Elaborating ethnobotanical knowledge of bael (*Aegle marmelos* (L.) Corrêa) in augmented reality-based learning media with a STEM approach to increase students' naturalist intelligence

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Research

Abstract

Background: Bael (*Aegle marmelos* (L.) Corrêa), a culturally and medicinally significant fruit in Asia, is increasingly unfamiliar to younger generations. This lack of ethnobotanical knowledge threatens its preservation. We propose an educational approach integrating science, technology, environment, and mathematics (STEM) with augmented reality (AR) to address younger generations' lack of ethnobotanical knowledge.

Methods: This research employed a research and development (RnD) design involving ethnographic research and learning media development. Ethnographic research was conducted to assess respondents' ethnobotanical knowledge of bael, including general knowledge and misconceptions. The collected data informed the development of an AR-based learning media with a STEM approach using a 4D framework (defining, designing, developing, and disseminating).

Results: The study revealed a low level of ethnobotanical knowledge among respondents, regardless of prior exposure to bael. A significant misconception was the confusion between bael and calabash. The developed AR-based learning media received positive feedback from validators and students. Large-scale trials demonstrated its effectiveness in significantly improving students' naturalistic intelligence scores.

Conclusions: This research highlights the need to preserve ethnobotanical knowledge and offers an innovative solution through AR-based learning media with a STEM approach. The developed learning media can potentially enhance students' understanding of bael and other local plants, contributing to their naturalistic intelligence and promoting sustainable practices. Future iterations can be expanded to include more in-depth explanations of bael's uses and explore other local plant species.

Keywords: STEM Education; Augmented Reality; Naturalistic Intelligence; Ethnobotanical knowledge; Bael fruit

Background

Bael tree (Aegle marmelos L Corrêa) is an annual tree that exhibits remarkable adaptability, thriving in diverse habitats across the Indian subcontinent to Southeast Asia, including Java, Indonesia. Previous study explain that unique characteristics and high adaptability allow it to withstand drought conditions (Logesh *et al.* 2023). Held sacred in Hindu rituals, the bael tree (Rutaceae family) is widely cultivated in temples. Due to their therapeutic properties, the bael tree's various parts, including leaves, roots, bark, and fruit pulp, have been used for centuries in Ayurvedic medicine. Modern research further supports its potential in treating abdominal ailments, hepatitis, tuberculosis, diarrhea, and dysentery (Agrawal *et al.* 2024; Babu *et al.* 2022). Beyond medicinal uses, the versatile fruit pulp of the Bael tree is widely consumed fresh and finds application in producing beverages, traditional sweets, jams, and puddings

In Indonesia, the Bael tree is primarily valued for its shade, with its fruit generally perceived as bitter, poisonous, and unsuitable for consumption. This perception is compounded by a decline in ethnobotanical knowledge among younger generations due to socio-cultural shifts, globalization, and the modernization of pharmaceuticals (Dapar & Alejandro, 2020). This decline in ethnobotanical knowledge is concerning, as it threatens the cultivation and preservation of traditional medicinal plants, including the Bael fruit (Weckmüller *et al.* 2019). This loss of knowledge erodes cultural identity, sustainable resource use, and biodiversity (Constant & Tshisikhawe, 2018; Spennemann, 2022). Furthermore, the erosion of ethnobotanical knowledge is correlated with a decline in community concern for sustainable environmental and resource utilization (Alves *et al.* 2022; Dapar & Alejandro, 2020), a decrease in biodiversity (Ali, 2021), and the loss of alternative livelihoods for rural communities (Kumar *et al.* 2021; Kusumawati *et al.* 2022; N'Woueni & Gaoue, 2021) In essence, the bael fruit is a valuable plant with immense medicinal and nutritional potential, and its utilization is intertwined with significant cultural importance in various communities.

