

Students frequently sacrifice security for access speed. For instance, although they know (Knowledge)

that public Wi-Fi without a VPN is highly susceptible to data interception, they continue to use it (Behavior) to access academic portals due to the urgent need for a free connection [24]. In the fast-paced academic workflow, immediate utility and seamless access (e.g., connecting to unencrypted campus Wi-Fi networks without activating a Virtual Private Network) routinely override delayed security considerations. Convenience acts as a primary behavioral inhibitor. For Gen-Z, accustomed to a seamless digital ecosystem, compliance with security protocols is frequently perceived as a procedural friction that diminishes efficiency and speed (instant gratification) in both their academic and social activities.

2. *Optimism Bias and Illusion of Control*

There is a false psychological belief among students that large-scale data breach incidents will only target institutional entities or prominent figures, rather than students' personal accounts. Students exhibit a cognitive distortion wherein they perceive themselves as statistically less vulnerable to cyber incidents than their peers or major corporations. This illusion of safety undermines the necessity of executing repetitive safety actions like updating complex passwords or managing active sessions. As digital natives, Gen-Z often equates digital fluency with digital security, thereby generating an illusion of safety. This bias degrades their sense of urgency, resulting in theoretical knowledge not being internalized into daily vigilance.

3. *Consent Fatigue in the Attention Economy Era*

The consequence of massive interactions with academic and non-academic applications causes students to mechanically click "Agree" on privacy terms and conditions without reading or considering the implications. Driven by the attention economy of modern mobile and web applications, students are exposed to an overwhelming frequency of privacy notices, cookies pop-ups, and user agreements. This triggers a mechanical, reflexive clicking behavior ("I Accept") without cognitive processing, bypassing affective safety attitudes entirely. In the midst of the attention economy era where students experience cognitive overload their initial attitude of caring about privacy is ultimately defeated by digital routines that demand practicality. This dismissive behavior does not stem from ignorance, but rather from the mental fatigue of continuously processing risk mitigation.

D. *Implications of the Findings for Campus Security Policies*

These empirical findings carry fundamental strategic and reflective implications for information technology management and policymakers in West Java higher education institutions. The fact that high Knowledge and Attitude fail to produce safe Behavior proves that blaming students for their negligence is an oversimplification of the problem. Campus cybersecurity policies must no longer be designed conventionally under the assumption that unidirectional

socialization or the distribution of information brochures (knowledge-based approach) is sufficient to alter the institution's security posture.

Since the primary issue lies in the conversion failure from attitude to behavior, interventions implemented must shift towards cyber environment engineering that enforces the formation of new habituations (behavioral nudging) [25]. Higher education institutions must transform their system architecture from voluntary compliance to secure-by-design.

Higher education institutions are recommended to implement proactive technological policies that close the gap of human negligence. This can be realized through the mandatory utilization of Multi-Factor Authentication (MFA) on all student academic information system accounts systemically, without providing a bypass option. Furthermore, campuses need to provide easily accessible and "low-friction" security support infrastructure, such as official campus virtual private network (VPN) facilities directly integrated into students' devices, as well as integrating practical-simulative cybersecurity education into new student orientation activities. Through the strengthening of architectural habituation-based policies, students are not merely encouraged to "know and care," but are systematically forced to "behave securely" collectively, thus enabling them to realize their role as a robust human firewall in protecting the campus's personal data ecosystem.

V. CONCLUSION

A. *Conclusion*

This study successfully demonstrated a significant structural discrepancy in the cybersecurity posture of students in West Java through the lens of the Knowledge-Attitude-Behavior (KAB) model. Although students possess strong cognitive capital regarding cyber risks and demonstrate an affective disposition that highly supports personal data privacy protection, their capacity as a human firewall remains highly vulnerable in practice. This privacy paradox phenomenon is triggered by the compromise of access convenience, the presence of optimism bias, and psychological fatigue in scrutinizing digital consent (consent fatigue). This gap emphasizes that strengthening theoretical knowledge aspects and conventional cyber awareness campaigns are no longer adequate if not balanced with structured behavioral interventions.

The significance of this study lies in the deconstruction of the assumption that the younger digital generation (digital natives) automatically possesses secure digital behavior. The results of this study provide a new empirical foundation for information security governance in the higher education sector, confirming that systemic vulnerabilities frequently do not stem from technological failures, but rather from the weak points of user behavior. Traditional, information-centric awareness campaigns are proven insufficient to bridge

the KAB gap among West Java students. Higher education institutions must shift from passive socialization to active environmental engineering employing behavioral nudging mechanisms. This includes implementing mandatory Multi-Factor Authentication (MFA) for all institutional portal accesses, forcing a default security habit.

B. Suggestions for Practical Application and Research Extension

As a practical application step, higher education institutions are recommended to immediately adopt cyber defense policies based on the formation of new habituations (behavioral nudging). This can be realized through the mandatory implementation of systematic two-factor authentication across the entire academic ecosystem, periodic cyberattack simulations (phishing drills) to train students' situational awareness, and the provision of an easy-to-use internal campus virtual private network (VPN) facility.

For further research extension, it is suggested that future researchers expand the scope of variables by integrating external control factors, such as the influence of organizational security culture and the effectiveness of the Personal Data Protection Law (UU PDP) regulation on individual compliance. The use of mixed-methods with in-depth interview techniques or direct cyber behavior experiments is also highly recommended to explore the deepest psychological motives behind students' compromising actions in the digital space.

- Longitudinal Intervention Studies

Future research should deploy a longitudinal framework, tracking student behavioral data across multiple semesters specifically pre- and post-implementation of mandatory institutional security controls (e.g., mandatory MFA rollout) to accurately quantify the long-term efficacy of environmental nudges.

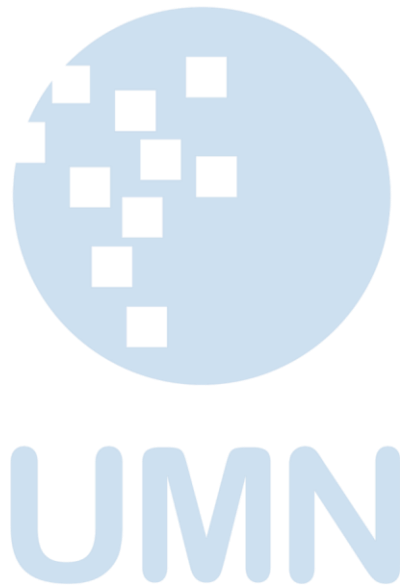
- Macro-Systemic Control Integration

Models should expand to incorporate organizational security culture and assess how national regulatory mechanisms, such as enforcement metrics of the UU PDP, structurally incentivize or alter individual behavioral accountability within public spheres.

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An IoT-Based Intelligent Waste Segregation System with Real-Time Capacity Monitoring

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Abstract— Waste management in Indonesia is confronting a critical crisis, marked by the accumulation of 85% of waste in nearly full landfills and persistently low rates of source segregation, particularly in university campus environments. This study presents the development of RecyClean Smart Bin, a prototype IoT-based intelligent waste bin that integrates an ultrasonic sensor for real-time bin capacity monitoring, proximity and capacitive sensors for automatic classification of organic, inorganic, and metallic waste, and a web-based application for remote monitoring. The methodology encompasses hardware–software co-design, firmware programming, system implementation, and functional validation conducted over five days using fifteen representative waste samples. Results indicate excellent ultrasonic sensor accuracy (maximum deviation of 0.6 cm) and an overall sorting success rate of 80% (12 out of 15 samples), with particularly high precision in metallic waste detection. The proposed system offers a practical contribution toward advancing the circular economy and enabling sustainable smart environments.

Index Terms— Capacity Monitoring; IoT; Waste Segregation

I. INTRODUCTION

Waste management in Indonesia is facing a severe crisis. National data indicate that, of the approximately 68.5 million tons of waste generated annually, the majority (85%) accumulates in landfills that are nearing or have already reached maximum capacity, according to the National Waste Management Information System (SIPSN). Data from the SIPSN, managed by the Ministry of Environment and Forestry (KLHK), show that in 2023 Indonesia generated around 35.9 million tons of waste, with food waste constituting the largest share (41.5%) followed by plastics (18.5%) [1]. Statistical reports covering the last three years (2022–2024) further reveal that plastic and metal waste together account for an average of 20.88% of the total waste composition. In the region under study, annual waste production reaches approximately 862,013 tons, predominantly consisting of plastic bottles and aluminum cans. However, only 60.71% of this waste is successfully processed through formal management systems, while the remainder accumulates in final

disposal sites or is discarded illegally in open areas [2]. These conditions underscore the urgent need to strengthen source-level segregation, particularly in university campus environments characterized by high mobility and the generation of highly diverse waste streams.

Inaccurate segregation at the source significantly degrades the quality of recyclable materials and drives up overall management costs. Recent studies have shown that properly sorted waste commands an economic value 4–10 times higher than mixed waste [3]. This evidence reinforces the critical need for accurate, real-time sorting to boost recycling productivity and advance the circular economy, particularly within university campuses. In addition, conventional waste collection systems suffer from notable inefficiencies; it has been reported that up to 40 % of collection trips are made while bins are still not full, resulting in substantial energy wastage and elevated carbon emissions.

A substantial body of prior research has applied information and communication technologies to improve environmental sanitation. These studies encompass IoT-based monitoring of environmental conditions, which plays a vital role in protecting human well-being and preserving ecosystems [4], [5], [6], [7], [8]. Beyond sensor-driven IoT monitoring, information technology has also been deployed through web-based [9] or mobile software applications to support broader environmental cleanliness initiatives [10], [11]. The application most directly addressing the root cause of environmental degradation—waste itself—is the development of smart waste bins and intelligent waste management systems. These solutions utilize IoT technology together with specialized sensors to detect bin fill levels and automatically classify waste types [1], [3], [12].

A growing body of literature has examined innovations in smart waste bins as a means of overcoming the inefficiencies inherent in conventional waste management. Studies [13] and [14] focus on the development of automated, contactless containment

prototypes in which an ultrasonic sensor triggers the lid to open automatically for several seconds upon detecting the physical presence of a user. To address the upstream problem of mixed recyclable materials, the system presented in [13] further incorporates capacitive sensors and servo motors to enable autonomous segregation of organic and inorganic waste. This hardware-centric automation approach is consistent with the findings of [15], which underscore that the implementation of segregation technologies is essential for supporting sustainable urban planning practices while simultaneously paving the way for the integration of more advanced intelligent algorithms that can enhance operational scalability in the future.

In the domain of logistics management and remote monitoring, the integration of the Internet of Things (IoT) has proven critical in mitigating waste accumulation caused by lapses in manual inspections. Studies [13] and [16] specifically developed early-warning systems based on NodeMCU microcontrollers that monitor ultrasonic sensor thresholds and promptly dispatch full-capacity notifications to sanitation personnel via the Telegram platform. A more comprehensive monitoring ecosystem was engineered in [17], which not only acquires volume metrics but also calculates waste weight in real time using load cells. In that study, all data transmitted from the ESP32 module is streamed to a Firebase cloud architecture and visualized through a web interface. This functionality effectively provides relevant authorities with a robust data foundation for making precise logistical decisions while substantially minimizing human intervention.

This study addresses the technical challenges in modern waste management by formulating three interrelated research questions. First, it investigates the development of an Internet of Things (IoT)-based automatic waste sorting system capable of detecting and classifying metallic, inorganic, and organic waste with high accuracy and real-time response. Second, the study evaluates the effectiveness of integrating proximity sensors to enhance the precision of metallic waste detection within inorganic waste piles, thereby enabling targeted separation that supports more efficient recycling processes. Finally, it examines the design and implementation of a web-based management application that facilitates remote monitoring of bin capacity. While previous studies [13] and [15] often focus on binary classification or standalone automated bins, this research contributes a novel two-stage sequential sorting architecture. The first stage utilizes inductive proximity for high-precision metallic isolation, while the second stage employs a majority-voting capacitive sensing algorithm to differentiate organic from inorganic waste. Furthermore, unlike [16] which uses simple notification triggers, our system integrates a relational MySQL database for historical trend analysis of bin capacity, providing a data-driven foundation for waste collection logistics.

In alignment with the related studies outlined earlier, the primary objective of this research is to design and implement a prototype of an integrated IoT-enabled smart waste sorting system capable of automatically and precisely segregating waste categories at the point of generation. More specifically, the study aims to validate the reliability of proximity sensor integration as a means of improving the accuracy of metallic waste extraction from inorganic materials, while simultaneously developing a comprehensive web-based information system. This platform is intended to empower stakeholders with real-time bin capacity monitoring and more structured logistics management for waste collection.

The urgency and significance of this research lie in its contribution to the transition toward smart environments and sustainable smart cities. By automating waste segregation at the source and digitalizing its monitoring, the outcomes of this study have the potential to reduce manual workloads, lower the risk of pathogen exposure for sanitation workers, and increase the recovery rate of high-value recyclable materials such as metals. Furthermore, the availability of remote monitoring data delivered through the web application will provide an empirical foundation for sanitation authorities to optimize collection vehicle routes, ultimately minimizing operational costs and reducing the carbon footprint of urban waste management.

II. METHODOLOGY

This study builds upon a previous investigation that developed web- and mobile-based software to identify locations implementing the zero-waste concept [18]. The current research advances this foundation by developing an Internet of Things (IoT)-enabled smart waste bin integrated with web- and mobile-based software, named RecyClean Smart Bin. The overall research methodology employed in this study is illustrated in Figure 1 below.

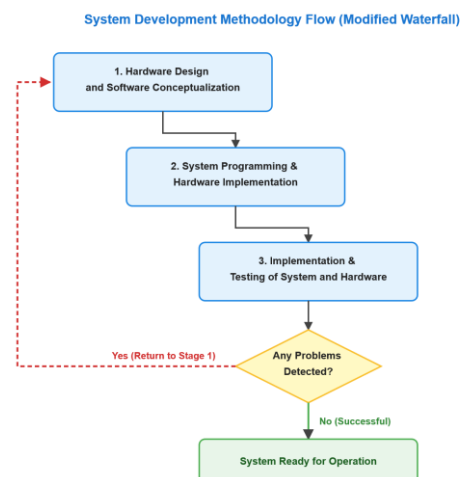


Fig. 1. Methodological Steps

The development of RecyClean Smart Bin followed a systematic sequence that began with the design of both hardware architecture and software concepts. This was followed by system programming and the fabrication of hardware components in accordance with the established design. The process then proceeded to full system implementation and functional testing of the device and integrated software. Should any issues arise during testing, the workflow returns iteratively to the design phase for refinement.

The hardware and software concept design phase began with the development of a three-dimensional model of the RecyClean Smart Bin. This was complemented by a block diagram that provided a comprehensive overview of the Internet of Things (IoT) architecture, detailing the integration of the microcontroller and associated sensor components. The system programming stage was presented in pseudocode format to ensure clarity and conciseness when describing the input, processing, and output operations of the embedded system running on the microcontroller. Hardware fabrication was subsequently executed in strict accordance with the finalized design specifications.

Following completion of the RecyClean Smart Bin prototype, the implementation phase advanced to functional testing to evaluate overall system performance. Testing was conducted and verified through live demonstrations and presentations using representative waste samples. This stage was critical in confirming that the system met field requirements and was ready for practical deployment. The primary evaluations performed on the RecyClean Smart Bin

consisted of two key tests: (1) assessment of internal waste height using the ultrasonic sensor over a continuous five-day period, and (2) sorting accuracy trials involving 15 distinct waste samples, during which the readings from the proximity sensors and the correctness of waste classification were systematically verified. The functional validation was conducted in a controlled indoor environment (27°C–30°C) to maintain sensor stability. A total of 15 representative waste items (4–6 samples per category: organic, inorganic, and metallic) were used.

III. RESULTS AND DISCUSSION

A. Results

In the software concept design phase, this study developed a web-based information system that serves as an integrated control dashboard for real-time monitoring of waste bin capacity. Architecturally, the system acquires telemetry data from the ultrasonic sensor on the IoT node via HTTP protocol transmission. The received data is subsequently processed and archived in a relational database management system (MySQL). The web interface was engineered to visualize the precise fill levels of each compartment according to material categories—namely organic, inorganic, and metallic waste. This software architecture enables effective remote monitoring, thereby eliminating the inefficiencies of manual physical inspections while providing a robust foundation for data-driven decision-making by municipal sanitation authorities.

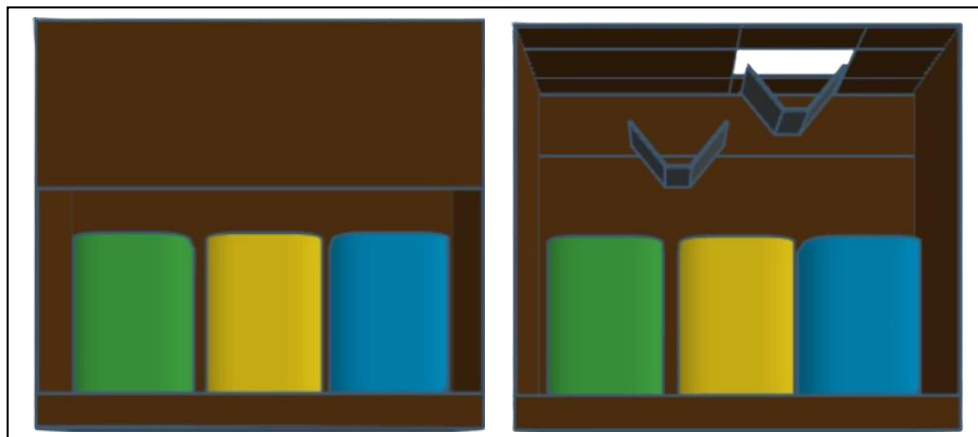


Fig. 2. Prototype Design of the RecyClean Smart Bin

Figure 2 above illustrates the prototype design of the RecyClean Smart Bin, which employs a primary structure fabricated from infraboard to accommodate the fully integrated automatic sorting mechanism. The interior of the system consists of three parallel compartments specifically allocated for the separate collection of organic (green), inorganic (yellow), and metallic (blue) waste. At the upper section of the bin, a dynamic sorting funnel mechanism is integrated, directly coupled with the sensor array and actuators.

This mechanical configuration was functionally engineered to direct each waste item into the appropriate collection compartment based on real-time material identification, while simultaneously optimizing the spatial layout to provide sufficient operational space for the electronic modules and mechanical motor movements.

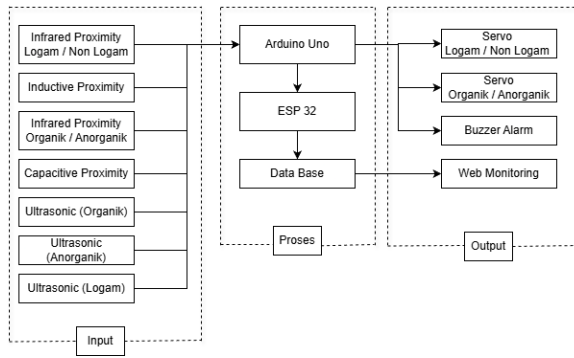


Fig. 3. Hardware Block Diagram

The operational architecture of the system is represented by a block diagram encompassing the input, processing, and output modules, as shown in Figure 3. The data acquisition module integrates multiple sensors, namely an infrared proximity sensor for object presence detection, an inductive proximity sensor for metallic material identification, a capacitive proximity sensor for organic/inorganic classification, and an ultrasonic sensor for monitoring the fill level of each compartment. All sensor readings are processed by an Arduino Uno microcontroller and transmitted via Universal Asynchronous Receiver-Transmitter (UART) serial communication to an ESP32 module, which serves as the IoT gateway. The ESP32 uploads the data to the database for real-time visualization on the web-based monitoring platform. For mechanical output, the system actuates two servo motors to execute sequential sorting—first isolating metallic waste, followed by separating organic from inorganic waste—while a buzzer actuator is triggered as an early-warning system whenever any compartment reaches its maximum capacity.