One effective strategy to enhance public awareness, particularly among younger generations, regarding the sustainability of potential medicinal plants is by integrating ethnobotanical knowledge into the education curriculum. This endeavor is supported by advancements in current technology that provide access to bring studied subjects from the environment into the classroom by using augmented reality (AR) (Chien *et al.* 2019; Zhao *et al.* 2018). Leveraging AR technology holds immense potential in developing ethnobotanical knowledge by facilitating subject visualization, expanding information access, and enabling the exploration of natural resources that are restricted by spatial and temporal constraints (Chien *et al.* 2019). AR technology integration exemplifies one aspect of science, technology, engineering, and mathematics (STEM)-based learning (Palazon & Santacruz-Valencia, 2022). Mounting evidence suggests that integrating AR and STEM approaches effectively promotes meaningful learning experiences, enriches the visualization of intricate topics, and bolsters problem-solving abilities (Suryanto *et al.* 2022). Moreover, this integration cultivates learning motivation, critical thinking abilities, and authentic inquiry activities (Gunalan *et al.* 2023). In ethnobotany, STEM education serves as a cornerstone for comprehending indigenous knowledge and practices through the lens of scientific principles (Nugraheni *et al.* 2023). By infusing STEM principles into the ethnobotanical learning process, students are expected to encourage a more scientifically grounded understanding of medicinal plants within ecological and cultural frameworks.

Integrating ethnobotanical knowledge of bael into an AR-based learning media with a STEM approach is expected to enable students to interact with objects and environments virtually in a more captivating and interactive way. As a result, this can cultivate students' natural intelligence in gaining a more comprehensive understanding of plants' innovative and sustainable utilization, including the bael fruit (Usta & Ültay, 2022; Sdravopoulou *et al.* 2021). Moreover, it is hoped that cultivating a deeper understanding of ethnobotany will nurture students' natural intelligence, culminating in heightened environmental consciousness, biodiversity conservation, and advocacy for inclusive, equitable, and high-quality education. Therefore, this study endeavors to develop and evaluate the efficacy of ethnobotanical learning materials for the bael fruit using a learning-based STEM approach-assisted AR to elevate students' naturalist intelligence.

Materials and Methods

This two-part study combines ethnographic qualitative research with a research and development (R&D) approach to develop AR-based learning media with a STEM approach to increase naturalist intelligence. Fifth-semester biology education students from Majalengka University and Universitas Islam Negeri (UIN) Syekh Nurjati Cirebon (2022/2023) participated.

Random sampling selected student groups from BIO A (Majalengka) for a limited trial and BIO B & C (UIN Syekh Nurjati Cirebon) for a large-scale trial.

Ethnobotanical Study of Bael Fruit

An ethnobotanical study evaluated the community's ethnobotanical knowledge regarding bael fruit consumption and application for particular purposes. Ninety-six respondents from diverse age groups and backgrounds in West Java were selected using random sampling. Ethnobotanical knowledge was assessed using a Guttman and Likert scale self-assessment questionnaire comprising 44 questions categorized into eight criteria. The self-assessment questionnaire was developed based on general perspectives and historical background involving bael fruit in the community (Table 1).

Table 1. Outline of Questions in the Self-Assessment Questionnaire on Community Knowledge of Bael Fruit

Understanding Aspects	**Parameter**	**Descriptor**		
		Purpose	Sum	Scale
General knowledge	Terminology	Explain fruit appearance based on respondents' perceptions	5	Guttman
	Interaction and application	Explaining the use of bael fruit for various purposes carried out by the community today.	8	Guttman
	Perception	The public's view of bael fruit.	4	Essay
	Cultivation and property	Knowledge of the efforts and reasons for bael fruit cultivation.	5	Guttman
Misunderstandings and Confusion	Health	Explaining public misconceptions about bael fruit in the health sector.	14	Likert
	Processed foods and products	Explain the public's misconceptions about bael fruit in food and processed products.	5	Likert
	Commercialization	Explain the public's misconceptions about bael fruit's potential efforts and commercialization.	3	Likert

The gathered data was tabulated and categorized based on the respondents' demographic profiles. Furthermore, descriptive analysis was utilized to evaluate the community's comprehension of bael fruit utilization and misleading information, classifying it into three levels of understanding according to the criteria outlined in Table 2.

Table 2. Criteria for ethnobotanical knowledge of bael fruit in respondents

Score	Criteria
≥ 0.76	high
0.5 ≤ x < 0.75	moderate
< 0.50	low

Statistical data analysis was performed using an independent t-test with a 95% confidence level and a p-value threshold of ≤ 0.050 to determine the significance of differences in understanding between community groups. The findings from the analysis and the insights gained into community perspectives on bael fruit were subsequently employed to guide the development of learning materials.

Development of AR-based Learning Media with a STEM Approach using Ethnobotanical Knowledge of Bael

Developing a learning model prototype for the bael fruit ethnobotany employed a four-stage process based on the Thiagarajan (1974) 4D model: define, design, develop, and disseminate. This research and development (RnD) 4D method was selected due to its straightforward, efficient, and practical nature in creating learning models.

Define Stage

This stage involved describing and developing the problem findings from the ethnographic-ethnobotany study of bael fruit into learning material concepts. The study further integrated four disciplines (STEM approach) into the learning process through structured assignments for students to address misconceptions about bael fruit in society. Specifically, the science aspect was realized in the use of plant morphology and physiology principles; the technology aspect in the use of augmented reality; the engineering aspect in students' ability to design problem-solving procedures; and the math aspect in students' ability to construct arguments supported by data and empirical evidence.

Design Stage

The design of an AR-based learning media with a STEM approach using ethnobotanical knowledge of bael was carefully planned in five stages: 1) selecting project-based learning as the instructional model; 2) developing an AR Plant Physiology content prototype; 3) creating an ethnobotany study implementation design for bael fruit as learning material; 4) integrating the STEM approach-assisted AR into the learning model; and 5) developing assessment instruments. Project-based learning was chosen to facilitate students in conducting experiments using bael plants to address misconceptions held by the public. The research instruments encompassed formative assessment questions to gauge naturalistic intelligence and a student response questionnaire to evaluate the effectiveness of AR-based learning media with a STEM approach using ethnobotanical knowledge of bael. The formative assessment of naturalistic intelligence aimed to measure students' ability to comprehend bael plants' biological aspects, roles, functions, and applications. A total of 40 multiple-choice questions were piloted on 30 fifth-semester Biology Education students in the 2022/2023 academic year at Universitas Majalengka before being used for the assessment. The pilot test results showed that ten questions were eliminated, and 30 questions were declared valid based on Bivariate Pearson (Pearson Product Moment) correlation. The pilot test's item-level significance values (p-value) were ≤ 0.050 at a 95% confidence level. Reliability testing indicated sufficient reliability using Cronbach's Alpha, with an α-value of 0.92, exceeding the recommended threshold of 0.70. Therefore, the questions were deemed reliable for use. All items' stage validity and reliability were tested using SPSS var. 21.

Development Stage

AR-based mobile application learning tools for plant physiology were validated by expert validators from Semarang State University, Indonesia, specializing in educational media, content, learning evaluation, and readability assessment. The validation process used a form with scores ranging from 1 (not appropriate) to 5 (proper), expressed as validator points. The assessment evaluated media aspects like topic relevance, material accuracy, presentation completeness and systematics, basic concepts, alignment with learning demands, and presentation method. Additionally, the design assessment examined general and specific appearance, along with media presentation. Finally, the language aspect was analyzed for adherence to rules, readability, and effective communication. Each media aspect's validation employed a modified Cohen's Kappa calculation (Laínez-Bonilla *et al.* 2020) using Formula 1.

$$\kappa = \frac{P_o - P_e}{1 - P_e} \quad (1)$$

Where the kappa (κ) value indicates the acceptance of validators representing the validity of the instrument; P_o is the relative observed agreement among validators, calculated by averaging the validator values divided by the maximum value; P_e is the hypothetical probability of chance agreement, the squared sum of the validator values divided by the sum of the descriptor values. The interpretation criteria for validation based on the calculation of Cohen's kappa are explained in Table 3.

Table 3. Validation criteria for the design of AR-based learning media with a STEM approach using ethnobotanical knowledge of bael.

κ-value	**Interpretation**	
	Validator's Agreement	**Validity**
0.81 - 1.00	Perfect agreement	Valid and does not need revision
0.61 - 0.80	Substantial agreement	Valid, with < 30% revision (minor)
0.41 - 0.60	Moderate agreement	Valid, with 30% - 50% revision (moderate)
0.21 - 0.40	Slight agreement	Invalid, need ≥ 50% revision (major)
0.01 - 0.20	Poor agreement	Invalid, needs total revision
≤ 0.00	Disagree	Invalid and cannot be used

Source: Laínez-Bonilla *et al.* (2020).

Dissemination Stage

Limited and Extended Field Testing of Learning Models

After assessing the model's validity, a limited field test was conducted involving 23 fifth-semester Biology Education students enrolled in the Plant Physiology practicum course observed by Laboratory assistants independently. The results helped refine the learning model prototype, including its media, materials, and evaluation aspects. This refined model underwent a large-scale field test with five Biology Education (Bio A-E) classes at UIN Syekh Nurjati Cirebon, taking Plant Physiology during the 2022/2023 academic year. The experimental classes were chosen based on similar GPA values from the previous semester ($p > 0.050$) to ensure homogeneity. Finally, two classes (Bio B and Bio D) were randomly selected as the experimental group.