The next phase involved system programming and hardware fabrication. In this stage, the program code was structured into a two-stage identification process: first distinguishing metallic from non-metallic waste, followed by classification of organic versus inorganic waste. Figure 4 below presents the pseudocode for the first-stage material sorting mechanism. The process begins with object presence detection by the infrared proximity sensor (IR1). A stabilization delay of 300 milliseconds is then applied to prevent reading anomalies caused by physical movement of the object. Material identification is subsequently performed using an inductive proximity sensor with an oversampling technique consisting of five consecutive readings taken at 50-millisecond intervals. This oversampling method was employed to minimize signal noise and enhance detection accuracy. The final sensor value is validated through a majority-voting threshold, whereby a reading is considered valid if at least three of the five cycles register as HIGH. Based on this validated result, mechanical actuation is executed as follows: if the object is identified as metal (sensor output LOW), the servo motor directs it to the left; otherwise, non-metallic material is directed to the right. The dumping

mechanism remains active for three seconds to ensure complete discharge of the object into the designated compartment. The actuator then returns to the neutral center position, ready for the next sorting cycle.

```

ALGORITHM 1: First Stage Sorting (Metal Detection)
INPUT      : irValue (Infrared Sensor Status), sensorInduktif (Inductive Sensor Pin)
OUTPUT     : servo1 actuation, System Log, Updated fill-level data
CONSTANTS  : POS_KIRI (Left Position), POS_KANAN (Right Position), POS_TENGAH (Neutral Position)

START ALGORITHM
// 1. Object Detection
IF irValue == HIGH THEN
  PRINT "Objek terdeteksi oleh IR1!"

// 2. Position Stabilization
WAIT for 300 milliseconds

// 3. Data Acquisition (Oversampling)
SET induktifValue = 0
FOR i = 0 TO 4 DO
  READ current_state FROM sensorInduktif
  induktifValue = induktifValue + current_state
WAIT for 50 milliseconds
END FOR

// 4. Majority Vote Validation
IF induktifValue >= 3 THEN
  SET induktifValue = HIGH
ELSE
  SET induktifValue = LOW
END IF

// 5. Material Classification and Actuation
IF induktifValue == LOW THEN
  PRINT "Jenis: LOGAM"
  ACTUATE servo1 TO POS_KIRI
ELSE
  PRINT "Jenis: NON LOGAM"
  ACTUATE servo1 TO POS_KANAN
END IF

// 6. Object Drop and Actuator Calibration
WAIT for 3000 milliseconds
ACTUATE servo1 TO POS_TENGAH

// 7. Data Synchronization
CALL FUNCTION tampilkanKetinggian()

END IF
END ALGORITHM
  
```

Fig. 4. Pseudocode for a Program to Sort Metal and Non-Metal Waste

The subsequent sorting stage involves the identification and separation of organic and inorganic waste. The pseudocode for this second-stage identification process is presented in Figure 5 below.

```

ALGORITHM 2: Second Stage Sorting (Organic and Inorganic Classification)
INPUT      : ir2Value (Infrared Sensor 2 Status), sensorKapasitif (Capacitive Sensor Pin)
OUTPUT     : servo2 actuation, System Log, Updated fill-level data
CONSTANTS  : POS_KIRI (Left Position), POS_KANAN (Right Position), POS_TENGAH (Neutral Position)

START ALGORITHM
// 1. Object Detection
IF ir2Value == HIGH THEN
  PRINT "Objek terdeteksi oleh IR2!"

// 2. Transition Delay (Mechanical Compensation)
WAIT for 2400 milliseconds

// 3. Data Acquisition (Oversampling)
SET kapasitifValue = 0
FOR i = 0 TO 4 DO
  READ current_state FROM sensorKapasitif
  kapasitifValue = kapasitifValue + current_state
WAIT for 50 milliseconds
END FOR

// 4. Majority Vote Validation
IF kapasitifValue >= 3 THEN
  SET kapasitifValue = HIGH
ELSE
  SET kapasitifValue = LOW
END IF

// 5. Material Classification and Actuation
IF kapasitifValue == HIGH THEN
  PRINT "Jenis: ORGANIK"
  ACTUATE servo2 TO POS_KANAN
ELSE
  PRINT "Jenis: NON ORGANIK"
  ACTUATE servo2 TO POS_KIRI
END IF

// 6. Object Drop and Actuator Calibration
WAIT for 3000 milliseconds
ACTUATE servo2 TO POS_TENGAH

// 7. Data Synchronization
CALL FUNCTION tampilkanKetinggian()

END IF
END ALGORITHM
  
```

Fig. 5. Pseudocode for an Organic and Inorganic Waste Sorting Program

The second-stage sorting is initiated when the infrared proximity sensor (IR2) detects the presence of an object. A transition delay of 2,400 milliseconds is then applied to ensure the material has fully settled in the stable sensing area. Material classification is subsequently performed by the capacitive proximity sensor using an oversampling technique, in which five consecutive readings are acquired at 50-millisecond intervals to minimize signal noise and reading

anomalies. Applying the majority-voting threshold principle, the final reading is considered valid (HIGH) if at least three of the five iterations yield a positive result; in this case, the object is classified as organic waste and the servo motor is actuated to open toward the right. Conversely, if the accumulated readings fall below the threshold (LOW), the object is identified as inorganic waste and directed to the left side. The actuation position is held statically for three seconds to guarantee complete discharge of the material into the designated compartment. The actuator then automatically returns to the neutral position, preparing the system for the next sorting cycle.



Fig. 6. Results of the RecyClean Smart Bin Production Process

Figure 6 above presents the completed RecyClean Smart Bin prototype. The upper image shows the front side view, while the lower image displays the top view. The physical construction of the RecyClean Smart Bin strictly followed the hardware design established during the planning phase. Fabrication was carried out in four sequential steps as follows:

- The first step involved configuring all microcontroller components, including the ESP32 and Arduino Uno modules. After configuration, each sensor was individually tested to verify proper functionality. Any detected inconsistencies were calibrated before proceeding.
- The second step consisted of constructing the main bin frame. This process included precise measurement and cutting of infraboard panels,

followed by assembly and bonding with adhesive to produce a strong and rigid structure. Infraboard (polypropylene) was selected as the primary material due to its advantageous properties: lightweight, waterproof, and highly durable (resistant to tearing or damage).

- The third step involved drilling mounting holes in the panels at the designated locations for all components.
- The final step comprised the installation of all microcontroller modules and sensors onto the completed frame, followed by comprehensive functional testing of the assembled components.

The implementation phase of the smart waste bin was executed through the operational mechanism of the RecyClean Smart Bin, which consists of two sequential sorting stages directly integrated with the web-based monitoring platform. The process is initiated when the first infrared sensor (IR1) detects an incoming object. The material is then identified by the inductive proximity sensor: metallic waste is immediately directed by the servo motor actuator to its dedicated compartment, while non-metallic materials proceed to the second sorting stage. In the subsequent stage, the object is detected once more by the second infrared sensor (IR2) and classified by the capacitive proximity sensor, separating organic and inorganic waste into their respective compartments. Complementing the overall system management, ultrasonic sensors mounted in each compartment continuously measure the volume fill level and transmit the data via the ESP32 microcontroller to the database. This enables real-time visualization of storage capacity on the website dashboard, which automatically triggers an early-warning system consisting of a local buzzer alarm and digital notifications on the web platform whenever any compartment reaches its maximum capacity. The website system provides three types of digital notifications—one each for metallic, organic, and inorganic waste. These notifications are shown in the following figures.



Fig. 7. Metal Trash Can Full Notification

Figure 7 displays the full-capacity warning for the metallic waste compartment. The dashboard indicates that the ultrasonic sensor detected a distance of 2 cm between the sensor and the waste surface. This measurement signifies that the metallic waste has reached close proximity to the sensor, thereby

classifying the compartment as full. In response, the system presents a pop-up alert with the message “Warning!! Metallic Waste Bin Full,” indicating that immediate handling of the compartment is required.



Fig. 8. Organic Waste Bin Full Notification

Figure 8 shows the monitoring dashboard when the organic waste compartment is declared full. The ultrasonic sensor records a distance of 2 cm to the surface of the organic waste, signifying that virtually no empty space remains. Under this condition, the system automatically triggers a red pop-up warning displaying the message “Warning!! Organic Waste Bin Full.” This alert serves as a clear visual notification that the organic waste compartment requires urgent emptying.



Fig. 9. Inorganic Waste Bin Full Notification

Figure 9 illustrates the full condition of the inorganic waste compartment. As shown on the dashboard, the ultrasonic sensor detected a distance of 2 cm to the inorganic waste surface, confirming that the compartment has reached its maximum capacity. The system then displays a pop-up alert with the message “Warning!! Inorganic Waste Bin Full.” These notifications demonstrate the system’s capability to automatically detect near-full conditions and promptly inform users.

B. Discussion

The web-based monitoring system was tested to evaluate the accuracy of the waste fill level data acquired by the ultrasonic sensor against actual field conditions. Testing was conducted by incrementally adding waste samples belonging to three categories—organic, inorganic, and metallic—into the smart bin, followed by a direct comparison between the sensor readings and manual measurements performed over five consecutive working days. Table 1 below presents the results of the ultrasonic sensor monitoring of the distance to the waste surface.

TABLE I. TEST RESULTS FOR MONITORING THE DISTANCE OF TRASH TO AN ULTRASONIC SENSOR

Waste Categories	Time	Sensor Output (cm)	Actual Distance (cm)	Error
Organic	2025-12-05 08:59:58	10.4	9.8	0.6
Inorganic		10.2	9.7	0.5
Metal		29.7	30.2	0.5
Organic	2025-12-08 09:00:34	10.5	11.1	0.6
Inorganic		20.1	18.7	0.4
Metal		29.1	29.3	0.2
Organic	2025-12-09 08:58:21	11.6	11.4	0.2
Inorganic		25.3	24.9	0.4
Metal		29.1	29.3	0.2
Organic	2025-12-10 08:59:43	10.2	11.8	0.4
Inorganic		15.3	14.9	0.4
Metal		27.2	27.5	0.3
Organic	2025-12-11 08:58:54	10.8	11.2	0.4
Inorganic		14.9	15.2	0.3
Metal		28.1	28.2	0.1

The monitoring test results showed a minimal discrepancy between the ultrasonic sensor readings of waste distance and the actual field measurements, with a maximum deviation of only 0.6 cm. This confirms that the ultrasonic sensor performed reliably, owing primarily to the calibration performed prior to testing. Subsequent performance evaluation of the system was conducted using 15 representative waste samples drawn from the metallic, inorganic, and organic categories. Overall, the automated sorting mechanism achieved a satisfactory success rate, correctly identifying and classifying 12 out of the 15 items. In particular, testing of metallic materials demonstrated that the sensor system operated with high precision and optimal performance; all tested samples—including beverage cans, scissors, iron fragments, and staple pieces—were successfully detected and accurately classified into the designated bin.

This performance consistency was also evident in the testing of inorganic materials, where the system successfully recognized items such as paper cups, plastic bottles and cups, as well as dry paper and tissues with high accuracy. Nevertheless, a classification anomaly occurred during testing of the dry leaf sample, which was misclassified as inorganic material. This failure is strongly attributed to the reduced density and extremely low moisture content of the dry leaves, which triggered a dielectric response in the capacitive sensor that closely resembled the physical characteristics of inorganic waste.

Validation of the organic waste category, using samples of fresh leaves, cucumber, and tomato, confirmed that the system performed accurate and targeted sorting. However, the instrument's sensitivity limitations became apparent when tested with wet paper and wet tissue samples, which were erroneously classified as organic material. This shift in sensor response is technically attributed to the high moisture retention within the pores of the paper and tissue. The elevated water content significantly distorted the capacitive sensor readings, causing the system to interpret the samples as liquid-rich biological structures. The complete performance evaluation results are presented in Table 2 below.

TABLE II. PERFORMANCE EVALUATION OF THE RECYCLEAN SMART BIN SYSTEM

Sample Materials	Sensor Detection			Results
	Metal	Organic	Inorganic	
Can	✓	-	-	correct
Scissors	✓	-	-	correct
Metal Scraps	✓	-	-	correct
Staple Remnants	✓	-	-	correct
Paper Cups	-	-	✓	correct
Plastic Cups	-	-	✓	correct
Paper	-	-	✓	correct
Tissue Paper	-	-	✓	correct
Plastic Bottles	-	-	✓	correct
Dried Leaves	-	-	✓	incorrect
Leaves	-	✓	-	correct
Cucumbers	-	✓	-	correct
Tomatoes	-	✓	-	correct
Wet Paper	-	✓	-	incorrect
Wet Wipes	-	✓	-	incorrect

Compared to the system developed by [13], which achieved a sorting accuracy of 75% for two categories, our proposed RecyClean bin achieved a higher accuracy of 80% across three categories. Additionally, our ultrasonic sensor's maximum deviation of 0.6 cm outperforms the average error reported in [12], which ranged between 1.0–1.5 cm. This precision is attributed to the implemented stabilization delay and majority-voting algorithm.

The selection of a capacitive sensor was based on its ability to detect changes in the dielectric constant. However, the misclassification of wet paper as organic waste occurs because water has a high dielectric constant (~80). When paper absorbs moisture, its dielectric properties shift to mimic biological/organic materials. Similarly, dried leaves were misclassified as inorganic due to the loss of moisture, reducing their

dielectric response below the organic threshold. Future calibration will involve multi-threshold logic to account for moisture-dependent variables.

IV. CONCLUSION

Based on the experimental results, this study has successfully addressed key technical challenges in modern waste management by developing an integrated Internet of Things (IoT) solution that tackles three interrelated issues: automatic waste classification, real-time capacity monitoring, and remote data accessibility. The RecyClean Smart Bin prototype effectively classifies metallic, organic, and inorganic waste with satisfactory accuracy. Evaluation results confirm that the integrated proximity sensor reliably detects metallic materials, while the web-based application enables accurate remote monitoring of bin fill levels. Overall, the study has achieved its primary objective of designing and implementing a functional smart waste-sorting prototype.

Reliability validation of the multi-sensor integration demonstrated that 12 out of 15 representative waste samples were correctly identified and sorted. The web-based information system further exhibited high precision, with a maximum deviation of only 0.6 cm between ultrasonic sensor readings and actual waste levels, thereby providing users with dependable real-time capacity information.

Future development will focus on enhancing both software and hardware aspects. On the software side, additional features such as integration with waste collection truck routing systems are planned. On the hardware side, the implementation of protective covers or enclosures for the proximity sensor is recommended to minimize the influence of moisture and wet waste conditions on sensor performance. These improvements are expected to further strengthen the system's robustness and practical applicability in real-world campus and urban environments. Future work will expand the experimental validation by increasing the sample size to 100+ items with higher diversity in moisture levels and shapes. Subsequent studies will also implement comprehensive statistical performance metrics, including a confusion matrix to calculate precision, recall, and F1-score for each waste category, providing a more rigorous evaluation of the system's reliability in real-world campus environments.

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UMN

Enhancing Operational Efficiency in FMCG Customer Care: Design and Implementation of a High-Performance Web-Based Knowledge Management System Using Next.js with Hybrid Rendering Architecture

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Abstract— In the highly competitive Fast-Moving Consumer Goods (FMCG) sector, the speed and accuracy of customer support are critical differentiators. This study addresses a significant operational bottleneck at PT Paragon Technology and Innovation, where reliance on fragmented, static documentation led to high information retrieval latency and service inconsistencies. To mitigate these issues, we designed and developed an integrated Knowledge Management System (KMS) serving as a Single Source of Truth (SSOT). Engineered using an Agile methodology, the system utilizes a modern Full-stack architecture based on the Next.js framework. It employs a hybrid rendering strategy, leveraging Server-Side Rendering (SSR) to optimize load performance and Client-Side Rendering (CSR) for interactive interfaces. The backend integrates a PostgreSQL database managed via Prisma ORM to ensure data integrity. Key features include a unified global search engine and a transparent audit trail mechanism for governance. Post-implementation evaluation was conducted through Lighthouse-based page-level performance testing and pilot usage observation. The proposed system achieved an average First Contentful Paint (FCP) of 0.35 seconds, Largest Contentful Paint (LCP) of 1.52 seconds, Total Blocking Time (TBT) of 20.00 ms, Speed Index of 0.82 seconds, and Cumulative Layout Shift (CLS) of 0.00 across repeated measurements. These results indicate that the proposed KMS provides fast initial rendering, responsive page behavior, and stable visual layout while supporting the transition from fragmented document-based workflows to a centralized customer-care knowledge platform.

Index Terms— Agile Software Development; Customer Service; Knowledge Management System; Next.js; Server-Side Rendering; Client-Side Rendering; Single Source of Truth

I. INTRODUCTION

The landscape of the Fast-Moving Consumer Goods (FMCG) industry has undergone a fundamental shift. In an era defined by hyper-connectivity, competitive

advantage is no longer solely derived from product differentiation but increasingly from the quality of the customer experience [1]. As consumer touchpoints expand across social media, instant messaging, and e-commerce platforms, organizations are compelled to adopt "Omnichannel" strategies to maintain seamless engagement [2]. Consequently, Customer Care divisions have evolved from traditional support centers into critical hubs for brand loyalty and retention. In this high-velocity environment, the speed and accuracy of information retrieval by support agents are paramount metrics defining operational success.

The management of organizational knowledge to support these operations has been extensively studied under the domain of Knowledge Management (KM). Foundational theories by Nonaka and Takeuchi establish the critical need to convert tacit knowledge (internal expertise) into explicit knowledge (documented procedures) to scale organizational capability [6]. Further studies by Davenport and Prusak emphasize that effective KM systems (KMS) are essential for preventing knowledge loss and ensuring consistency in decision-making [8]. In customer care contexts, operational indicators such as Average Handle Time (AHT) and First Contact Resolution (FCR) are commonly used to assess service performance. However, measuring these indicators requires longitudinal customer interaction records, ticket resolution outcomes, and service quality data. Therefore, this study positions the proposed KMS as an initial technical implementation that focuses on page-level performance, knowledge centralization, and update governance as foundational elements for future operational performance evaluation [15], [16]. Traditionally, organizations have relied on static repositories, such as intranets, shared file servers, or basic document management systems to store Standard Operating Procedures (SOPs) and product details.

While these methods solve the basic storage problem, they often function as passive archives rather than dynamic tools optimized for real-time retrieval.

Despite the availability of general KM theories, a significant gap exists in their technical implementation within high-volume FMCG environments. A case study at PT Paragon Technology and Innovation (ParagonCorp), Indonesia's leading cosmetic manufacturer, reveals that rapid growth often outpaces infrastructure development [3], [14]. The Customer Care division currently faces a "knowledge fragmentation" crisis. Vital information regarding thousands of Stock Keeping Units (SKUs) and evolving protocols is dispersed across hundreds of static PDF documents and spreadsheets [4]. This decentralized, document-centric approach presents two critical failures. First, the retrieval latency gap: agents must manually search through multiple files to answer a single query, a process incompatible with the real-time demands of live chat support. Second, the integrity gap: without a centralized control mechanism, there is a high risk of agents accessing obsolete document versions, leading to service inconsistencies [5]. Existing "off-the-shelf" KM solutions often lack the specific customization required for the complex product hierarchies of FMCG or suffer from performance issues associated with client-side rendering latency in web applications.