A large-scale field test used a pretest-posttest control group design to evaluate learning effectiveness. Naturalistic intelligence was assessed using a validated and reliable formative assessment instrument. The collected pretest and post-test scores were then analyzed to gauge learning achievement, with improvement in learning outcomes indicated by higher post-test scores

After the session, students completed a feedback questionnaire to assess the effectiveness of learning bael fruit ethnobotany with a STEM approach using augmented reality. A Likert scale measured their learning experience. The results were then analyzed using Formula 2:

$$Respond = \frac{score\ from\ student}{Maximum\ score} \quad (2)$$

After analyzing the data using Formula 2, the results were interpreted based on the criteria outlined in

Table 4. Interpretation of Values and Criteria for Student Responses to the Learning Model

Response score (%)	Criterion
0.81 - 1.00	Excellent
0.71 - 0.80	Good
0.61 - 0.70	Fair
0.41 - 0.60	Poor
0.00 - 0.40	Bad

Data Analysis and Media Effectiveness

The Shapiro-Wilk test was applied to post-test and pretest data to assess normality. A paired t-test was then employed to compare the variances between the two groups. All statistical analyses were performed using SPSS version 23, set at a 95% confidence level and a significance level (p-value) of less than 0.05. The results of these tests were subsequently explained in a narrative format to describe and analyze changes in students' ethnobotanical knowledge

Learning is considered adequate if it meets four criteria: 1) post-test scores are significantly higher than pretest scores, 2) the average post-test score in the experimental class meets the university's passing standard (≥ 75.00 points), 3) the average N-gain score in the experimental class is at least 0.70, and 4) more than 75% of students provide positive feedback ("good" or "excellent").

Results and Discussion

Ethnobotanical study of bael fruit: general knowledge and misconceptions among the community about bael fruit

The analysis of demographic data revealed a fascinating age gap in knowledge of the bael fruit. Over 65% of respondents claimed some general knowledge, with the 19-24 age group leading the way. Interestingly, most of those over 25 also possessed some basic understanding (Table 5). This result suggests that while younger generations may have easier access to information, older generations still hold valuable traditional knowledge about bael fruit.

Based on the general knowledge data, a concerning trend emerges among respondents under 25 (Generation Z) or still in school, who exhibit the lowest levels of bael fruit knowledge compared to older respondents. This pattern highlights a potential intergenerational ethnobotanical knowledge gap, particularly regarding bael fruit identification, potential, and utilization. This finding aligns with previous reports of declining ethnobotanical knowledge among younger generations, attributed to a complex interplay of socio-cultural and environmental factors (Constant & Tshisikhawe, 2018; Dapar & Alejandro, 2020; Hanazaki *et al.* 2013; van 't Klooster *et al.* 2019).

Generational communication gaps further exacerbate the decline in ethnobotanical knowledge transmission. Oral communication remains the primary mode of knowledge transfer in many communities, creating a barrier for younger generations accustomed to digital communication (Agudelo-Hurtado, 2020; Aswani *et al.* 2018). The pervasiveness of modernization, particularly in the healthcare sector, is further eroding the knowledge of medicinal plant utilization. This erosion stems from the emphasis on practicality and speed in modern approaches, leading to a decline in long-term ecological adaptation (Furusawa, 2016). Research also indicates that urbanization, lifestyle shifts, and rampant development are causing a shifting baseline syndrome in green spaces and rural areas, hubs for medicinal plant application. This trend risks eliminating learning resources and exacerbating the transmission gap of ethnobotanical knowledge from older to younger generations (Costa *et al.* 2022).