To bridge this gap, this research proposes the design and development of a bespoke, high-performance Knowledge Management System tailored for the FMCG sector. Unlike traditional static repositories, this work introduces a Single Source of Truth (SSOT) architecture built on modern web technologies. We utilize the Next.js framework with a hybrid rendering architecture, leveraging Server-Side Rendering (SSR) for public-facing pages to ensure near-instantaneous data retrieval and superior performance compared to conventional Single Page Applications, while employing Client-Side Rendering (CSR) for interactive agent interfaces that require dynamic user interactions and real-time updates. [7]. The system integrates a relational database (PostgreSQL) with a unified global search engine that queries across multiple data entities, unifying disparate data points into a cohesive, searchable platform. By moving from a file-based to a data-based architecture, this study demonstrates how modern software engineering practices can resolve the trade-off between information volume and retrieval speed in customer care operations.

The novelty of this study lies in the integration of performance-oriented web architecture and operational knowledge governance within the FMCG customer care context. Prior knowledge management studies have emphasized the importance of converting tacit knowledge into explicit organizational knowledge and maintaining knowledge consistency through structured

knowledge management systems [6], [8]. In customer support contexts, previous studies have also shown that knowledge-centric help desk systems can support problem resolution by integrating multiple knowledge sources into daily help desk operations [15]. Meanwhile, call center information system studies commonly evaluate operational success using broader service indicators such as system quality, user satisfaction, and net benefits [16].

Unlike prior KMS studies that primarily focus on knowledge storage, organizational learning, or help desk performance evaluation, this study proposes a real-time operational KMS tailored to FMCG customer care activities. The proposed system combines four key elements: a Single Source of Truth architecture to reduce knowledge fragmentation, hybrid rendering using SSR and CSR to support fast initial content delivery and interactive agent workflows, unified multi-entity keyword search across product and SOP data, and an audit trail mechanism to support transparency and accountability in knowledge updates.

The main contributions of this study are as follows. First, this study designs a web-based KMS architecture tailored to FMCG customer care operations. Second, it implements a hybrid-rendered Next.js application to support fast and interactive knowledge access. Third, it transforms fragmented PDF- and spreadsheet-based knowledge assets into a structured relational database with unified search capability. Fourth, it evaluates the system using Lighthouse-based technical performance metrics and pilot usage indicators.

II. METHODS

The development of the Knowledge Management System (KMS) adhered to a rigorous software engineering paradigm, prioritizing high scalability, performance optimization, and user-centric design. The project lifecycle followed an adapted Agile Scrum framework [9], characterized by weekly sprints and iterative refinement. This approach allowed for continuous validation of features against the evolving requirements of the operational team at PT Paragon Technology and Innovation.

A. Requirement Engineering and Gap Analysis

The study commenced with a comprehensive requirement engineering phase aimed at deconstructing the operational inefficiencies of the legacy workflow. Through semi-structured interviews with Team Leaders and direct observation of agents' daily interactions, specific functional gaps were identified. The primary imperative was the transition from a decentralized "document-based" retrieval system to a centralized "data-driven" search engine. As summarized in Table 1, the legacy system's reliance on static PDF files resulted in high retrieval latency and a lack of version control, whereas the proposed system necessitates granular indexing and transparency.

TABLE I. COMPARISON OF FUNCTIONAL CAPABILITIES BETWEEN THE LEGACY DOCUMENT-BASED WORKFLOW AND THE PROPOSED KNOWLEDGE MANAGEMENT SYSTEM.

Functional Aspect	Legacy System (PDF-Based)	Proposed System (Next.js SSR)
Data Storage Format	Unstructured Static Files (PDF, Excel) dispersed across local drives.	Structured Relational Database (PostgreSQL) centralized in the cloud.
Search Mechanism	File-Level: Agents search by file name; must open files to read contents.	Content-Level: Global Search queries across all text fields (titles, descriptions, content) for retrieval across multiple data entities.
Update Workflow	Manual: Manager edits file → converts to PDF → emails to team.	Real-Time: Manager edits via Dashboard → changes become available through the centralized system.
Version Control	None: High risk of agents utilizing outdated PDF versions.	Automated: System tracks all data modifications for accountability and transparency.
Accountability	Low: No record of who accessed or modified the documents.	High: AuditLog records every user action (Insert, Update, Delete).

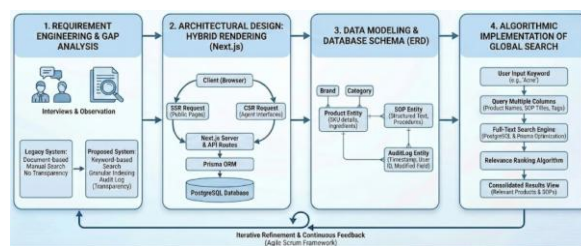


Fig. 1. Agile Software Engineering Approach for KMS Development

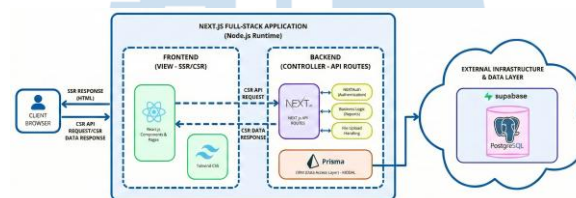


Fig. 2. High-Level System Architecture utilizing Next.js for Server-Side Rendering and Prisma ORM for database interaction

Agents required a system capable of indexing the specific contents of Standard Operating Procedures (SOPs) and product details, such as ingredients and usage instructions rather than merely retrieving file names. Furthermore, a critical non-functional requirement identified was "operational transparency." To ensure accountability, the system was required to log every modification to the knowledge base, a feature entirely absent in the previous workflow [10].

B. Architectural Design: The Full-Stack Monorepo Approach

To address the high-performance requirements of a fast-paced Customer Care environment, the system was built as a modern full-stack application. Figure 2 illustrates the high-level system architecture, highlighting the separation of concerns between the client-side presentation and server-side logic.

The core framework selected was Next.js, a production-grade framework for React [7]. The strategic decision to utilize Next.js was driven by its support for hybrid rendering architecture, combining Server-Side Rendering (SSR) and Client-Side Rendering (CSR) based on application requirements. For public-facing pages, the system leverages SSR,

where the server pre-renders the complete HTML page with necessary data before transmission to the client, as depicted in the request flow in Figure 2. This approach significantly reduces the First Contentful Paint (FCP) time and improves initial load performance compared to traditional Single Page Applications (SPA) that download a minimal HTML shell and render content via JavaScript, often causing "hydration" delays when parsing large text datasets [13]. For interactive agent interfaces requiring dynamic user interactions, real-time updates, and state management, the system employs CSR to provide responsive user experiences. This hybrid approach ensures that agents have immediate access to information during live customer interactions while maintaining optimal performance for both public and authenticated user experiences.

For the backend infrastructure, the system leverages PostgreSQL, an advanced open-source relational database management system selected for its ACID compliance and robust data integrity [11]. To bridge the application layer and the database, Prisma ORM (Object-Relational Mapping) was employed. As shown in the architecture diagram, Prisma serves as the data access layer. It was chosen over raw SQL queries to enforce strictly typed database access, ensuring "type safety." This mechanism ensures that potential data

structure errors are caught during the compilation phase rather than causing runtime crashes, thereby enhancing overall system stability [12].

C. Data Modeling and Database Schema

The data modeling phase focused on constructing a relational structure capable of handling the complex, hierarchical nature of FMCG product portfolios. An Entity-Relationship Diagram (ERD) was constructed to map these complexities, as shown in Figure 3.

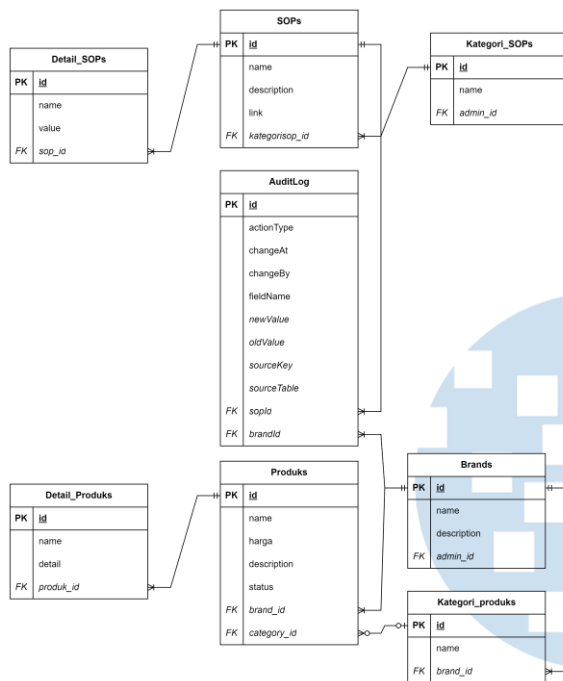


Fig. 3. Entity-Relationship Diagram (ERD) illustrating the relation structure between Products, SOPs, and the Audit Log mechanism.

The schema, visualized in Figure 3, comprises three core clusters:

1. **Product Entity:** Designed to store granular details of each Stock Keeping Unit (SKU). This entity maintains many-to-one relationships with *Brand* and *Category* entities, enabling the faceted navigation required by agents.
2. **SOP Entity:** Stores procedural knowledge. Unlike the legacy system, SOPs are stored as structured text blocks rather than binary files, enabling keyword-based search capabilities described in the subsequent section.
3. **AuditLog Entity:** A crucial component for system integrity. This entity is designed to automatically capture metadata for every INSERT, UPDATE, or DELETE operation. As illustrated in the schema, the log records the timestamp, the actor (User ID), and the specific field modified. This data model directly supports the organization's "One Voice Policy" by allowing supervisors to trace

exactly when and by whom a piece of information was altered.

D. Algorithmic Implementation of Global Search

A pivotal feature of the methodology was the implementation of a unified Global Search algorithm. The global search mechanism was implemented using case-insensitive keyword matching across multiple table columns, including product names, descriptions, meta-tags, and SOP titles.

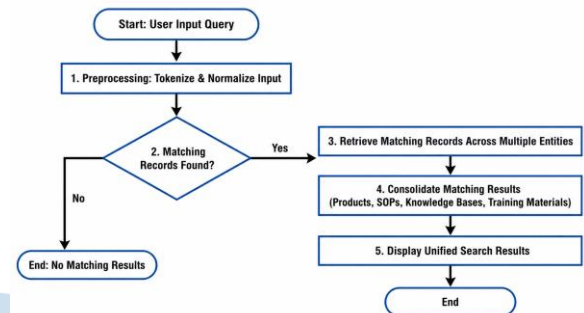


Fig. 4. Flowchart of the Global Search Algorithm using case-insensitive multi-entity keyword matching.

The logic flow, detailed in Figure 4, utilizes Prisma ORM's pattern matching capabilities with case-insensitive search across multiple database entities. The system performs parallel queries across different data types (products, SOPs, knowledge bases, and training materials) using the 'contains' operator, which enables flexible text matching. When an agent queries a keyword like "Acne," the system retrieves matching results from all relevant entities and consolidates them into a single, unified view. While the current implementation does not employ relevance-based ranking, the comprehensive search across multiple data sources ensures that agents can quickly access related products (e.g., acne serums) and corresponding handling procedures (SOPs) in one consolidated interface, thereby minimizing the agent's cognitive load by eliminating the need to search multiple separate systems.

E. Experimental Setup and Evaluation Procedure

The evaluation was designed to assess the front-end performance and page-level responsiveness of the proposed Knowledge Management System. The benchmarking process was conducted using Google Chrome Lighthouse, which provides standardized measurements for web performance indicators such as First Contentful Paint (FCP), Largest Contentful Paint (LCP), Total Blocking Time (TBT), Speed Index, Cumulative Layout Shift (CLS), and overall performance score.

The evaluation was conducted on the deployed KMS connected to a PostgreSQL database containing more than 1,000 SKU records and structured SOP entries. The tested pages represented common agent activities, including the main dashboard, product

knowledge page, SOP detail page, and update tracking page. These pages were selected because they represent the most frequently accessed areas of the system during daily customer care operations.

To reduce measurement bias, each tested page was evaluated using 30 repeated Lighthouse runs under the same testing environment. The repeated results were summarized using mean and standard deviation values. This approach was used to determine whether the reported performance values were consistent across multiple observations rather than being based on a single isolated measurement.

Since this study focuses on pilot implementation and front-end performance evaluation, concurrent-user load testing was not included in the current evaluation scope. Therefore, the reported results should be interpreted as page-level technical performance indicators rather than full server-side scalability measurements.

III. RESULTS

A. System Implementation and User Interface Performance

The culmination of the development phase resulted in the successful deployment of the “Customer Care Paragon Web” (CCPW), a centralized platform designed to consolidate the division’s fragmented knowledge assets. The user interface (UI), constructed using the Tailwind CSS utility-first framework, provides a responsive and uniform experience across devices, as illustrated in Figure 5.

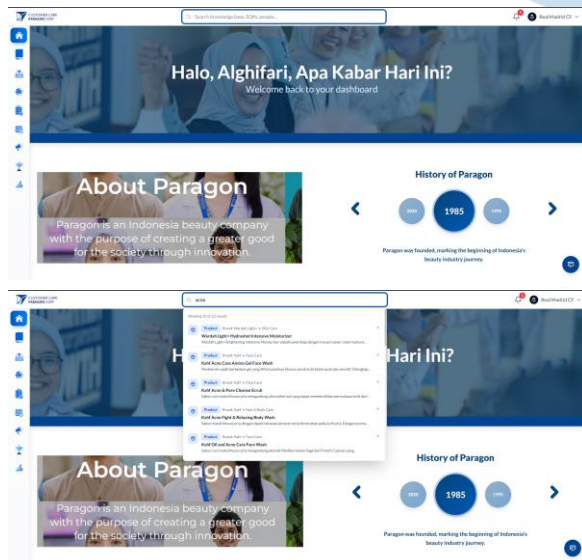


Fig. 5. The main dashboard of the Customer Care Paragon Web, featuring the centralized search bar and modular content categorization.

The implemented system transforms the previous document-based workflow into a centralized web-based knowledge management platform. In the legacy workflow, agents were required to manually search across multiple PDF and spreadsheet files, which

increased retrieval steps and created a risk of accessing outdated information. In contrast, the proposed KMS provides centralized access to product information, SOPs, update tracking, and audit logs through a Single Source of Truth architecture. The operational and performance comparison between the legacy workflow and the proposed KMS is summarized in Table II.

TABLE II. PERFORMANCE AND OPERATIONAL COMPARISON: LEGACY WORKFLOW VS. PROPOSED KMS

Metric	Legacy System (PDF/Static Files)	Proposed System (Next.js SSR)	Improvement
Initial Page Load / FCP	4.2 seconds	0.35 seconds	approximately 92% faster
Information Retrieval Flow	Manual search across multiple PDF/spreadsheet files	Centralized keyword-based search interface	Reduced retrieval steps
Update Propagation	Hours to days through manual redistribution	Near real-time update visibility through centralized database	Faster synchronization
Version Error Risk	High due to multiple document copies	Low due to Single Source of Truth architecture	Reduced outdated information risk
Update Accountability	No structured modification history	AuditLog records data changes	Improved governance

To validate the front-end performance of the proposed system, repeated Google Chrome Lighthouse measurements were conducted on the tested system interface. The evaluation focused on page-level performance indicators, including First Contentful Paint (FCP), Largest Contentful Paint (LCP), Total Blocking Time (TBT), Speed Index, and Cumulative Layout Shift (CLS). The results were summarized using mean and standard deviation values, as shown in Table III.

TABLE III. REPEATED LIGHTHOUSE PERFORMANCE EVALUATION RESULTS

Metric	N	Mean	Std. Dev.	Interpretation
First Contentful Paint (FCP)	30	0.35 s	0.28 s	Fast initial rendering
Largest Contentful Paint (LCP)	30	1.52 s	0.48 s	Good main content loading
Total Blocking Time (TBT)	30	20.00 ms	15.49 ms	Responsive interface
Speed Index	30	0.82 s	0.66 s	Fast visual loading, but varied
Cumulative Layout Shift (CLS)	30	0.00	0.00	Stable layout

As shown in Table III, the proposed KMS achieved strong page-level performance across 30 repeated Lighthouse measurements. The system recorded an average First Contentful Paint (FCP) of 0.35 seconds, Largest Contentful Paint (LCP) of 1.52 seconds, Total Blocking Time (TBT) of 20.00 ms, Speed Index of 0.82 seconds, and Cumulative Layout Shift (CLS) of 0.00. These results indicate that the system provides fast initial rendering, responsive page behavior, and stable visual layout for the tested interface. However, since the evaluation was limited to Lighthouse-based page-level testing, the results should be interpreted as front-end performance indicators rather than full server-side scalability or concurrent-user load testing results.

B. Page-Level Performance Interpretation

The Lighthouse evaluation indicates that the proposed KMS achieved fast page-level performance across repeated measurements. The average FCP of 0.35 seconds suggests that the system can render initial content quickly, while the LCP of 1.52 seconds indicates that the main content remains within an acceptable loading range. The TBT value of 20.00 ms shows that the interface remains responsive during loading, and the CLS value of 0.00 indicates stable visual layout. These results support the use of a hybrid rendering strategy for improving the front-end responsiveness of the proposed KMS. However, this evaluation does not measure API-level query latency, server-side throughput, or concurrent-user scalability.

C. User Adoption and System Usage

Post-deployment logs indicated a high adoption rate. Within the first month of implementation, the system recorded an average of 450 unique search queries per day. Additionally, the "Update Tracking" module logged 15 major SOP revisions during the pilot period, all of which were acknowledged by agents within 24 hours of publication. This provides quantitative evidence of the system's active role in daily information dissemination.

D. Technical Interpretation: The Efficacy of SSR in Corporate Intranets

The empirical results support the architectural decision to utilize a hybrid rendering approach that strategically combines Server-Side Rendering (SSR) and Client-Side Rendering (CSR) based on application requirements. While Banks and Porcello [13] argue that CSR offers smoother page transitions, this study argues that in a high-pressure Customer Care environment, the initial load time is the critical metric. The average FCP of 0.35 seconds supports the premise that optimized page delivery can reduce initial waiting time for agents. Simultaneously, the system leverages CSR for interactive agent interfaces where smooth transitions and real-time updates are essential, thereby combining the performance benefits of SSR with the interactivity advantages of CSR. This finding

contributes to the growing body of literature advocating for context-aware, performance-first web architectures in enterprise tools that balance initial load performance with dynamic user experience requirements.

E. The Impact of the Single Source of Truth (SSOT)

Beyond technical metrics, this system facilitates a fundamental shift in organizational behavior, aligning with Nonaka and Takeuchi's Knowledge Creation Theory [6]. By transitioning from scattered PDF files to a centralized database—a Single Source of Truth (SSOT)—the organization successfully converts tacit knowledge (often held by senior managers who edit documents) into explicit, accessible knowledge available instantly to all agents. The transition to a Single Source of Truth (SSOT) architecture has fundamentally restructured the division's information workflow, effectively mitigating the risks associated with data fragmentation [4]. Figure 6 contrasts the legacy dissemination process with the new centralized model.

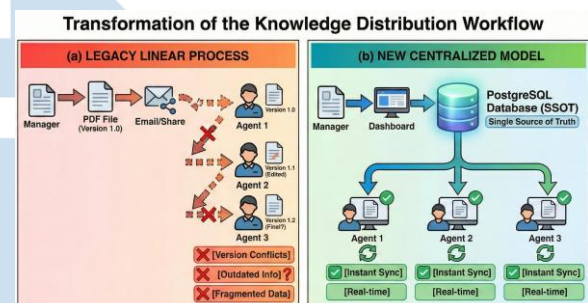


Fig. 6. Transformation of the Knowledge Distribution Workflow. (a) The legacy linear process prone to versioning errors. (b) The new centralized model supporting near real-time synchronization.

In the legacy model (Fig. 6a), updating a product specification was a multi-step manual process prone to human error and version control discrepancies. A manager was required to edit a master document, convert it to PDF, and redistribute it via disjointed communication channels such as email or chat groups. Conversely, the CCPW system (Fig. 6b) utilizes a centralized database architecture where updates committed by managers are immediately available to all users through a Single Source of Truth (SSOT). The "Update Tracking" feature, visualized on the agent dashboard, provides real-time notifications of recent changes through a polling mechanism that checks for updates every 30 seconds, ensuring agents are informed of modifications shortly after they occur. Upon login, agents are immediately presented with the latest dataset, and subsequent updates are detected through the notification system. This ensures that all agents, regardless of their physical location or shift, access an identical and synchronized dataset from the centralized database, thereby strictly adhering to the "One Voice Policy" and minimizing the risk of customer misinformation [5].

F. Operational Transparency and Governance

Beyond operational efficiency, the implementation of the AuditLog module has introduced a new layer of governance and transparency. Figure 7 presents the historical data view available to management, which details the chronological evolution of Standard Operating Procedures (SOPs).

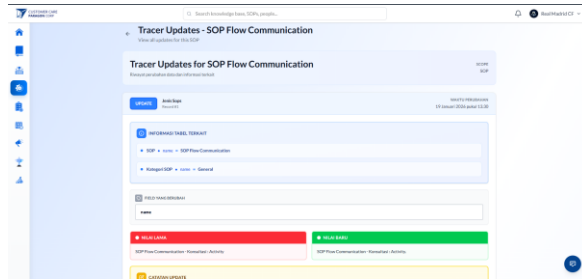


Fig. 7. The Audit Log interface displaying a chronological history of modifications to an SOP, ensuring data accountability.

This capability allows the quality assurance team to audit previous versions of service protocols and trace specific modifications to individual user accounts. By capturing metadata for every INSERT, UPDATE, and DELETE operation, the system fosters a culture of accountability [6]. This feature not only satisfies internal audit requirements but also facilitates continuous improvement by allowing management to analyze the frequency and nature of knowledge updates required to support dynamic market trends [3].

G. Limitations and Future Work

Despite its success, the current iteration has limitations. The system currently relies on manual data entry for stock levels, which introduces a potential latency between actual warehouse inventory and the information displayed to agents. Future development should focus on integrating an API connection to the company's ERP system to automate inventory updates. Additionally, the current search algorithm relies on exact keyword matching. Future work could explore Natural Language Processing (NLP) to handle semantic queries (e.g., understanding that "breakout" is related to "acne") to further enhance retrieval accuracy.

Another limitation of this study is that it has not yet measured direct customer-care performance indicators such as Average Handle Time (AHT), First Contact Resolution (FCR), agent productivity, and user satisfaction. The current evaluation focused on system design, implementation, and Lighthouse-based page-level performance testing. Measuring AHT and FCR requires longitudinal customer interaction logs, ticket resolution outcomes, and service quality records before and after implementation, which were outside the accessible scope of this pilot study. Therefore, the Lighthouse metrics and pilot usage observations in this study should be interpreted as initial technical feasibility indicators rather than direct evidence of customer service performance improvement. Future

research should conduct a pre-post operational evaluation to measure whether the proposed KMS can reduce AHT, improve FCR, increase agent productivity, and enhance user satisfaction.

IV. CONCLUSION

This study sets out to address the critical operational challenge of knowledge fragmentation within the high-velocity Customer Care environment of the FMCG sector. The diagnostic phase revealed that the prevalent reliance on decentralized, static document repositories (PDFs and spreadsheets) created significant bottlenecks in information retrieval latency and jeopardized service consistency. To mitigate these issues, this research successfully engineered and deployed a dynamic, web-based Knowledge Management System (KMS) designed as a Single Source of Truth (SSOT).

The technical implementation demonstrates that modern full-stack web technologies can support enterprise-grade internal tools when aligned with operational requirements. By leveraging the hybrid rendering architecture of the Next.js framework, which combines Server-Side Rendering (SSR) for fast initial content delivery and Client-Side Rendering (CSR) for interactive interfaces, the system achieved an average First Contentful Paint (FCP) of 0.35 seconds in repeated Lighthouse measurements. These findings indicate strong page-level front-end performance compared to the legacy document-based workflow. Furthermore, the structured relational data model implemented via PostgreSQL and Prisma ORM successfully transformed disconnected product details and SOPs into a cohesive, searchable knowledge repository accessible through a unified keyword-based search mechanism.

Beyond technical metrics, the substantive impact of this work lies in the fundamental transformation of the organizational workflow. The shift from a manual, linear information dissemination process to a centralized database architecture with a Single Source of Truth (SSOT) has significantly reduced the risk of agents accessing obsolete data, as all users now access an identical and synchronized dataset. Updates committed to the database are immediately available to all agents upon their next data access, with periodic polling mechanisms ensuring agents are informed of changes within 30 seconds. The integration of granular Audit Logs has further introduced a necessary layer of digital governance, shifting the culture from reliance on tacit, individual knowledge to explicit, accountable organizational knowledge.

While the current iteration successfully centralizes static product data and procedural protocols, it is not without limitations. The system currently relies on manual updates for dynamic information, such as warehouse stock levels, creating a potential latency between data availability and reality. Consequently, future development work should prioritize the integration of external APIs to connect the KMS directly with the company's Enterprise Resource

Planning (ERP) or Inventory Management Systems for automated, real-time stock updates. Additionally, further research could explore enhancing the current keyword-based search algorithm with semantic analysis capabilities through Natural Language Processing (NLP) to better handle ambiguous agent queries.

However, the current evaluation was limited to Lighthouse-based page-level performance testing and pilot usage observation. This study did not measure direct customer-care indicators such as AHT, FCR, agent productivity, or user satisfaction. Therefore, the findings should be interpreted as evidence of technical feasibility and workflow improvement potential rather than a complete measurement of customer service performance improvement. Future work should incorporate longitudinal operational data to evaluate the direct impact of the KMS on AHT, FCR, and agent productivity.

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Determinants of Student Test Scores: Academic, Family, and Learning Environment Factors a Multiple Linear Regression Analysis

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Abstract— This study aims to analyze the influence of academic, family, and learning environment factors on student exam scores. The study employs a quantitative approach using secondary data in the form of the Student Performance Factors dataset comprising 6,607 observations. The dependent variable in this study is student exam scores (Exam Score), while the independent variables include study hours (Hours Studied), attendance (Attendance), previous scores (Previous Scores), tutoring sessions (Tutoring Sessions), parental involvement (Parental Involvement), and access to learning resources (Access to Resources). The analytical techniques used were descriptive statistics and multiple linear regression. The results indicate that the regression model is statistically significant simultaneously with $F=1,601$ and $p < 0.001$, and explains 66.0% of the variance in students' exam scores ($R^2 = 0.660$). Partially, study hours, attendance, previous scores, and tutoring sessions have a positive and significant effect on test scores. Additionally, students with higher levels of parental involvement and access to learning resources tend to achieve better test scores. These findings indicate that students' academic achievement is not solely determined by individual study effort but is also influenced by family support and the availability of an adequate learning environment.

Index Terms—Determinants of Exam Scores; Learning Environment; Multiple Linear Regression; Parental Involvement; Student Academic Performance.

I. INTRODUCTION

Exam scores are a key indicator in assessing students' academic achievement [1]. Good learning outcomes not only reflect mastery of the material but also demonstrate the effectiveness of the learning process occurring both at school and at home. In practice, students' academic achievement is influenced by various interacting factors, such as study habits, attendance rates, family support, and learning environment conditions[1].

Academic factors such as study intensity, discipline in attending school, prior learning experiences, and participation in tutoring are often considered direct determinants of student success [1]. The higher a student's engagement in the learning process[2], the

greater their chances of achieving better grades. However, academic factors are not the sole explanatory. The family environment [3], particularly parental involvement [4], also plays a crucial role in shaping students, motivation, study habits, and academic supervision.

Additionally, a supportive learning environment such as the availability of adequate learning resources can help students understand the material more effectively [5]. Students with better access to instructional materials, supporting tools, or learning facilities tend to develop academic understanding more easily compared to those with limited access [6]. Therefore, analyses of academic achievement must consider students holistically, not only from an individual perspective but also in terms of the external support they receive [7]. Discussing the use of learning analytics and educational data mining to predict student achievement. It's an educational analytics approach, not linear regression [8]. Given these conditions, this study was conducted to examine the determinants of students' exam scores through academic, family, and learning environment factors using multiple linear regression analysis [1][3]. This study is expected to provide an empirical overview of the factors most influential on exam scores, thereby serving as a basis for improving the quality of learning and educational support for students [9]. Previously, the study focused on a single aspect of academic performance, such as learning, individual, or learning environment. Other studies use data-based education or multilevel education to predict academic performance [10]. However, a joint study that examines academic, familial, and learning environment factors using a berganda regression on a large student skala dataset consisting of more than 6,000 observations is still unreliable. Because of this, this study integrates these three dimensions into a single regression model in order to identify the factors that have the greatest impact on student test scores [8].

II. RESEARCH METHODS

This study uses a quantitative eksplanatory approach to analyze the impact of academic, familial, and learning environment factors on students' exam scores (Exam_Score). The first phase of research is completed by identifying research challenges and determining research objectives based on observed phenomena [11].

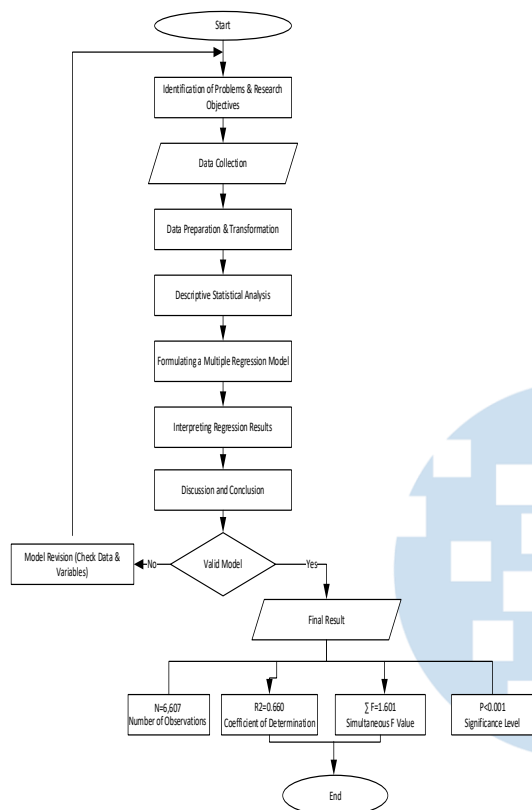


Fig 1. Research Methodology Flow

The next step involves gathering data using a publicly available dataset under Student Performance Factors. This dataset consists of 6.607 observations with a dependent variable called Exam_Score, while independent variables include academic, familial, and learning environment factors.

Following data collection, data transformation and persiapan are carried out. This article discusses data consistency, outliers, and missing values. The categorical variable is then transformed into a dummy variable so that it may be used in regression analysis. "High" is used as a reference category for the variables Parental Involvement and Access to Resources during the coding process.

Next, a deskriptif statistical analysis is performed to illustrate the characteristics of the research data. The analysis results show that the rata-rata Exam Score is 67.24 with a standard deviation of around 3.89. In addition, rata-rata Hours Studied was approximately 19.98 hours, while rata-rata Attendance reached 79.98%. This analysis also compares the rata-rata ujian based on each category of the research variables.

The next step is to use the linear regression model to increase the influence of independent variables on student test. The regression model that is used can be described as follows:

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + b_6X_6 + e$$

In the aforementioned model, variables X_1 – X_4 are continuous academic variables, while variables X_5 – X_6 are dummy variables that represent family and learning environment factors.

Subsequently, the hypothesis is tested using uji simultan (Uji F) and uji parsial (Uji t). The uji F result is $F = 1.601$ with $p < 0.001$, indicating a fully significant regression model. Conversely, the results of the uji t indicate that every independent variable has a p-value of less than 0.001, meaning that every variable has a significant impact on the student's. The next step is to understand the results of the regression. The coefficient of determination (R^2), which is approximately 0.660, indicates that the model can explain 66.0% of the variation in student ujian, although other factors outside the study model have an impact. The variable Tutoring Sessions has a coefficient of 0.504, making it a factor with the most positive impact on the increase in ujian. Conversely, the category Low Access_to_Resources has a coefficient of 2,037, which indicates a greater negative impact on student achievement.

The study's findings indicate that academic factors are the most powerful and reliable predictors of students' learning performance[12]. In addition, academic performance is affected in a multifaceted way by the combination of academic, familial, and learning environment factors .

Based on the aforementioned results, recommendations that might be made include increasing learning discipline, improving student kehadiran, increasing access to learning resources, and increasing individual participation in the educational process [13].

This study employs a quantitative approach with an explanatory research design, as it aims to explain the influence of several independent variables on a single dependent variable [7]. The data used are secondary data from the Student Performance Factors dataset, comprising 6,607 students.

The factors considered in this investigation are shown in Table 1. Exam score is the dependent variable, and the independent factors are two categorical variables (Parental Involvement and Access to Resources) and four numerical variables (Hours Studied, Attendance, Previous Scores, and Tutoring Sessions). Prior to regression analysis, the categorical data were converted into dummy variables.

The results of this investigation are mostly in line with earlier studies. Consistent with the current findings, [1] found that attendance and study habits have a major impact on students' academic progress.

Similarly, using multiple linear regression, [7] discovered that academic-related factors are among the best indicators of exam achievement. Additionally, the results of [3] who highlighted the significance of family support in enhancing kids' learning outcomes, are consistent with the substantial impact of parental participation seen in our study. In contrast to other research, this study uses a reasonably large dataset of 6,607 observations to integrate academic, family, and learning environment elements into a single regression model, offering a more thorough understanding of the factors influencing students' examination performance.

TABLE I. RESEARCH VARIABLES AND MEASUREMENT

Variable	Symbol	Type	Scale	Description
Exam Score	Y	Dependent	Numerical	Student final examination score
Hours Studied	X1	Independent	Numerical	Number of study hours per week
Attendance	X2	Independent	Percentage	Student attendance rate (%)
Previous Scores	X3	Independent	Numerical	Previous academic achievement score
Tutoring Sessions	X4	Independent	Numerical	Number of tutoring sessions attended
Parental Involvement	X5	Independent	Categorical	High, Moderate, Low
Access to Resources	X6	Independent	Categorical	High, Moderate, Low

A. Data Preprocessing

Preprocessing makes sure the dataset meets the multiple linear regression assumptions. The "High" category was used as the reference level when applying dummy variable encoding to categorical variables. Data Preprocessing Procedure the accuracy and dependability of the model are directly impacted by the quality of the input data, data preparation is an essential stage in regression analysis. The dataset was put through a number of preparation steps to make sure it satisfied the statistical presumptions needed for analysis before the multiple linear regression model was developed. These processes comprised categorical variable encoding, data transformation, outlier detection, missing value identification, duplicate checking, and data quality inspection. Specifically, the High category was used as the reference level to convert the variables Parental Involvement and Access to Resources into dummy variables.

Based on earlier research and the goals of this study, a conceptual framework was created to give a clear picture of the relationships between the research

variables. The framework outlines the independent variables academic, familial, and learning environment that are thought to have an impact on children's test performance. The multiple linear regression model employed in this study was built using this conceptual framework. Figure 2 displays the suggested research framework.

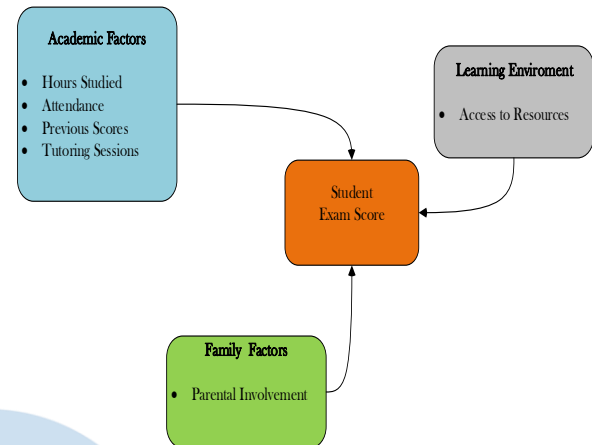


Fig 2. Conceptual Framework of the Proposed Research

A conceptual framework was developed to provide a clear picture of the interactions between the research variables based on previous research and the objectives of this study. The framework describes the independent factors academic, familial, and learning environment that are believed to affect kids' test scores. This conceptual framework was used to construct the multiple linear regression model used in this investigation. The proposed research framework is shown in Figure 2.

TABLE II. DATA PREPROCESSING PROCEDURE

Step	Activity	Purpose
Data Collection	Student Performance Factors Dataset	Obtain research data
Data Cleaning	Duplicate checking	Remove duplicate observations
Missing Value Inspection	Check missing values	Ensure data completeness
Outlier Detection	Boxplot and IQR inspection	Reduce abnormal observations
Data Transformation	Dummy variable encoding	Convert categorical variables
Feature Selection	Select six predictor variables	Improve model relevance
Statistical Assumption Test	Normality, multicollinearity, homoscedasticity	Ensure regression assumptions
Model Development	Multiple Linear Regression	Predict student exam score
Model Evaluation	R ² , F-test, t-test	Evaluate model performance

The analytical approach used in this study is also demonstrated by the conceptual framework. The

multiple linear regression model was used to estimate the contribution of each independent variable to the exam scores of the students. The t-test was used to determine the statistical significance of each predictor, and the F-test and the coefficient of determination (R^2) were used to evaluate the overall model performance. Through statistical analysis, this analytical process guarantees the empirical validation of the links suggested in the conceptual framework.

B. Regression Model Parameters

A number of model evaluation parameters were examined in order to assess the suggested multiple linear regression model's overall performance. These parameters give information about the regression model's predictive power, statistical significance, and goodness-of-fit. Table 3 provides a summary of the evaluation's findings.

TABLE III. REGRESSION MODEL PARAMETERS

Parameter	Value
Number of observations	6,607
Number of predictors	6
Regression model	Multiple Linear Regression
Dependent variable	Exam Score
R^2	0.660
Adjusted R^2	(isi sesuai output software)
F-statistic	1601
Significance (F-test)	$p < 0.001$
Significant predictors	6 variables

Six independent variables and 6,607 observations were used to create the multiple linear regression model, as shown in Table 3. With a coefficient of determination (R^2) of 0.660, the model's predictor variables account for about 66.0% of the variation in students' exam scores. Additionally, the regression model is statistically significant and appropriate for understanding the association between academic, family, and learning environment characteristics and student academic performance, as confirmed by the F-statistic of 1601 with a significance level of $p < 0.001$. These findings show that the suggested regression model fits the data well generally and can be trusted to evaluate how the chosen factors affect students' test scores.

The dependent variable in this study is student exam scores (Exam Score). The independent variables used consist of six main variables, namely study hours (Hours Studied), attendance (Attendance), previous scores (Previous Scores), tutoring sessions (Tutoring Sessions), parental involvement (Parental Involvement), and access to learning resources (Access to Resources). The variables for parental involvement and access to learning resources are categorical [8]; therefore, in the analysis, they were converted into

dummy variables with the "high" category as the reference category.