Table 5. Demographic breakdown of bael fruit knowledge

Demographic	General knowledge of Bael fruit			
	Knowing		Not Knowing	
	N	%	N	%
Gender				
Male	15	15.63	11	11.46
Female	48	50.00	22	22.92
Age				
< 18	6	6.25	10	10.42
19-24	27	28.13	13	13.54
25-30	13	13.54	2	2.08
>31	17	17.71	8	8.33
Jobs				
Junior-Senior School	7	7.29	8	8.33
College Student	27	28.13	14	14.58
Teacher	21	21.88	6	6.25
Lecturer	3	3.13	2	2.08
Civil Servant	1	1.04	-	-
Private worker/ employee	2	2.08	3	3.13
Enterpriser	1	1.04	-	-
Freelancer	1	1.04	-	-
Total	63	65.63	33	34.37

The decline of ethnobotanical knowledge among younger generations is compounded by environmental degradation, which further diminishes the quality of knowledge (Filho *et al.* 2021). This decline in ethnobotanical knowledge has been observed to lead to shifting baseline syndrome, where the low environmental awareness of younger generations contributes to the loss of natural medicinal plant resources (Hanazaki *et al.* 2013). Further findings reveal a significant erosion of medicinal plant preparation skills among younger generations compared to older generations, encompassing plant identification and utilization (Bruschi *et al.* 2019; Navia *et al.* 2022; Weckmüller *et al.* 2019). Furthermore, corroborating the previous studies, our study also found a link between ethnobotanical knowledge of the bael fruit and the ability to describe the fruit accurately. Based on the mapping of respondent responses, over 50% of those who self-identified as knowledgeable about bael fruit provided incorrect descriptions (Table 6).

Table 6. Number of respondents' general knowledge, learning experience/socialization, and ability to describe bael fruit appropriately

Aspect	General knowledge				Able to describe			
	Knowing		Not Knowing		True		False	
	N	%	N	%	N	%	N	%
Active learned*								
Once or more	42	43.75	6	6.25	25	26.04	23	23.96
Never	21	21.88	27	28.13	10	10.42	38	39.58
Able to describe								
True	28	29.17	7	7.29				
False	35	36.46	26	27.08				

Description: *) Respondents have tried to actively learn about bael fruits both through watching mass media and in formal education.

Based on the result, many respondents still made mistakes when explaining the bael fruit's characteristics and benefits despite having prior knowledge or learning experiences. As many as 23 out of 48 respondents who had acquired general knowledge fell into this category. Furthermore, 35 out of 63 total respondents (approximately 36.46%) also struggled with accurate identification and explanation, even with some basic understanding. Unsurprisingly, misinterpretations and inaccurate explanations were even more common among respondents who never got appropriate information about the bael fruit (Table 6).

This study's findings, where some respondents accurately described bael fruit despite lacking formal knowledge, bolster the idea that active learning plays a crucial role in building general knowledge and the ability to provide detailed descriptions. Interestingly, a small percentage (10.42%) of respondents who never received formal information still provided accurate descriptions. This result could be attributed to external factors like local legends surrounding the bael fruit or personal experience with the fruit. Additionally, younger generations often acquire ethnobotanical knowledge through family traditions regarding using plants for daily needs (Costa *et al.* 2022). Active learning emerges as a critical factor in fostering comprehensive ethnobotanical knowledge, particularly regarding the significance and benefits of bael fruit, as highlighted by the data in Table 6. Conversely, passive exposure to information may lead to fragmented knowledge and misconceptions about potential plants like the bael fruit. Therefore, active learning methodologies should be prioritized in ethnobotanical knowledge education to ensure accurate and comprehensive knowledge acquisition.

The study further revealed that most respondents who self-identified as knowledgeable about bael fruit exhibited misconceptions passed down through generations (Table 7). This understanding assessment result highlights the potential impact of passive exposure to misleading information about bael fruit, possibly through cultural narratives, media portrayals, or overheard conversations. The findings also indicate misidentification and misunderstandings of the bael fruit, particularly among those who have never encountered the fruit. Common errors stem from confusion between bael fruit (*Aegle marmelos*) and calabash (*Crescentia cujete* L., commonly known as **berenuk**, Indonesian vernacular name) or **majapahit** fruit, despite their shared therapeutic potential even though they hold similar immense potential in therapeutic and economic applications.

Calabash exhibits promising anti-osteoporosis, antibacterial, antioxidant, and anthelmintic properties, attributed to its rich content of secondary metabolites like phenolic compounds, flavonoids, and saponins (Gonzales *et al.* 2022; Herayati *et al.* 2022). Traditionally, calabash has been employed to treat hypertension, diarrhea, respiratory issues, and even snakebites (Balogun & Sabiu, 2021). Economically, its hard outer shell is used in crafting musical instruments, containers, and bioethanol production (Suhita, 2023). On the other hand, Bael fruit is a popular edible fruit with therapeutic benefits in managing digestive ailments like diarrhea, constipation, and dysentery. The confusion between these plans likely stems from their overlapping traditional medicinal uses, passed-down beliefs, and shared vernacular names. Furthermore, misconceptions about the bael fruit are fueled by folk tales portraying it as a bitter and poisonous fruit.