Data analysis was conducted in two stages. The first stage was a descriptive analysis to describe the characteristics of the data[9]. The second stage was a multiple linear regression analysis to test the simultaneous and partial effects of the independent variables on students' test scores. The regression model used can be formulated as follows [14] [15]:

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + b_6X_6 + e$$

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + b_6X_6 + e$$

where:

1. Y = student's test score
2. X_1 = study hours
3. X_2 = attendance
4. X_3 = previous score
5. X_4 = tutoring sessions
6. X_5 = parental involvement
7. X_6 = access to learning resources
8. a = constant
9. e = error

Hypothesis testing was conducted using a t-test to examine the partial effects of each variable and an F test to examine the simultaneous effects of all independent variables on students' test scores [16].

III. RESEARCH RESULTS

The results of the descriptive analysis show that the average student exam score was 67.24 with a standard deviation of 3.89. The average number of study hours was 19.98 hours, the average attendance rate was 79.98%, the average previous score was 75.07, and the average number of tutoring sessions was 1.49 sessions.

Categorically, students with high parental involvement had an average test score of 68.09, higher than the moderate category at 67.10 and the low category at 66.36. A similar pattern was also observed regarding access to learning resources, where students with high access had an average score of 68.09, the moderate category 67.13, and the low category 66.20. These findings provide initial indications that family support and the learning environment are associated with academic achievement.

The results of multiple linear regression indicate that the research model is simultaneously significant with an F-value of 1601 and $p < 0.001$. The coefficient of determination, $R^2 = 0.660$, indicates that 66.0% of the variation in students' exam scores can be explained by the six independent variables in the model, while the remaining 34.0% is explained by other factors outside the model.

Partially, all the main variables in the model have a significant effect on students' exam scores. A summary of the regression results is as follows:

TABLE IV. SUMMARY OF THE REGRESSION

Variable	Coefficient	Significance
Study hours	0.294	< 0.001
Attendance	0.199	< 0.001
Previous score	0.048	< 0.001
Tutoring session	0.504	< 0.001
Low parental involvement	-1.996	< 0.001
Moderate parental involvement	-1.035	< 0.001
Low access to learning resources	-2.037	< 0.001
Moderate access to learning resources	-0.943	< 0.001

Based on the table, study hours have a positive effect on test scores. This means that every additional hour of study tends to increase test scores by 0.294 points, assuming other variables remain constant. Attendance also has a positive effect, where each one-point increase in attendance raises the exam score by approximately 0.199 points. This indicates that discipline in attending school is a crucial factor in supporting academic achievement.

Previous scores have a positive effect on current exam scores. This indicates that past academic performance remains an important indicator of future academic performance. Meanwhile, tutoring sessions also have a positive effect, meaning that additional learning support outside the classroom can help students improve their exam results.

Regarding family factors, students with low parental involvement have average test scores nearly 2 points lower than students with high parental involvement. Similarly, regarding the learning environment, students with low access to learning resources have test scores approximately 2 points lower than those with high access. These findings confirm that differences in academic achievement stem not only from students' own study efforts but also from the social support and learning resources available to them.

IV. DISCUSSION

The research findings indicate that academic factors have the most significant impact on students' test scores. Attendance and study hours are the two variables that most consistently show a positive influence. This finding makes sense because students who attend class more frequently have a greater opportunity to follow the teacher's explanations, understand the material, and participate in the learning process. Similarly, students who spend more time

studying tend to have a better understanding of the material and are better prepared when taking exams.

The positive influence of previous scores indicates continuity in academic performance. Students with a strong academic foundation tend to maintain their performance in subsequent evaluations. This suggests that educational interventions should be implemented as early as possible, as learning achievements in earlier stages can influence outcomes in subsequent stages.

Findings regarding tutoring sessions show that additional academic support remains relevant in improving learning outcomes. Tutoring can serve as a means of reinforcing material, deepening concepts, and addressing students' learning weaknesses. Thus, academic support programs can be one strategy to improve student achievement, particularly for those with lower initial performance.

In the family dimension, parental involvement has been shown to significantly influence test scores. This involvement can be manifested through monitoring of study habits, providing motivation, or creating a conducive learning environment at home. High levels of parental support appear to reinforce students' study habits and enhance their academic responsibility.

In the learning environment dimension, access to learning resources also plays a crucial role. Students with high access to learning resources achieve better scores compared to those with limited access. This indicates that the quality of the learning environment including instructional materials, supporting tools, and learning facilities serves as a supportive factor that enhances the effectiveness of students' learning efforts.

Overall, the results of this study indicate that students' academic achievement is multidimensional. Test scores are determined not only by internal student factors but also by the quality of external support received. Therefore, efforts to improve learning outcomes should be undertaken in an integrated manner, involving students, families, and the learning environment.

V. CONCLUSIONS

This study concludes that academic, family, and learning environment factors simultaneously have a significant influence on students' exam scores. The regression model indicates that the six variables tested account for 66.0% of the variation in students' exam scores. Partially, study hours, attendance, previous scores, and tutoring sessions have a positive and significant effect on exam scores. Additionally, students with high parental involvement and high access to learning resources tend to achieve better exam results compared to students in the moderate or low categories.

These findings indicate that improving academic achievement cannot be focused solely on students as individuals. Family support and the availability of an adequate learning environment are also important

factors that must be considered. Thus, strategies to improve learning outcomes need to be implemented comprehensively through strengthening study discipline, improving attendance, providing tutoring, fostering parental involvement, and providing better learning resources.

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Immersive Culinary Simulation With FSM-Based NPCs in a 3D Game for Promoting Sundanese Restaurants

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Abstract— The development of a 3D interactive game entitled “Sapiring Rasa” aims to promote traditional Sundanese restaurants while supporting the preservation of Indonesia’s culinary heritage through digital media. The game is designed for desktop platforms with a top-down perspective, allowing players to manage a traditional eatery, serve customers, and address various resource management challenges. The development process employed the Unity3D Engine and applied the Multimedia Development Life Cycle (MDLC), which includes the stages of Concept, Design, Material Collecting, Assembly, Testing, and Distribution. The main contribution of this study lies in the practical implementation of artificial intelligence-based non-player characters (NPCs) using a Finite State Machine (FSM) approach to create dynamic and responsive customer interactions, thereby improving gameplay immersion and user experience. System functionality was validated through alpha testing using black-box methods, while usability evaluation was conducted through beta testing using the System Usability Scale (SUS) involving 30 participants. The results showed an average SUS score of 73.5, classified as “Good” and “Acceptable.” These findings indicate that the proposed game is usable and well received by users. Overall, the integration of local cultural elements into interactive gameplay demonstrates the potential of digital games as effective media for cultural promotion and educational purposes.

Index Terms— Artificial Intelligence (FSM); Cultural Game; Interactive 3D Game; Multimedia Development Life Cycle (MDLC); Sundanese Restaurant Simulation.

I. INTRODUCTION

Traditional Sundanese restaurants represent an important part of Indonesia’s cultural heritage that continues to endure today. Their uniqueness is reflected in the use of natural materials such as bamboo and wood in architectural design, as well as floor-seating (lesehan) arrangements that embody the communal values of Sundanese society. Signature dishes, including nasi liwet, pepes ikan, karedok, and lalapan, are not merely served as meals but also represent cultural values and local wisdom passed down through generations [1][2]. Despite the pressures of modernization and changing lifestyles, traditional

Sundanese restaurants strive to preserve the authenticity of their flavors, presentation, and atmosphere. Beyond functioning as dining places, these restaurants also serve as cultural spaces that introduce and transmit traditions to younger generations [3][4]. Therefore, factors such as service quality, pricing, taste, and comfort play a crucial role in attracting customers, while innovative promotional strategies are increasingly needed to remain relevant in a rapidly evolving era [5][6].

Along with technological advancements, cultural promotion no longer relies solely on conventional media but increasingly adopts interactive media, particularly digital games. Such media are widely used because they can engage younger audiences through more enjoyable and participatory approaches. Digital games have evolved from simple entertainment into effective educational media for conveying cultural messages [7]. Several studies indicate that digital games can enhance cognitive and socio-emotional abilities, making them a promising alternative for introducing cultural values to younger generations [8].

Previous studies have employed digital games and interactive media to promote local culture using structured development methods such as the Multimedia Development Life Cycle (MDLC). Research findings show that this approach is effective in increasing user interest in traditional cultural and culinary content [9][10]. In addition, the application of artificial intelligence techniques, such as Finite State Machines (FSM), has been proven to create more dynamic character behavior and enhance gameplay experience in interactive 3D games[11][12]. Usability evaluation methods, such as the System Usability Scale (SUS), are also widely applied to assess user experience and system acceptance in educational and cultural applications[13] [14].

Three-dimensional game development using Unity has been widely applied in educational and culture-based media. Unity supports graphics, audio, scripting, animation, and artificial intelligence features such as NavMesh and NavMeshAgent for NPC movement [13][14]. Previous studies have also combined FSM with pathfinding methods to improve NPC behavior in

Unity-based simulations [17]. In addition, Behavior Trees have been widely discussed as an alternative NPC behavior architecture because they provide more modular and extensible behavioral control for complex agents [18].

Based on the identified gap, this study develops an immersive 3D culinary simulation game focused on Sundanese traditional restaurants, integrating cultural elements, restaurant simulation, and FSM-based NPC behavior. The novelty of this study does not lie in proposing a new FSM algorithm, because FSM is already a well-established approach in game AI. Instead, the novelty lies in addressing the limited explanation of structured NPC service behavior in culturally themed restaurant simulations and in integrating FSM-based NPC behavior with Sundanese culinary representation as a promotional medium for traditional restaurants. The scientific contribution of this study is the design, implementation, and evaluation of structured NPC service behavior in a culturally themed 3D culinary simulation environment. This study aims to provide a promotional medium that is not only visually rich but also interactive, participatory, and relevant for introducing Sundanese culinary culture in the digital era.

I. METHODS

The development of the proposed 3D Sundanese restaurant simulation game follows the Multimedia Development Life Cycle (MDLC), which consists of concept, design, material collecting, assembly, testing, and distribution stages. In the concept stage, the main idea, target users, cultural content, and gameplay objectives were defined. The game was designed as an interactive promotional medium that introduces Sundanese restaurant atmosphere, traditional dishes, and restaurant service activities through a 3D simulation environment [19][20]. The overall workflow is illustrated in the Work Breakdown Structure (WBS) shown in Figure 1.

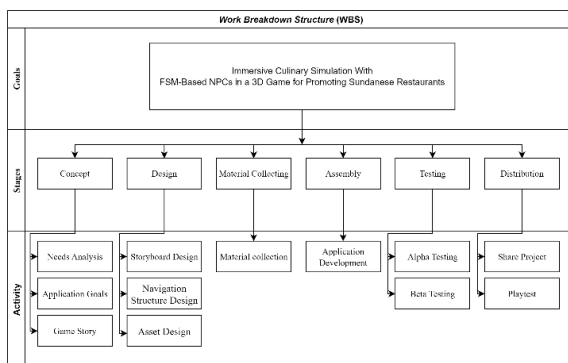


Fig. 1. Work Breakdown Structure

A. Concept

This initial phase focuses on analyzing user needs, defining development goals, and drafting the game narrative [19]. Key activities include identifying user requirements, setting development objectives,

determining the target users, and formulating a storyline that serves as the foundation for development. In this study, the concept phase also determined the main cultural elements to be represented in the game, including Sundanese restaurant atmosphere, traditional dishes, and restaurant service activities.

B. Design

In this stage, the visual elements, navigation system, and overall game structure are designed [19]. Activities include creating a storyboard, designing the navigation flow, and planning the visual assets. The outputs guide the development of the game's UI/UX and user interaction flow. The Finite State Machine (FSM) was also designed in this stage to define the behavior of NPCs in the restaurant service process. The FSM design includes the definition of NPC states, transition conditions, and event triggers that determine how NPCs move from one behavior to another. In this study, FSM was applied to service-related NPC behavior, such as entering the restaurant, moving to a table, viewing the menu, ordering food, waiting, eating, paying, and leaving the restaurant.

C. Material Collecting

This phase involves gathering all necessary assets and resources to support game development [19]. These materials include visual assets such as 3D models and illustrations, audio components like background music and sound effects, and cultural references to enhance the authenticity of local cultural elements featured in the game. References related to Sundanese restaurant interiors, traditional dishes, and restaurant atmosphere were also collected to support the cultural representation in the simulation.

D. Assembly

At this stage, all previously prepared components are integrated into the game application [19]. Activities involve developing the game using Unity3D, importing 3D assets, adding animations, and implementing game logic through C# scripting. The FSM logic was implemented at this stage to control NPC behavior according to predefined states and transitions. Each NPC behavior was represented as a state, and the transition between states occurred when specific user actions or in-game events were triggered. The output of this stage is a playable game prototype ready for testing.

E. Testing

The testing phase aims to ensure the functionality, NPC behavior, and usability of the game [19]. It was carried out in two stages: alpha testing and beta testing. Alpha testing was conducted internally to identify technical issues, validate gameplay functions, and examine whether FSM-based NPC behavior worked according to the designed scenario. The FSM behavior was evaluated by observing whether each NPC state

and transition was executed correctly based on predefined triggers. The observed aspects included state transition accuracy, NPC response to events, and completion of the restaurant service flow. Beta testing was conducted after the prototype had passed functional testing. At this stage, users were asked to play the game, interact with the restaurant environment, observe NPC behavior, and complete the System Usability Scale (SUS) questionnaire. Therefore, SUS data collection was conducted during the beta testing stage after users interacted with the playable prototype.

F. Distribution

The final phase focuses on delivering the game to end users [19]. This includes distributing the game via digital platforms such as itch.io. This step plays a crucial role in introducing the game as a medium for promoting Sundanese culinary culture to a broader audience.

G. FSM-Based NPC Behavior Implementation

The FSM was implemented to control NPC behavior in the restaurant service simulation. Each NPC behavior was represented as a state, and the transition between states occurred when specific conditions or events were triggered. The customer NPC behavior consists of several sequential states, namely Idle, Enter Restaurant, Move to Table, View Menu, Place Order, Wait for Food, Eat, Pay, and Exit. The NPC initially stays in the Idle state before entering the restaurant. When the game scenario starts, the NPC enters the restaurant and moves to an available table. After reaching the table, the NPC views the menu and places an order based on user interaction. The NPC then waits for the food, performs the eating activity after the food is served, continues to the payment process, and finally leaves the restaurant. This FSM structure was used because the restaurant service process follows a clear and predictable sequence, making it suitable for deterministic NPC behavior in the proposed simulation game.

II. RESULT AND DISCUSSION

A. Concept

1) Needs Analysis

The needs analysis was carried out through literature review and interviews. The literature review aimed to gather references related to educational game development, game technologies, and effective game design principles. References were sourced from academic journals, books, and previous research. In addition, interviews with the Garut Department of Tourism and Culture (Disparbud) were conducted to collect information on traditional Sundanese cuisine and interior design of traditional restaurants. This information ensured the visual and content elements in the game were culturally appropriate and reflective of Sundanese identity.

2) Application Goals

This game is designed to introduce Sundanese culinary traditions in an engaging and interactive way through a restaurant management simulation. Users are expected to become familiar with various traditional dishes while also learning basic management skills.

3) Game Story

The core concept of the game is managing a traditional Sundanese restaurant, where players serve customers, deliver food, hire cleaning staff, and expand the dining area. The game emphasizes traditional Sundanese atmosphere through visuals and interior design. Table I presents a detailed breakdown of the game concept.

TABLE I. GAME CONCEPT

No	Element	Description
1	Title	<i>Sapiring Rasa</i> , A top-down 3D simulation game themed on a traditional Sundanese restaurant.
2	Target Users	General audience, with no specific age restrictions.
3	Features	Open and manage the restaurant, serve customers, hire cleaners, expand dining area, rating and finance system.
4	2D and 3D Assets	3D characters, 3D top-down layout of the restaurant, 3D interior and exterior assets, and 2D game UI.
5	Audio	Traditional Sundanese background music and sound effects.

B. Design

1) Storyboard Design

The storyboard outlines the scenes and interaction flow within the game, helping visualize the player experience. Table II describes the storyboard in detail.

TABLE II. GAME STORYBOARD

No	Scene	Content	Description
1	Scene 1	Splash Screen Page	Displays the game logo as an opening screen.
2	Scene 2	Main Menu Page	Includes options such as Start, Settings, Info, and Exit.
3	Scene 3	Info Page	Shows information about the game developer.
4	Scene 4	Gameplay Page	The main scene where players manage the restaurant and interact with customers.
5	Scene 5	Gameplay Food Menu Page	Displays traditional Sundanese dishes with short descriptions.
6	Scene 6	Gameplay Menu Shop Page	Allows players to purchase staff (NPCs) and upgrade dining areas.
7	Scene 7	Gameplay Settings Page	Offers options to adjust audio, effects, and screen display.
8	Scene 8	Gameplay Results Page	Shows earnings and customer satisfaction ratings after gameplay ends.

2) Navigation Structure Design

This step involves designing the game's menu navigation system. The structure is illustrated in Figure 2.

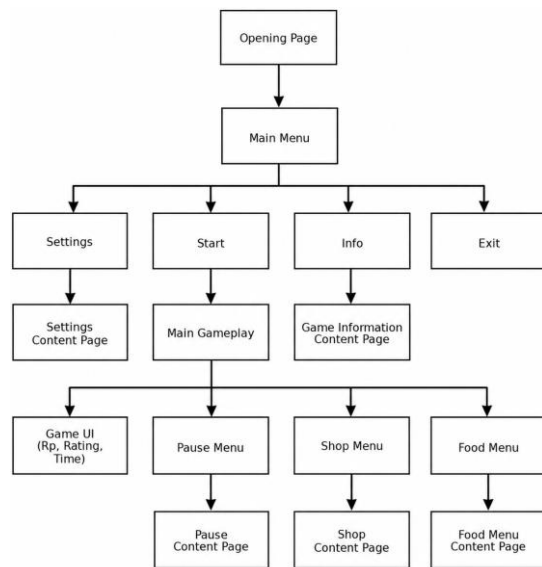


Fig. 2. Navigation Structure

Fig. 2 shows the main menu interface of the game. This interface provides access to the main features, including starting the simulation, viewing information, and exiting the game

3) Asset Design

The visual assets such as characters, restaurant layout, interior and exterior design, and UI elements were created with a Sundanese cultural theme as show as Figure 3 and Figure 4.



Fig. 3. UI asset designing

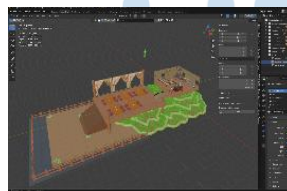


Fig. 4. Asset design Sundanese restaurant layout

Fig. 3 shows the exterior or initial environment of the restaurant simulation, while Fig. 4 shows the interior area where user interaction and restaurant service simulation take place. Therefore, these figures are not identical because they represent different spatial contexts in the game.

C. Material Collecting

In the Material Collecting phase, various assets were prepared to support game development. 3D models were created using Blender in .fbx format with designs reflecting traditional Sundanese restaurant themes. 2D assets, including UI elements, icons, logos, and illustrations, were produced in Adobe Illustrator to match the game's cultural aesthetic, along with a storyboard as a visual reference. Audio components

were sourced from royalty-free libraries and converted to .wav format for use in Unity. Additionally, all text elements were formatted using the Beach Lombok font to enhance the traditional atmosphere of the game.