The prevalent confusion and misconceptions surrounding calabash and bael fruit may contribute to the overall low level of ethnobotanical knowledge among the general population, particularly concerning Bael fruit. Assessment results indicate that the ethnobotanical knowledge of Bael fruit generally falls within the moderate-low category, particularly regarding its interactions and applications (Table 7).

Table 7. respondent's ethnobotanical knowledge covering general knowledge and understanding of bael fruit

Understanding Aspect	Descriptors	Ethnobotanical Knowledge			
		Learned		Not Learned	
		Score	Cat.	Score	Cat
Knowledge of Bael fruit					
Morphology	Explaining the fruit's appearance	0.56 ± 0.09 [a]	Moderate	0.17 ± 0.03 [b]	Low
Interaction and application	Explaining the beneficial use of Bael fruit for various purposes.	0.06 ± 0.10	Low	0.02 ± 0.01	Low
Perception	People's views about bael fruit.	0.11 ± 0.10	Low	0.06 ± 0.01	Low
Culture and properties	Knowledge about the efforts and reasons for cultivating bael fruit.	0.41 ± 0.08 [a]	Low	0.31 ± 0.05 [b]	Low
Necessity and Usefulness			Low		Low
Health	Explaining people's misunderstandings about bael fruit in the health sector.	0.46 ± 0.07	Low	0.40 ±0.05	Low
Food and derivate product	Explaining people's misunderstandings about bael fruit in food and processed products.	0.50 ± 0.07 [a]	Low	0.42 ± 0.05 [b]	Low
Commercial and economic	Explaining public misunderstandings about the potential for business and commercialization of bael fruit.	0.44 ± 0.07 [a]	Low	0.38 ± 0.04 [b]	Low

Note: superscript ([a-b]) showed significant differences based on variant analysis using an independent t-test at a confidence level of 95% and a p-value < 0.050. Cat. = category of ethnobotanical knowledge.

An investigation into the ethnobotanical knowledge of bael fruit revealed a stark contrast between those who have actively studied the fruit and those who have not. Active learning experiences emerged as a crucial factor in comprehensively understanding various aspects of the bael fruit. This is evidenced by the statistically significant differences in average ethnobotanical knowledge scores between the groups across several categories. Respondents who had actively studied bael fruit demonstrated a moderate level of knowledge regarding its origin and appearance (0.56 ± 0.09), while those who had not learned it had significantly lower comprehension (0.17 ± 0.03). Despite this, both groups exhibited overall limitations in their knowledge of certain bael fruit aspects. Both "active learners" and "passive learners" scored low in interaction (understanding and application of bael fruit uses), perception (societal views), and needs and uses. This highlights potential gaps in general knowledge about bael fruit's practical applications and cultural significance.

Intriguingly, data from Table 8 reveals a positive trend in ethnobotanical knowledge scores regarding health and food applications. Here, respondents who had studied bael fruit exhibited a better understanding of misconceptions surrounding its health benefits (0.46 ± 0.07) and its uses in food products (0.50 ± 0.07) compared to those who had not (0.40 ± 0.05 and 0.42 ± 0.05, respectively). While these differences are statistically significant, the overall scores for both groups remain relatively low, indicating the need for improved education to address these misconceptions. Notably, the knowledge gap widens again when considering the commercialization and economic aspects. Respondents who had studied bael fruit demonstrated a basic understanding (0.44 ± 0.07), while those who had not scored 0.38 ± 0.04. This highlights potential under-awareness of the economic prospects of bael fruit cultivation and processing.

In contrast to the bael fruit, which has widespread cultural, medicinal, and economic significance in South Asian nations, most Indonesian communities remain largely unexplored and underutilize the bael fruit for commodity purposes. While the fruit holds deep cultural roots, its perception is primarily anchored in religious and mythological contexts, particularly among Hindu communities. These communities have the bael tree in high reverence, associating it with Lord Shiva (Choudhary *et al.* 2021; Khanal *et al.* 2023). Within Hindu communities, the bael fruit, known as **buah maja** in Indonesia, holds a position of deep reverence. This reverence extends to all parts of the bael tree, including its fruit, leaves, bark, and roots, traditionally used to treat various ailments. Studies have documented the potential therapeutic effects of bael in addressing conditions such as diarrhea, dysentery, diabetes, and skin disorders (Logesh *et al.* 2023; Pathirana *et al.* 2020; Sharma *et al.* 2022b). Beyond its cultural significance, the bael fruit, or bael fruit, is highly valued for its rich nutritional profile. It boasts a wealth of carbohydrates, proteins, vitamins, and minerals, along with a diverse array of phytochemicals, including alkaloids, flavonoids, and phenolic acids (Prajakta & Sahil, 2023; Sawale *et al.* 2019; A. Sharma *et al.* 2020; Venthodika *et al.* 2021). The bael fruit's culinary versatility further enhances its appeal. Its flesh can be transformed into various delectable products, including jams, syrups, puddings, and juices, adding to its economic value (Kumawat *et al.* 2021). Educating the younger generation is vital to increasing interest in bael fruit as a functional food and nutraceutical, driven by a growing awareness of the health benefits of plant-derived compounds.

Development of bael fruit ethnobotany learning

Define Stage

This stage was to develop an AR-based learning media with a STEM approach using ethnobotanical knowledge of bael in Plant Physiology education. Students will interact with a 3D plant model using AR technology, gaining detailed information on its anatomy, uses, and cultural significance. This approach, informed by ethnobotanical data collected from participants, aims to seamlessly integrate the bael fruit's unique ethnobotanical value into the Plant Physiology curriculum (refer to Table 9 for details).

Informed by content identification, problem analysis, and field observations, STEM-based ethnobotany learning multimedia with AR assistance was developed using the project-based learning (PBL) model. This multimedia fosters an interactive, innovative, engaging learning experience that enables independent use. The PBL learning model facilitates students' active and independent exploration of relevant findings related to the topic matter. Additionally, PBL has demonstrated its effectiveness in enhancing students' critical thinking, communication skills, and naturalistic intelligence through its straightforward learning structure. AR technology is transforming ethnobotanical learning by creating immersive experiences that captivate students. 3D models come alive with detailed text, audio, and video explanations, fostering more profound understanding and sparking curiosity (Chien *et al.* 2019; Hidayat *et al.* 2020). This approach goes beyond mere information delivery. By integrating ethnobotanical knowledge, like the medicinal plants used by the Baduy people, AR applications create a contextual learning environment that resonates with students' cultural backgrounds (Zhao *et al.* 2018).

Table 8. Respondents' collective general knowledge and misleading information about Bael fruit in Indonesia

Observed Aspect	General Knowledge of Bael Fruit	
	Knowing	Not Knowing
Active learned		
Fruit characteristic	- The bael fruit, resembling a mango, apple, custard apple, or melon in size and shape, is round with a rough, greenish-yellow rind. The vibrant green exterior gives way to a golden interior with segmented flesh like a starfruit. - 36.46% of respondents in this group described the bael fruit as round the size of a volleyball with a smooth skin texture, shiny green color, white and mushy flesh with an unpleasant aroma leading to a swollen fruit (refer to *C, cujete* L).	- Green in a round shape smaller than a cantaloupe, which is more significant than an orange. The texture is hard, and it has an unpleasant aroma. - Rounded with a diameter of 5-12.5 cm and green in color. The texture of bael's fruit and seeds is like **kawista** or wood apple (*Limonia acidissima* L). - The fruit's flesh is white, turns black if left for too long, and has an unpleasant aroma.
Inherited knowledge or beliefs	- related to the legend/folklore of Nyi Rambut Kasih and the origins of Majalengka Regency. - Use for traditional ceremonies.	- Related to the folklore of the origin of the Majapahit Kingdom (referring to the words "**Maja**" = bael fruit and "pahit" = bitter taste). In Javanese tradition, it is common to name places after prominent or abundant trees or fruits found in the area.
Misleading information	- that the bael's flesh tastes bitter and poisonous	- considers the fruit bitter and poisonous.
Passive learned or never informed		
fruit characteristic	- Most respondents in this group did not know about the bael fruit because they had never encountered it, describing it as a round, green fruit with a reasonably large size and a smooth skin texture that leads to the characteristics of the calabash fruit.	- Like grapefruit, it is round in shape and large in size. However, the skin texture is shiny, and the flesh is white with a distinctive pungent aroma, characteristic of the calabash.
inherited knowledge or beliefs	- The origin of the Majapahit legend	- most respondents answered that they did not know; the story of the bael fruit symbolizes the greatness and victory of Majapahit after destroying Kediri
Misleading information	- Most respondents assumed that the **maja** fruit is calabash only. They also believed that the fruit flesh tasted bitter and poisonous	- The majority of respondents do not recognize the bael fruit and assume that the **maja** fruit is calabash only, fruit. They also believed that the fruit flesh tasted bitter and poisonous

Table 9. Proposed definition and integration of ethnobotanical values of bael fruit in higher education learning concepts.