D. Assembly

In this stage, all assets and design components were integrated into Unity3D to implement game mechanics, interaction systems, animations, user interfaces, and NPC behavior. Core features, including the main menu, settings, information page, gameplay interface, shop, food menu, and game result summary, were developed with a strong emphasis on Sundanese cultural elements.

Figs. 5–11 show the main interface and interaction features implemented in the game. Fig. 5 presents the main menu, which features background music and visual elements to create the ambiance of a traditional Sundanese restaurant. Fig. 6 shows the settings menu, which allows players to adjust audio and display preferences stored locally using Unity's PlayerPrefs system. Fig. 7 presents the information page, which introduces the game content. Fig. 8 shows the main gameplay interface with information such as money, rating, and time. Fig. 9 presents the shop system, which enables players to hire cleaners and expand the dining area. Fig. 10 shows the food menu, which presents authentic Sundanese dishes through images and descriptions. Fig. 11 presents the game result summary, which displays total earnings and customer satisfaction scores.

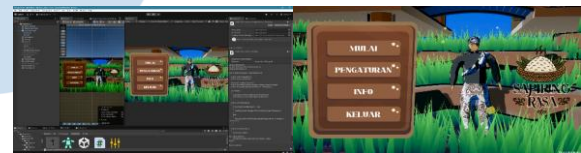


Fig. 5. Main Menu Implementation in Unity and In-Game Display

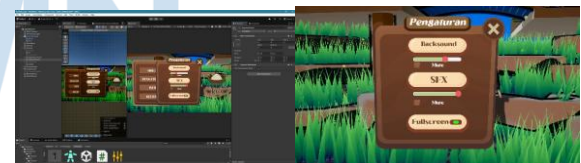


Fig. 6. Settings Menu Implementation in Unity and In-Game Display

Customer and cleaner NPCs were also implemented during this stage. Customer NPCs were programmed using Finite State Machine (FSM) logic to simulate structured restaurant service behavior, such as entering the restaurant, moving to a seat, ordering food, eating, providing ratings, and exiting the restaurant. Cleaner NPCs were implemented to support restaurant maintenance activities, such as moving around the restaurant area, detecting stains or trash, cleaning the area, and returning to patrol behavior. Fig. 12 presents the FSM state transition diagram used to describe the behavior flow of the NPC in the restaurant service scenario. This diagram shows how the NPC changes from one state to another based on specific triggers, such as entering the restaurant, moving to the table, viewing the menu, ordering food, waiting, eating,

paying, and leaving the restaurant. Fig. 13 presents the game flow diagram, which describes the overall interaction flow between the user, game system, and restaurant simulation environment.

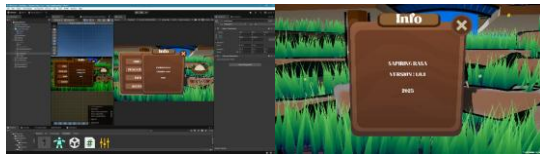


Fig. 7. Information Page Implementation in Unity and In-Game Display



Fig. 8. Gameplay Implementation in Unity and Display in Game



Fig. 9. Shop System Implementation in Unity and In-Game Display



Fig. 10. Food Menu Information Implementation in Unity and In-Game Display



Fig. 11. Game Result Summary Implementation in Unity and In-Game Display

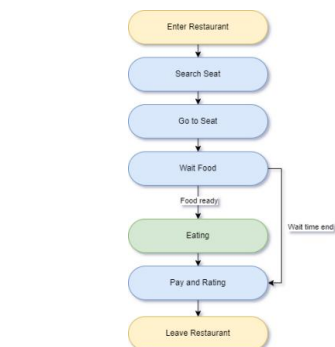


Fig. 12. Customer NPC Behavior Flow and In-Game Implementation

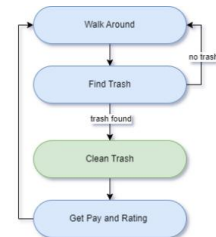


Fig. 13. Cleaner NPC Behavior Flow and In-Game Implementation

E. Testing

The testing phase aimed to ensure that the Sapiring Rasa game functioned properly, was free from critical bugs, and provided a smooth user experience. This phase consisted of alpha testing and beta testing. Alpha testing was carried out by the development team using the Black Box Testing method to evaluate whether each feature responded correctly to user inputs without assessing the internal code [21][22][23]. In addition to testing interface functions, alpha testing was also used to examine FSM-based NPC behavior. The observed aspects included whether customer NPCs could enter the restaurant, move to a seat, order food, eat, provide ratings, and exit according to the designed service flow.

TABLE III. SYSTEM USABILITY SCALE (SUS) QUESTIONS

No	Code	Question
1	P1	I think that I would like to use this system frequently
2	P2	I found the system unnecessarily complex.
3	P3	I thought the system was easy to use.
4	P4	I think that I would need the support of a technical person to be able to use this system.
5	P5	I found the various functions in this system were well-integrated.
6	P6	I thought there was too much inconsistency in this system.
7	P7	I would imagine that most people would learn to use this system very quickly.
8	P8	I found the system very cumbersome to use.
9	P9	I felt very confident using the system.
10	P10	I needed to learn a lot of things before I could get going with this system.

After the main features and NPC behavior had been functionally validated, beta testing was conducted to evaluate usability using the System Usability Scale (SUS) [24][25]. A total of 30 purposively selected respondents participated in the beta testing. The

respondents were selected based on their familiarity with digital games, computer use, or interactive applications. Participants were asked to play the game, interact with the restaurant environment, observe the NPC behavior, and answer ten SUS questionnaire statements. These statements consist of positively and negatively worded items used to assess perceived usability [26]. The statements are listed in Table III.

After completing the SUS questionnaire, participants also rated the game using a 5-point Likert scale to evaluate aspects such as interface comfort, ease of interaction, and gameplay flow. This provided additional insight into user satisfaction. Data were then processed using the SUS scoring method, where unanswered questions were assigned a neutral score of 3. Scores for positive (odd-numbered) items were calculated as (response – 1), while negative (even-numbered) items used (5 – response); the total was multiplied by 2.5 to yield a final SUS score ranging from 0 to 100. This process was applied to each respondent individually before calculating the average score [26]-[29]. The formula used is illustrated in Formula 1.

$$\bar{x} = \frac{\sum x}{n} \quad (1)$$

Description :

$\bar{x}$: Average score

$\sum x$: Total SUS score

n : Number of respondents

The final SUS score represents the overall usability of the game, where scores above 70 are considered good and acceptable, while those below 60 indicate the need for improvement [25][31]. Beta Testing was conducted on 30 participants aged 18–30 years with backgrounds in design, IT, or game development, chosen for their familiarity with games and computer use. The SUS results ranged from 45.0 to 100.0, with an average score of 73.5, placing *Sapiring Rasa* in the “Good” and “Acceptable” categories. However, the low minimum score indicates that some users faced issues, particularly related to functionality or interface comfort, highlighting areas for further refinement in future development.. Details of the questionnaire scores can be seen in table IV.

F. Distribution

The game *Sapiring Rasa* was distributed digitally through the Itch.io platform in a compressed .rar format. This package includes the executable file and all required assets, allowing users to easily download, extract, and play the game on desktop devices without needing installation. This method ensures simple and accessible gameplay for users.

TABLE IV. SUS TEST SCORES

R	Score Calculation Results										T o t a l	S U S S c o r e	
	P 1	P 2	P 3	P 4	P5	P6	P7	P 8	P 9	P 1 0			
1	4	2	4	4	4	4	3	3	3	4	4	35	87.5
2	4	4	4	4	4	4	4	4	4	4	4	40	100.0
3	4	4	4	2	4	4	3	3	4	4	4	36	90.0
4	2	3	3	3	2	2	4	2	3	3	3	27	67.5
5	4	2	4	3	3	2	3	3	3	2	2	29	72.5
6	4	0	4	1	4	2	4	4	4	2	2	29	72.5
7	4	3	4	4	4	3	3	3	3	3	3	34	85.0
8	4	0	4	1	4	4	4	4	4	3	3	32	80.0
9	2	1	2	2	3	1	2	2	3	1	1	19	47.5
10	4	3	4	1	4	3	4	3	4	3	3	33	82.5
11	4	4	4	4	4	4	4	4	4	2	2	38	95.0
12	4	2	3	1	3	2	3	2	4	1	1	25	62.5
13	4	0	3	0	4	0	4	0	4	0	0	19	47.5
14	4	2	2	1	4	2	3	4	4	0	0	26	65.0
15	3	1	4	0	3	1	3	1	3	1	1	20	50.0
16	3	4	4	2	4	4	4	4	4	0	0	33	82.5
17	4	4	4	3	4	4	4	4	4	4	4	39	97.5
18	3	2	2	1	4	2	3	2	4	1	1	24	60.0
19	4	1	3	2	2	1	3	0	2	0	0	18	45.0
20	3	4	4	3	4	3	4	4	3	2	2	34	85.0
21	3	3	3	2	3	2	3	3	3	2	2	27	67.5
22	3	2	3	3	3	1	3	3	3	1	1	25	62.5
23	4	0	4	0	4	0	4	0	4	0	0	20	50.0
24	4	2	2	2	3	2	2	2	2	2	2	23	57.5
25	4	4	4	3	4	2	4	4	4	2	2	35	87.5
26	2	3	2	1	2	2	3	2	2	1	1	20	50.0
27	3	3	3	3	3	3	3	3	3	3	3	30	75.0
28	4	4	4	4	3	4	3	4	4	4	4	38	95.0
29	3	4	4	3	4	3	4	4	4	3	3	36	90.0
30	4	4	4	3	4	3	4	4	4	4	4	38	95.0
Average SUS Score												73.5	

III. CONCLUSION

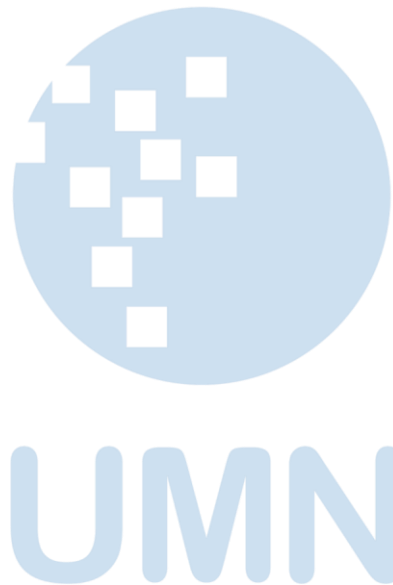
This study led to the development of Sapiring Rasa, a 3D restaurant simulation game designed to promote traditional Sundanese restaurants, developed using the MDLC method and Unity3D. The game implemented key features such as restaurant management, ordering systems, food menu information, customer interaction, and NPC behavior controlled using FSM-based AI. The FSM implementation enabled customer NPCs to follow a structured service flow, including entering the restaurant, being seated, ordering food, eating, rating the experience, and leaving.

Usability testing with 30 participants produced an average SUS score of 73.5, placing the game in the Good and Acceptable range. This result indicates that the game is generally usable and has potential as a digital medium for promoting Sundanese culinary culture. However, the variation in user scores shows that some participants still experienced difficulties. These shortcomings may be related to limited user guidance, interface comfort, interaction consistency, and limited variation in NPC behavior. Future improvements should focus on providing clearer instructions, refining UI/UX consistency, expanding NPC behavior variation, and comparing FSM with other NPC behavior architectures such as Behavior Trees. Further development may also include broader platform compatibility and more diverse user testing to strengthen the evaluation results and improve the game's effectiveness as a cultural promotion medium.

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CNN-Transformer Fusion for Indonesian Traditional Cake Recognition: An EfficientNet-ViT Approach with Grad-CAM Explainability

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Abstract— Visual recognition of Indonesian traditional confectionery is an underexplored problem in deep learning research, partly due to high inter-class visual ambiguity and the scarcity of well-curated local food benchmarks. We address this gap by fusing EfficientNet with a Vision Transformer (ViT) encoder into a unified classification network. The rationale for this pairing is straightforward: EfficientNet's compound-scaled convolutional stack efficiently encodes low and mid-level texture cues, while the ViT's self-attention layers then relate those cues across distant image regions—a capability that convolution alone cannot replicate. Post-hoc explainability is provided through Grad-CAM, which produces class-discriminative spatial maps confirming that activations concentrate on cake surfaces rather than background. We train and evaluate on a publicly available eight-class Kaggle corpus of 1,833 images, applying a two-stage fine-tuning regimen totaling 25 epochs. The resulting system attains 94.37% accuracy, 94.57% precision, 94.37% recall, and 94.31% F1 on the reserved test split. Beyond the metrics, the Grad-CAM evidence suggests the network learns genuinely food-discriminative features, lending credibility to deployment in culinary archiving and nutrition-monitoring applications.

Index Terms— deep learning; EfficientNet; food image classification; Grad-CAM; Vision Transformer

I. INTRODUCTION

The intersection of deep learning and culinary heritage has attracted growing research attention as institutions seek scalable ways to catalogue and preserve regional food cultures. Recognition systems that can automatically identify food items from photographs can support digital menu generation, dietary tracking, and cultural documentation. However, food images are notoriously difficult to classify because the same dish may look strikingly different depending on the lighting, plating convention, and camera perspective, whereas distinct dishes can appear deceptively similar. These difficulties compound when the target domain is

underrepresented in standard benchmarks, a situation faced by Indonesian traditional cakes, which receive far less systematic study than popular international food [1].

Two architectural advances make this problem more tractable. First, EfficientNet demonstrated that scaling a network along depth, width, and resolution axes simultaneously—rather than along any single axis—yields accuracy improvements without proportional parameter growth [2]. Second, the ViT established that treating an image as a sequence of linearly embedded patches and applying multi-head self-attention can model global feature correlations that CNN receptive fields miss [3]. A hybrid that routes feature maps from EfficientNet into a ViT encoder therefore inherits both advantages—local discriminative power and global contextual awareness [2], [4].

Alongside predictive performance, this work integrates Gradient-weighted Class Activation Mapping (GradCAM) to make predictions auditable. Rather than trusting accuracy figures alone, we verify that the model attends to the food object itself—not to incidental background cues—before drawing conclusions about its suitability for real-world use [5], [6].

Three gaps motivate this work specifically: (i) hybrid CNN-Transformer classifiers have rarely been benchmarked on traditional food datasets; (ii) explainability analysis via Grad-CAM in such hybrid settings is nearly absent from the food-recognition literature; and (iii) Indonesian confectionery classification remains a relatively open problem compared with globally popular food benchmarks [7]. The contributions of this paper directly target all three gaps.

II. LITERATURE REVIEW

A. Food Image Recognition with Deep Learning

Convolutional networks have served as the workhouse of food image recognition for over a decade, progressively delivering higher accuracy as architectures matured from shallow networks to VGG, ResNet, and beyond [4]. Prior work has consistently demonstrated that CNN-based models can learn discriminative representations capturing texture gradients, contour patterns, and color distributions which are directly from food imagery without handcrafted feature engineering [8]. However, the majority of these investigations focus on internationally recognized food categories, and localized cuisines such as Indonesian traditional cakes remain underserved. Dataset scarcity continues to constrain the development of robust classifiers for regional food varieties [9].

B. Hybrid Architecture: CNN-Transformer Models

Purely convolutional classifiers excel at encoding local spatial patterns but are bounded by the receptive field of their filters. EfficientNet exemplifies this trend through compound scaling that simultaneously optimizes depth, width, and resolution, surpassing conventional CNNs in accuracy-to-parameter ratio [2]. ViT has equally gained traction by segmenting images into fixed-size patches and applying transformer-style self-attention to capture global semantic relationships across the entire image [3]. Studies integrating CNN local feature extraction with transformer global context modelling consistently report performance improvements over either paradigm individually [10]. However, systematic evaluation of such hybrid models on traditional food datasets remains sparse.

C. Explainable AI with Grad-CAM

As model complexity increases, interpretability has become an essential counterpart to raw predictive performance. Grad-CAM addresses this need by computing class-specific gradient signals flowing into the final convolutional feature maps and aggregating them into a spatial activation map that highlights discriminative image regions [11]. This visualization allows researchers to verify that a model focuses on semantically relevant areas rather than spurious background patterns, supporting more rigorous validation of classification behavior [5]. Applications of Grad-CAM within hybrid CNN-Transformer pipelines targeting food image recognition, however, remain limited in the existing literature.

III. METHOD

A. System overview

The study implements a Hybrid EfficientNet-ViT model for Indonesian cake image classification. EfficientNet extracts local visual representations while

ViT captures long-range inter-feature dependencies, together enabling robust recognition across visually diverse food categories. Fig.1 schematizes the end-to-end pipeline proceeds from raw image input through preprocessing and augmentation, EfficientNet-based feature extraction, ViT-based global relational modelling, softmax-based classification, and Grad-CAM visualization.

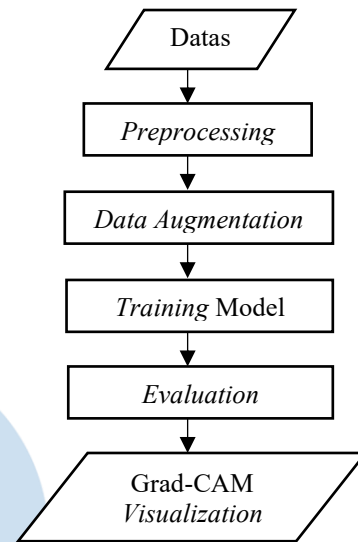


Fig. 1. Research design pipeline of the proposed model.

B. Dataset

The dataset was sourced from the Kaggle platform (<https://www.kaggle.com/datasets/ilhamfp31/kue-indonesia/data>) and serves as the experimental corpus. It consists of approximately 1,846 JPEG images (~303 MB) organized into eight traditional Indonesian cake categories. Each class exhibits natural variation in appearance, color, and lighting, providing conditions suitable for training deep learning classifiers. Table I details the image distribution per category.

TABLE I. CORPUS STATISTICS

Category	Number of Images
Dadar Gulung	±200
Kastengel	±200
Klepon	±200
Lapis	±200
Lumpur	±200
Putri Salju	±200
Risoles	±200
Serabi	±200

Source: Kaggle – Kue Indonesia (2024)



Fig. 2 Representative images from each cake category in the dataset.

C. Data Preprocessing and Augmentation

Every image is resized to 224×224 pixels before entering the network, prior to training to satisfy EfficientNet's input requirements, followed by pixel intensity normalization to promote stable gradient propagation [2], [4]. The spatial mapping from original image $I(x,y)$ to normalized output $I'(x',y')$ is expressed as shown in Eq. (1).

$$I'(x',y') = I(T(x,y)) \quad (1)$$

To expand training diversity and reduce overfitting risk, online augmentation was applied throughout training. The selected transformations synthesize plausible visual variants while preserving each class's defining characteristics, an approach with well-documented benefits for generalization on constrained datasets [12]. Table II summarizes the augmentation configuration.

TABLE II. DATA AUGMENTATION TECHNIQUES

No	Technique	Description
1	Rotation	Angular rotation by a random degree
2	Horizontal Flip	Mirror reflection along the horizontal axis
3	Zoom	Randomized scale enlargement or reduction
4	Width Shift	Lateral translation along the image width
5	Height Shift	Vertical translation along the image height

D. Model Architecture

The proposed architecture unifies EfficientNet with ViT into a single classification backbone. EfficientNet fulfills the role of a convolutional feature extractor that encodes local visual patterns, while ViT subsequently models global inter-token relationships through self-attention [2], [3]. A fully connected softmax classifier projects the resulting embedding to per-class probabilities, with Grad-CAM applied post-hoc to produce interpretable spatial activation maps [11]. Fig. 3 illustrates the complete architecture.

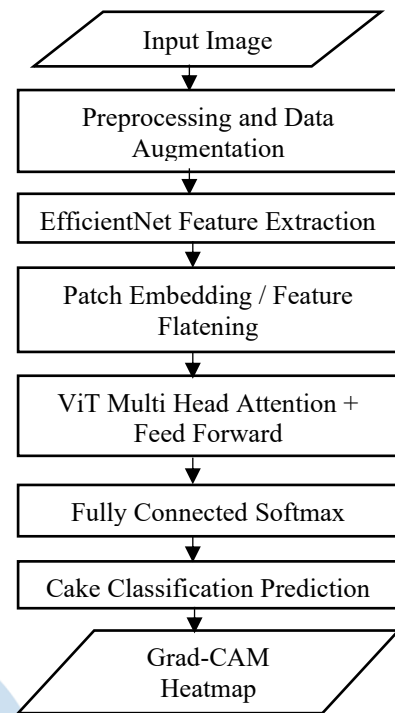


Fig. 3 Architecture of the proposed Hybrid EfficientNet-ViT model

EfficientNet-B0 is deployed as the initial visual encoder. Its compound scaling strategy jointly optimizes network depth, width, and resolution, achieving strong feature capacity at reduced computational cost compared with equivalently accurate conventional CNNs [2]. Hierarchical convolutional processing encodes key visual attributes from each cake image, including surface texture, geometric contour, and dominant color. The convolution operation generating feature map F at spatial position (i,j) is given by Eq. (2).

$$F(i,j) = \sum_m \sum_n I(i+m,j+n) \cdot K(m,n) \quad (2)$$

The output feature vector from EfficientNet-B0 is then fed into the ViT encoder. In this implementation, the ViT component follows the base configuration (ViT-Base) with the following specifications, patch size of 16×16 , embedding dimension of 768, 12 transformer layers, and 12 attention heads. The feature vector is projected into the ViT embedding space before being processed by the transformer encoder. The ViT encoder transforms each feature token into Query (Q), Key (K), and Value (V) projections and computes inter-token affinities through scaled dot-product attention [3] as shown in Eq. (3).

$$\text{Attention}(Q,K,V) = \text{softmax}\left(\frac{QK^T}{\sqrt{d_k}}\right)V \quad (3)$$

Finally, a fully connected layer maps the encoder output to a class score vector. Softmax normalization

converts these scores into a valid probability distribution [13] as shown in Eq. (4).

$$P(y_i) = \frac{e^{z_i}}{\sum_{j=1}^n e^{z_j}} \quad (4)$$

E. Training Protocol

Training proceeded in two sequential phases to maximize the utility of ImageNet pre-training. Phase 1 froze the EfficientNet-B0 backbone and optimized only the classification head for 15 epochs at a learning rate of 0.001, enabling stable initial feature adaptation. Phase 2 then unlocked the final 30 backbone layers and continued training for up to 30 epochs at a reduced learning rate of 0.00001, preserving pre-trained low-level representations while adapting higher-level features to the target domain [2]. This staged approach has demonstrated effectiveness for constrained datasets by exploiting ImageNet priors prior to domain-specific fine-tuning [14]. Table III lists all training hyperparameters.

The Adam optimizer was chosen for its per-parameter adaptive learning rate adjustment, which facilitates convergence in deep network optimization [15]. Categorical cross-entropy was used as the loss function, as defined in Eq. (5) [16].

$$L = - \sum_{i=1}^n y_i \log \hat{y}_i \quad (5)$$

TABLE III. TRAINING CONFIGURATION

Parameter	Value
Architecture	Hybrid EfficientNet-ViT
Input Image Size	224×224 pixels
Phase 1 - Epochs	15
Phase 2 - Epochs	30
Batch Size	32
Phase 1 - Learning Rate	0.001
Phase 2 - Learning Rate	0.00001
Optimizer	Adam
Loss Function	Categorical Cross-Entropy
Output Activation	Softmax
Dataset Split	80% / 10% / 10%

F. Evaluation Protocol

Four complementary metrics were used to evaluate classification performance across all eight categories: accuracy in Eq. (6), precision in Eq. (7), recall Eq. (8), and F1-score in Eq. (9) [17], [18].

$$\text{Accuracy} = \frac{TP + TN}{TP + TN + FP + FN} \quad (6)$$

$$\text{Precision} = \frac{TP}{TP + FP} \quad (7)$$

$$\text{Recall} = \frac{TP}{TP + FN} \quad (8)$$

$$F1 = 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}} \quad (9)$$

G. Grad-CAM Explainability

To provide visual interpretability, Grad-CAM was applied to generate class-discriminative activation maps that localize image regions with the greatest influence on each prediction [11], [19]. Importance weights for each feature map channel are derived via global average pooling of class-specific gradient signals as shown in Eq. (10) and Eq. (11).

$$\alpha_k^c = \frac{1}{Z} \sum_i \sum_j \frac{\partial y^c}{\partial A_{i,j}^k} \quad (10)$$

$$L_{\text{Grad-CAM}}^c = \text{ReLU} \left(\sum_k \alpha_k^c A^k \right) \quad (11)$$

These weights are combined with their corresponding feature activations and passed through ReLU to generate the final heatmap.

IV. RESULT AND DISCUSSION

A. Dataset Partitioning and Training Results

The full dataset was split into training (80%), validation (10%), and test (10%) subsets to ensure evaluation on previously unseen data. Table IV details the resulting partition sizes.

TABLE IV. DATA PARTITIONING

Subset	Proportion	Images
Training	80%	1,514
Validation	10%	159
Test	10%	160

Training terminated at epoch 25 when early stopping was triggered, with the peak validation accuracy of 0.9434 recorded at epoch 9 of the first phase. Fig. 4 plots the accuracy and loss trajectories across both training phases.

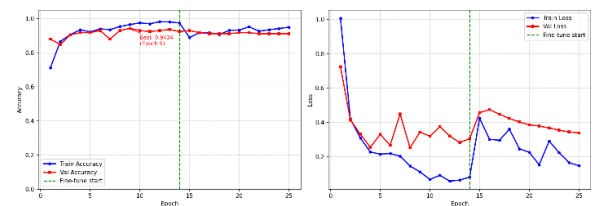


Fig. 4 Accuracy and loss progression across training epochs

B. Preprocessing and Augmentation Results

All images were successfully resized to 224×224 pixels and normalized before training. The applied augmentation operations included rotation, horizontal flipping, zoom, and directional shift. These operations produced diverse training variants without distorting the defining visual identity of each cake class. Fig. 5 shows representative augmented samples.

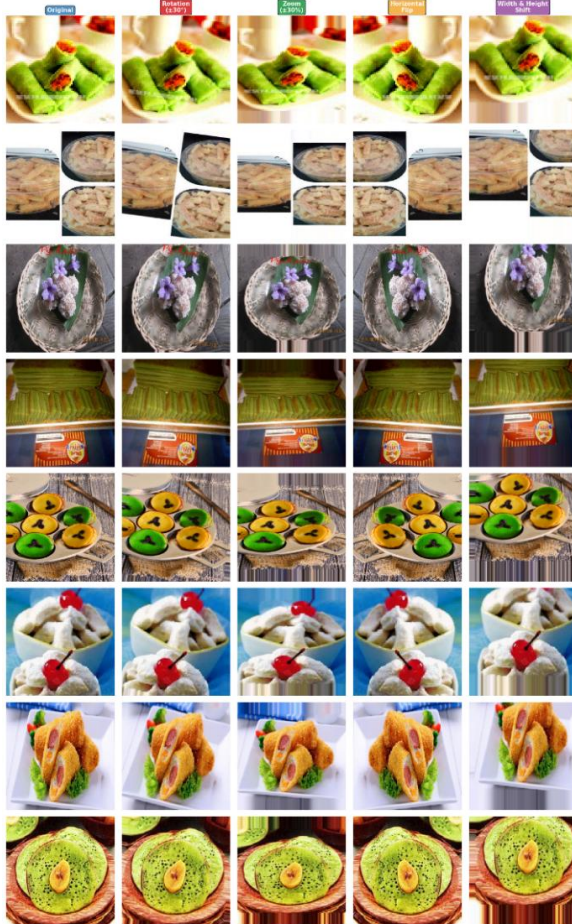


Fig. 5 Examples of augmented training images.

C. Overall Evaluation Results

Evaluation on the 160-image test set yielded an overall accuracy of 94.37%, corresponding to 151 correctly classified images. Table V summarizes all aggregate performance metrics.

TABLE V. AGGREGATE TEST METRICS

Metric	Value
Accuracy	94.37%
Precision	94.57%
Recall	94.37%
F1-score	94.31%

D. Class-Level Breakdown

Per-class results are reported in Table VI. Kastengel, klepon, and lapis achieved perfect recall

(1.0000), indicating complete retrieval of all test samples in those classes. Putri salju and risoles attained perfect precision (1.0000), signifying an absence of false positives. Dadar gulung recorded the lowest recall at 0.8000, likely owing to visual similarity with adjacent categories, including overlapping surface texture and color profile.

TABLE VI. PER-CLASS RESULTS

Class	Prec.	Recall	F1	Supp.
Dadar Gulung	0.9412	0.8000	0.8649	20
Kastengel	0.9565	1.0000	0.9778	22
Klepon	0.9524	1.0000	0.9756	20
Lapis	0.9091	1.0000	0.9524	20
Lumpur	0.9474	0.9000	0.9231	20
Putri Salju	1.0000	0.9444	0.9714	18
Risoles	1.0000	0.9500	0.9744	20
Serabi	0.8636	0.9500	0.9048	20
Wtd. Avg	0.9457	0.9437	0.9431	160

The evaluation results demonstrate that the Hybrid EfficientNet-ViT model effectively classifies Indonesian traditional cake images. Per-class performance is illustrated in Fig. 6, which presents the precision, recall, and F1-score for each class.

As shown in the figure, the Kastengel, Klepon, and Lapis classes achieved perfect recall scores of 1.0000, indicating that all images in these categories were correctly classified. The Putri Salju and Risoles classes also exhibited excellent performance with perfect precision scores of 1.0000. In contrast, the Dadar Gulung class recorded the lowest recall at 0.8000, suggesting some misclassifications with other categories.

The overall prediction distribution is visualized in the confusion matrix presented in Fig. 7. Most classification errors occurred in the Dadar Gulung class, with one image each misclassified as Klepon, Lapis, Lumpur, and Serabi. Additionally, two images from the Lumpur class were misclassified as Kastengel and Lapis. Overall, the dominant diagonal values in the confusion matrix indicate strong classification performance across most traditional cake categories.

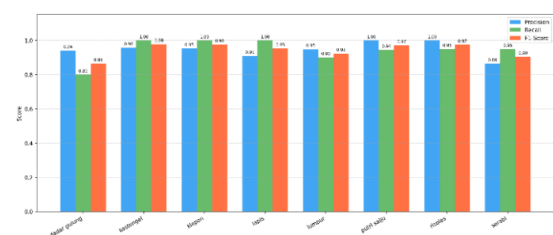


Fig. 6. Per-class precision, recall, and F1-score

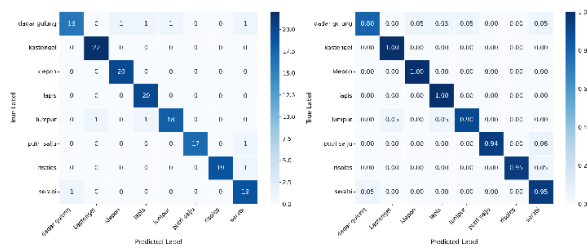


Fig. 7. Confusion matrix of test set predictions

E. Grad-CAM Analysis

Grad-CAM heatmaps were generated for all eight categories to validate the spatial reasoning of the classifier. Fig. 8 presents three-column panels for each class: (i) the original image, (ii) the standalone activation map, and (iii) the overlay. Across all categories, the heatmaps consistently localize attention to the cake object itself rather than surrounding background regions. This spatial alignment between model attention and object location confirms that the network has acquired class-discriminative feature representations and that its predictions are visually grounded.

F. Discussion

The 94.37% test accuracy achieved by the proposed hybrid model is competitive with recent works on fine-grained food classification using single-paradigm architectures on datasets of similar scale. The model also demonstrates the ability to focus on semantically relevant regions, as evidenced by the Grad-CAM visualizations.

Dadar gulung's lower recall (0.80) indicates a need for targeted improvement in future work. The confusion pattern, which is distributed across four different classes, suggests that this category does not exhibit strong visual overlap with any single class but rather lacks a well-defined cluster in the feature space. Future improvements could involve class-specific data augmentation or rebalancing strategies to enhance discrimination for this class.

The Grad-CAM analysis serves as an important validation tool. Correctly classified images generally produce compact activation maps centered on the food object, whereas misclassified samples tend to exhibit more diffuse or background-focused activations. This behavior provides useful insight into model uncertainty and supports the practical value of Grad-CAM beyond its role as an explainability tool.

V. LIMITATIONS

One limitation of this study is the absence of direct experimental comparisons with EfficientNet-only and ViT-only baselines, making it difficult to isolate the contribution of each architectural component. Although additional baseline comparisons are provided in Appendix A, future work will focus on more comprehensive ablation studies under a unified

experimental setup. Another limitation is the use of a single train-validation-test split for evaluation. While commonly practiced, this approach may not fully demonstrate the model's robustness. Future research will therefore incorporate repeated experiments or k-fold cross-validation to better assess the generalizability and stability of the proposed approach.

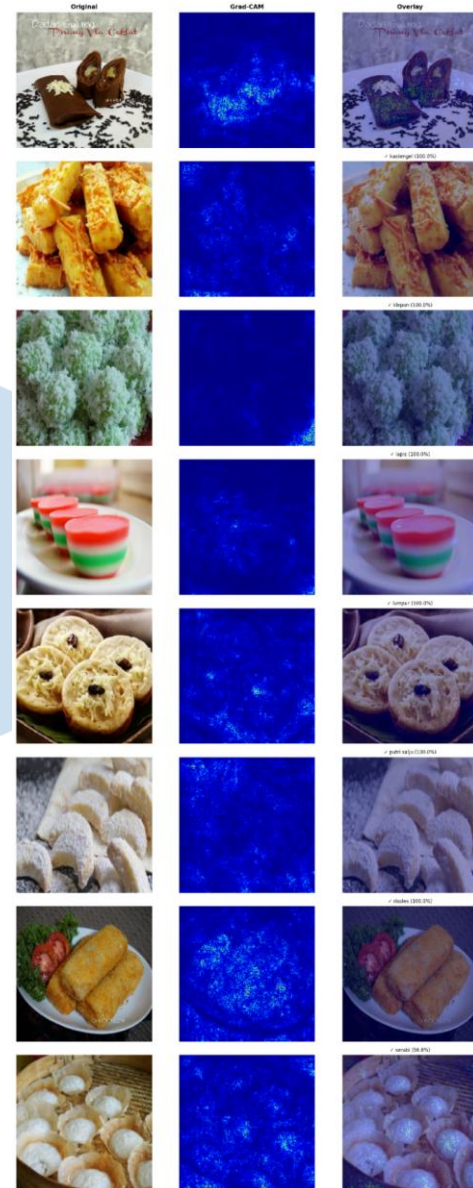


Fig. 8 Grad-CAM activation maps for all eight cake categories.

VI. CONCLUSION

We presented a recognition system for Indonesian traditional cake photography that fuses EfficientNet's convolutional feature extraction with a ViT encoder's global self-attention, trained under a warm-start two-stage schedule and audited through Grad-CAM. Across an eight-class, 1833 image benchmark, the system achieves 94.37% accuracy, 94.57% precision, 94.37% recall, and 94.31% of F1. Grad-CAM heatmaps confirm that high activations cluster on cake

surfaces rather than background content, supporting the trustworthiness of the predictions for downstream applications.

Several directions are open for future investigations. Expanding coverage-both in number of classes and images per class-would test the scalability of the fusion design. Multi-scale attention, guided by the confusion analysis reported here, could specifically improve discrimination among visually ambiguous categories. Finally, knowledge-distillation into a compact mobile-friendly model would enable on-device inference for culinary documentation applications.

APPENDIX A

Additional Baseline Comparison

Additional baseline experiments were conducted to provide a clearer understanding of the proposed hybrid model's performance relative to several well-known architectures. All models were evaluated using the same dataset split and training protocol. The results are presented below as supplementary material.

TABLE A1. PERFORMANCE COMPARISON WITH BASELINE MODELS

Model	Accuracy	Precision	Recall	F1-Score
MobileNet V2	95.62	95.73	95.62	95.59
EfficientNet B0	98.12	98.18	98.12	98.12
ResNet50	96.88	96.99	96.88	96.89
ViT B16	85.62	86.28	85.62	85.65
Hybrid EfficientNet-ViT	95.00	95.23	95.00	95.01

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Enhancing Public Knowledge on Sugar Consumption Limits Through Educational Games with Fuzzy Logic Implementation

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Abstract— The creation of educational games utilising fuzzy logic to increase public awareness of Banten's daily sugar consumption restriction is predicated on the fact that there will be around 536 million instances of diabetes mellitus by 2021. By 2030, it is expected to reach 642 million. With a frequency of 10.6%, or around 19.4 million cases, Indonesia is among the top five countries in the world for the most instances of diabetes mellitus. In Indonesia, the prevalence of Banten is approximately 2.2%. An educational game is used in this study. Based on the results of the first and second pre-test quizzes, fuzzy logic will be employed in the game to calculate the player's additional time. According to the analysis's findings, of the 33 respondents, around 57.57% or 19 had increased their knowledge, whereas roughly 42.42% or 14 did not. Furthermore, the average GUESS-18 user satisfaction score is 77.84%, indicating that users "agree/satisfied" with the game. Based on the findings, it can be concluded that creating educational games with fuzzy logic to increase public awareness of Banten's daily sugar consumption limit can be an alternate method of learning.

Index Terms— Banten Indonesia; Daily Sugar Consumption; Fuzzy Logic; Education Game;

I. INTRODUCTION

Diabetes mellitus (DM), commonly known as diabetes, is a severe chronic disease characterized by the body's inability to regulate blood sugar levels [1]. DM occurs when the pancreas fails to produce sufficient insulin or when the body cannot use insulin effectively. Insulin is a hormone produced by the pancreas that acts as a key to process glucose from the bloodstream into body cells for energy production [2], [3]. The body breaks down all carbohydrates into glucose in the bloodstream, and insulin facilitates glucose uptake into the cells. If left untreated, DM can lead to various health complications, including nerve damage, vision impairment, kidney failure, and organ dysfunction [4].

Type 1 diabetes is marked by the pancreas's inability to produce insulin or producing it in insufficient amounts. This type of diabetes can affect individuals of all ages but is most commonly diagnosed

in children and young adolescents [5]. Patients with type 1 diabetes require insulin injections to regulate blood sugar levels, as the absence of insulin can be fatal. The most common symptoms of type 1 diabetes include excessive thirst, dry mouth, sudden weight loss, frequent urination, fatigue, persistent hunger, and vision problems [6], [7].

According to the International Diabetes Federation (IDF), approximately 90% of diabetes cases are type 2 diabetes. Type 2 diabetes occurs when the body cannot effectively use insulin, a condition known as insulin resistance [8], [9]. When insulin fails to function properly, blood sugar levels rise, prompting the pancreas to produce more insulin. This overproduction can overwork and eventually damage the pancreas, leading to a reduced ability to produce insulin, which in turn results in persistently high blood sugar levels [10].

There are several risk factors that contribute to diabetes. The exact cause of type 1 diabetes remains unknown, whereas type 2 diabetes is influenced by genetic factors, metabolic conditions, family medical history, age, overweight status, unhealthy diet, lack of physical activity, and smoking habits. Additionally, the frequent consumption of foods and beverages high in added sugar increases the risk of developing type 2 diabetes [2], [6].

According to the International Diabetes Federation (IDF), in 2021, the number of diabetes cases worldwide among individuals aged 20-79 years reached 536 million, accounting for 9.8% prevalence (the total number of disease cases occurring at a specific time in a given region) [10], [11]. The IDF also projects that this number will continue to rise, with an estimated 642 million cases or 10.8% prevalence by 2030. In 2021, Indonesia ranked fifth among countries with the highest number of diabetes cases, with 19.4 million people affected, representing a 10.6% prevalence rate. Specifically, the Banten province recorded a prevalence rate of 2.2% [10], [12], [13].

In designing educational game mechanisms, feedback in the form of extra time is generally

determined using crisp logic rules, such as standard *if-else* conditional structures. However, this conventional approach has limitations as it creates rigid boundaries (the cliff effect), where negligible score differences can result in drastically different time allocation decisions. The justification for implementing fuzzy logic in this study is to overcome this rigidity. Fuzzy logic is selected due to its capability to model gradual human reasoning and to handle the uncertainty of player performance in a more adaptive manner [14], [15]. Consequently, the calculation of additional game time based on pre-test quiz 1 and pre-test quiz 2 scores can operate with smoother transitions, higher flexibility, and proportionality relative to each player's baseline understanding.

Based on these issues, this study aims to develop an educational game to enhance public knowledge regarding the daily sugar consumption limit in Tangerang, utilizing fuzzy logic. The objectives of this research are to design and develop an educational game to raise public awareness about daily sugar intake limits in Banten using fuzzy logic and to measure the improvement in public knowledge regarding daily sugar consumption limits in Banten.

The selected learning medium for this study is a game-based educational tool. Educational games can incorporate text, animations, videos, images, and sound, which can effectively enhance interest and engagement in learning. Game-based learning has been proven to increase motivation, interest, and active participation in educational activities, making it an effective method for disseminating health-related information.

II. RELATED WORK

In the study conducted by Puja [16], it was stated that fuzzy logic is used to determine the difficulty level of quizzes based on the player's status. By utilizing fuzzy logic, various difficulty levels can be created, making the assessment not limited to binary correct or incorrect results. In a study conducted by Jonathan [17], [18], it was also stated that fuzzy logic is used to determine the movement speed of opponents, which is influenced by the player's health points and the opponent's health points.

Unlike previous studies that utilized fuzzy logic to determine quiz difficulty levels or to control the movement speed of non-player characters (NPCs), this research applies fuzzy logic to determine the duration of additional time awarded to players based on their pre-test quiz 1 and pre-test quiz 2 scores [19]. Utilizing this fuzzy-based approach provides a significant competitive advantage over conventional game-balancing systems (non-fuzzy baselines), which tend to be rigid, as fuzzy logic can dynamically evaluate a combination of multiple input variables without being constrained by binary true-false decisions [15], [20]. This study specifically employs the Sugeno fuzzy logic

method, as it yields a crisp constant output that can be directly integrated into the game's time computation system to establish a precise amount of bonus time for the player.

III. METHODOLOGY

A. Problem Identification

At this stage, problem identification process will be carried out. This problem identification is obtained from various internet resources. Some of the sources used for problem identification such as, World Health Organization (WHO), the International Diabetes Federation (IDF), journals, websites, and others.

B. Data Collection and Processing

At this stage, the main focus on data collection such as nutrients fact from food and drinks especially sugars. This data collection is obtained from internet sources. Some of the sources that used for searching data such as, National Health Agency, World Health Organization (WHO), Food and Agriculture Organization (FAO), journals, and others. The data that has been collected will then be processed to remove none relevant data for the research. This process is carried by checking the data from 1 source with other different sources.

C. Fuzzy Design

In this research, fuzzy logic is used to determine the additional time that players will receive based on the score from pre test quiz 1 and pre test quiz 2. The type of fuzzy that being used for this study is fuzzy sugeno. The difference between fuzzy sugeno and fuzzy mamdani lies in the output that produced. In fuzzy mamdani, the output is a decision set, whereas in fuzzy sugeno, the output is a crisp constant [9]. The steps for designing the fuzzy system are as follows:

D. Fuzzy Variables and Linguistic Value

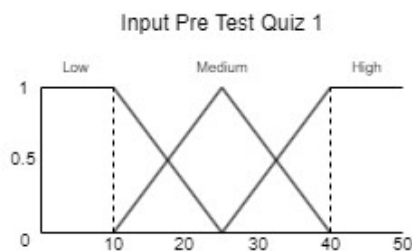
This research will use three fuzzy variables consisting of two input variables and one output variable [21], [22]. The variables for input and output for the fuzzy are as follows:

- Input Variables, pretest quiz 1 score divided into 3 (low, medium, and high).
- Input Variables, pretest quiz 2 score divided into 3 (low, medium, and high).
- Output Variables, total extra time for players divided into 3 (many (represented by the constant value of 10), intermediate (represented by the constant value of 7), and little (represented by the constant value of 5)).

E. Fuzzyfication

Fuzzyfication is done to mapping crisp value into fuzzy set for determine memberships value for each variables. The steps for fuzzyfication are as follows [23], [24]:

Input variables pre test quiz 1 score, low = 0-25, medium = 10-40, high = 25-50. In Figure 1, the graph of the input variable for pre test quiz 1 value range from 0-50. The set of pre test quiz 1 is divided into low has score value range from 0-25, medium has score value range from 10-40, and high has score value range from 25-50.



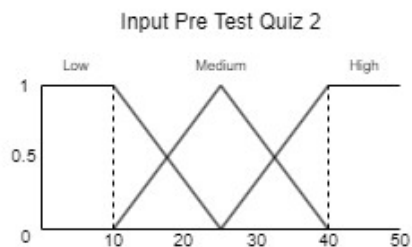
$$\mu_{\text{low}}(x) = \begin{cases} 1 & : x \leq 10 \\ \frac{25-x}{25-10} & : 10 < x < 25 \\ 0 & : x \geq 25 \end{cases}$$

$$\mu_{\text{medium}}(x) = \begin{cases} 0 & : x \leq 10 \\ \frac{x-10}{25-10} & : 10 < x < 25 \\ \frac{40-x}{40-25} & : 25 < x < 40 \\ 0 & : x \geq 40 \end{cases}$$

$$\mu_{\text{high}}(x) = \begin{cases} 0 & : x \leq 25 \\ \frac{x-25}{40-25} & : 25 < x < 40 \\ 1 & : x \geq 40 \end{cases}$$

Fig. 1. Pre Test Quiz 1 Input Graph

Input variables pre test quiz 2 score, low = 0-25, medium = 10-40, high = 25-50. In Figure 2, the graph of the input variable for pre test quiz 1 value range from 0-50. The set of pre test quiz 1 is divided into low has score value range from 0-25, medium has score value range from 10-40, and high has score value range from 25-50.



$$\mu_{\text{low}}(x) = \begin{cases} 1 & : x \leq 10 \\ \frac{25-x}{25-10} & : 10 < x < 25 \\ 0 & : x \geq 25 \end{cases}$$

$$\mu_{\text{medium}}(x) = \begin{cases} 0 & : x \leq 10 \\ \frac{x-10}{25-10} & : 10 < x < 25 \\ \frac{40-x}{40-25} & : 25 < x < 40 \\ 0 & : x \geq 40 \end{cases}$$

$$\mu_{\text{high}}(x) = \begin{cases} 0 & : x \leq 25 \\ \frac{x-25}{40-25} & : 25 < x < 40 \\ 1 & : x \geq 40 \end{cases}$$

Fig. 2. Pre Test Quiz 2 Input Graph

Output variables total extra time for players, many (represented by the constant value of 10), intermediate (represented by the constant value of 7), and little (represented by the constant value of 5).

F. Fuzzy Rules

This rules will be created based from two fuzzy input variables and the result from output variables. The variables for input such as, pre test quiz 1 and pre test quiz 2. The output variable for the fuzzy rules is total extra time for players. Table 1 provides an illustration of the fuzzy rules.

TABLE I. TABLE FUZZY RULES

IF	Pre test quiz 1	And	Pre test quiz 2	Then	Extra times
IF	Low	AND	Low	THEN	Little
IF	Low	AND	Medium	THEN	Little
IF	Low	AND	High	THEN	Intermediate
IF	Medium	AND	Low	THEN	Little
IF	Medium	AND	Medium	THEN	Intermediate
IF	Medium	AND	High	THEN	Many
IF	High	AND	Low	THEN	Intermediate
IF	High	AND	Medium	THEN	Many
IF	High	AND	High	THEN	Many

G. Inference and Defuzzification

In this research, the inference used is the maximal function or MAX. During the defuzzification stage, the weighted average method will be employed, using Equation 1 as follows:

$$\text{Output} = \frac{\sum_{i=1}^n (\text{Membership Function} \times \text{Constant Value}_i)}{\sum_{i=1}^n \text{Membership Function}_i}$$

Equation 1. Equation for Output

H. Game Design

The educational tool developed in this study is a 3D single-player serious game. The core gameplay loop is structured into three sequential phases to measure knowledge acquisition systematically: a pre-test assessment phase, an educational intervention segment, and a post-test evaluation phase. The game environment is bound by invisible walls to maintain a controlled testing environment and ensure players remain focused on the designated tasks. To isolate the learning process, character movement and standard navigation features are temporarily restricted during assessment segments, requiring players to complete

each evaluation phase before progressing further in the game.

I. Player

In this game, which is an offline single-player game, the player will strive to complete all the given missions. These missions consist of two pre-test quizzes, followed by an educational segment, and then the player will complete two post-test quizzes.

J. Objective

The player aims to complete the quizzes by answering all the provided questions. The player must complete the game in stages, starting with the 2 pre-tests, followed by the educational segment, and then completing the post-tests. The player will receive a score for each quiz, except for the educational segment.

K. Game Explanation

- Controls:

Character Movement: The player can control the character using the left joystick to move in the desired direction.

Camera Control: The player can control the character's camera view to look left or right using the right joystick.

- Pause Menu:

Pause button is located at the top left corner, which can be pressed to bring up the pause menu.

The pause menu includes options such as resume (to continue the game), settings (to adjust music, sound, etc.), restart (to restart the game), and quit (to exit the game).

Players can also open doors by approaching them.

L. Quiz Rules

- First Quiz:

Players answer multiple-choice questions, earning 10 points for each correct answer.

- Second Quiz:

Players are presented with different types of food and their nutritional content.

Players must label the food items with options such as "very good," "good," "fair," "poor," and "very poor."

- Timer:

A timer is present during the quizzes. If the timer reaches zero, the game will stop, and the player must restart the game.

M. Boundaries

- Invisible Walls:

There are invisible walls that limit how far players can walk within the game area.

- Quiz Restriction:

Once a quiz starts, the player cannot move the character or access a back button, meaning the player must complete the quiz before proceeding.

IV. RESULT AND DISCUSSION

A. Fuzzy Implementation

The fuzzy logic used in this game will be employed to provide additional time for the players. This additional time will be based on the scores of pre-test quiz 1 and pre-test quiz 2. Time will only decrease when the player is taking a quiz. If the time runs out, the player will lose and have to restart the game from the beginning.

In this game, players will be given a timer of 10 minutes at the start of the game, which will run while the player is taking quizzes. The fuzzy logic system will take two input values, namely the scores of pre-test quiz 1 and pre-test quiz 2, and will produce an output value in the form of additional time based on these input values. Figure 3 illustrates the timer application in the game.

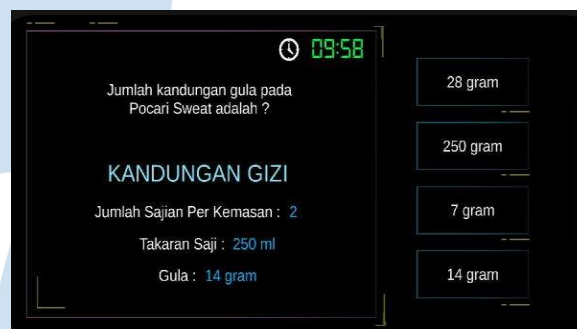


Fig. 3. Timer Application in Game

The next stage, after the player successfully completes pre-test quiz 1 and pre-test quiz 2, the scores from each quiz will be used as input variables to generate an output in the form of additional time for the players using the fuzzy method. Figure 4 shows the additional of time after the player successfully completes the pre-test quizzes.

If the timer reaches zero, the game will automatically stop, and a game over menu will appear. In the game over menu, the player can select the restart button to restart the game from the beginning. The addition of the timer system is expected to make the game more challenging for the players. Figure 5 illustrates the game over menu that appears when the timer reaches zero.



Fig. 4. Additional Time for Player

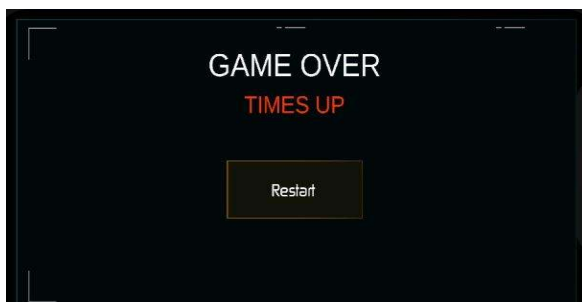


Fig. 5. Game Over Screen

B. Respondent Result

At this stage, testing will be conducted with respondents. The respondent testing process will follow these steps:

1. Respondents will download the game via the provided link.
2. After downloading, respondents will install the game.
3. Respondents will play the game according to the given missions.
4. After playing, respondents will be directed to a Google Form to fill out a survey.
5. The final step is for respondents to complete all the questions in the survey and submit it.

The data to be used will come from individuals aged 5 to 55 years. According to the Regional Health Research Report (Risesdas), based on doctor diagnoses among residents of all ages by characteristics in the Banten province in 2018, the highest number of diabetes diagnose were recorded in the 5 to 55 age group. In this survey stage, 35 respondents were successfully gathered. Out of these 35 respondents, data from 33 respondents will be used, as 2 of the 35 respondents did not meet the data usage criteria. According to Mizanur [25], [26], a suitable sample size for research ranges from 30 to 500. Table 2 below shows the pre-test and post-test scores of the 33 respondents.

Based on the data in Table 2, the following average calculation will be conducted. According to the survey conducted, it was found that 19 out of 33 respondents

showed improvement, while 14 out of 33 respondents showed no improvement. From this data, a calculation will be carried out to determine the percentage of respondents who improved versus those who did not. The percentage of respondents who showed improvement is 57.57%, while the percentage of respondents who showed no improvement is 42.42%.

TABLE II. SCORE OF 33 RESPONDENTS

No	Pre test	Post test	Result
1	70	80	Increase
2	80	90	Increase
3	60	80	Increase
4	10	70	Increase
5	80	90	Increase
6	30	80	Increase
7	100	100	Not Increase
8	90	70	Not Increase
9	60	90	Increase
10	100	90	Not Increase
11	50	50	Not Increase
12	80	90	Increase
13	90	100	Increase
14	100	100	Not Increase
15	50	70	Increase
16	80	90	Increase
17	30	50	Increase
18	80	100	Increase
19	50	90	Increase
20	70	100	Increase
21	70	70	Not Increase
22	60	70	Increase
23	30	90	Increase
24	80	80	Not Increase
25	10	0	Not Increase
26	60	50	Not Increase
27	70	80	Increase
28	60	90	Increase
29	80	90	Increase
30	80	80	Not Increase
31	80	70	Not Increase
32	80	70	Not Increase
33	70	70	Not Increase

Next is the calculation of the average score from GUESS-18 for each subscale from a total of 33 respondents shown at Table 3.

TABLE III. AVERAGE SCORE GUESS-18

Subscale	Average
Usability	76,19%
Narratives	80,95%
Play Engrossment	61,26%
Enjoyment	79,65%
Creative Freedom	72,73%
Audio Aeshetics	84,85%
Visual Aesthetics	84,20%
Personal Gratification	82,90%
Total Average	77,84%

A deeper analysis of the GUESS-18 subscale scores reveals critical implications for the game's design and educational efficacy. The dimensions that received the highest satisfaction scores were Audio Aesthetics (84.85%) and Visual Aesthetics (84.20%), followed

closely by Personal Gratification (82.90%). These high metrics indicate that the 3D environment, interface design, sound effects, and rewarding mechanics were highly successful in creating an appealing and immersive atmosphere for learning. Visually and audibly stimulating elements are vital in serious games, as they directly lower cognitive load and sustain players' initial interest when absorbing complex health data, such as daily sugar intake limits.

Conversely, the Play Engrossment dimension recorded the lowest score at 61.26%, falling into the 'tend to agree/satisfied' category. This lower rating implies that while players found the game visually appealing, their deep absorption or state of 'flow' within the gameplay loop was occasionally disrupted by external factors or the rigid pacing of the mandatory quiz blocks. For future game design iterations, this indicates a clear need to improve narrative integration and introduce more fluid, dynamic interaction mechanics rather than abrupt assessment transitions. Enhancing Play Engrossment is essential to ensure that players remain deeply focused on the educational content for longer durations, thereby maximizing knowledge retention.

V. CONCLUSION

Based on the research conducted, it was concluded that the design and development of an educational game to increase public knowledge about daily sugar consumption limits in Banten using fuzzy logic was successfully designed and built. Through the respondent trials of the successfully designed and developed game, several values such as pre-test, post-test, and GUESS-18 scores were obtained. Based on the calculations from a total of 33 respondents, it was found that 19 respondents, or 57.57%, showed an increase in knowledge scores, while 14 respondents, or 42.42%, did not show an increase in knowledge scores.

This study successfully designed and developed a 3D educational serious game implementing Sugeno fuzzy logic to enhance public knowledge regarding daily sugar consumption limits in Banten. Experimental evaluations yielded definitive quantitative support for the game's efficacy as an alternative learning medium. Specifically, post-test analysis demonstrated a measurable knowledge improvement in 57.57% of the respondents (19 out of 33 participants). Furthermore, evaluation of user experience via the GUESS-18 framework resulted in an overall satisfaction score of 77.84%, confirming that users were highly satisfied with the game's usability, engagement, and aesthetic design. Future work should focus on optimizing narrative elements to further elevate player engrossment and maximize long-term knowledge retention.

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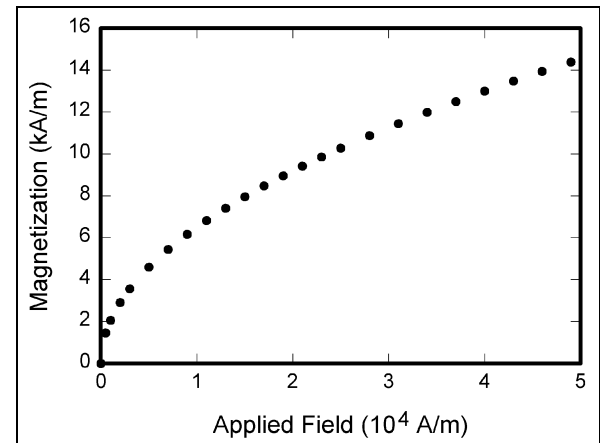


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- [2] J. Clerk Maxwell, *A Treatise on Electricity and Magnetism*, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68-73.
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