Concepts in learning	**Purpose**	**The relevance of the findings of the ethnographic-ethnobotanical study of bael fruit on the learning process in the material of the plant-related topic courses**
Contributions to Biology	- Improving understanding of potential plant diversity in the environment. - Opening insights into the morphological structure and physiology of bael plants.	- This research involves an in-depth study of plant adaptation to the environment. A case study on bael plants growing in Majalengka district. - Learning Material: The basics of plant life, morphological structure, and environmental adaptation. - STEM Integration: Exploration of bael plants by investigating distribution, habitat conditions, plant morphological characteristics, and general diversity.
Relevance in Local Agriculture:	- Introducing the function of bael fruit as an alternative food source - Introducing the potential of cultivation as an alternative source of livelihood. - Introducing the potential of bael fruit cultivation for industrial purposes.	- Bael is a local agricultural commodity. Learning about bael planting, caring for, and harvesting techniques provides an understanding of agricultural practices and the economic role of these plants at the local level. - Learning Material: Discusses important bael farming, care, and harvesting techniques to provide an understanding of local agriculture and economics - STEM integration: The research focus may center on the bael plant agricultural innovation, yield improvement, or sustainable management strategies.
Nutritional and Health Value	- Exploring the medicinal potential of bael plants in various countries. - Explaining the nutritional content of bael fruit in traditional medicine in Indonesia.	- An analysis of the nutritional content and health benefits of bael fruit provides an understanding of the positive contribution of this plant to a healthy diet and health. - Learning Material: Understanding bael fruit's nutritional value and health benefits is relevant for promoting a healthy diet. - Research: exploring the content and potential sources of bael nutrients
Environmental Perspective:	- Explaining the relationship between ethnobotanical knowledge and ecological sustainability - Explain the role of bael fruit in environmental sustainability. - Improving understanding of sustainable use of natural resources.	- The study of bael plants opens up insights into the role of ecology and sustainability, teaching students the importance of natural resources and ecosystem conservation. - Learning Material: Investigating the ecological role of bael plants helps students understand conservation's environmental impact and importance. - Research: Research can relate to sustainable agricultural practices, natural resource management, or the environmental impact of bael farming.
Local Cultural Aspects:	- Explain the use of bael fruit in cultural and religious rituals. - Explain the relationship between ethnobotanical knowledge and the preservation of culture and tradition in Indonesia. - Exploring the benefits of bael fruit based on community mobilization in utilizing bael fruit.	- Bael has cultural and traditional values, especially in Majalengka. Understanding how locals use bael provides a deeper understanding of cultural diversity and local values. The study can also explore the role of bael in traditional ceremonies, festivals, and local mythology to preserve cultural heritage. - Learning Materials: Exploring bael's cultural values and role in local communities can improve students' understanding of cultural diversity. - Research: Research can focus on the preservation of cultural heritage related to bael and how these plants are integrated into people's daily lives

Extensive research validates AR as a powerful and effective tool for ethnobotanical education. Studies confirm its validity, practicality, and ability to significantly improve learning outcomes (Abdullah *et al.* 2022; Kariadinata *et al.* 2023). The strength of AR is its ability to create focused, yet rich learning experiences grounded in real-world contexts. For example, AR apps can bring host plants into the classroom, enriching outdoor learning experiences and fostering a connection with nature (Julkarnain *et al.* 2021). By harnessing the potential of AR and integrating ethnobotanical knowledge, educators can create innovative STEAM-based learning tools. These tools promote scientific literacy and play a crucial role in preserving and promoting cultural heritage captivating and engagingly (Khastini *et al.* 2019; Lo & Lai, 2019; Rochmadi *et al.* 2023).

Design Stage

The development of AR-infused ethnobotany learning for Plant Physiology follows a structured two-step design process. The preparation phase lays the groundwork by defining specific learning objectives, selecting a teaching model aligned with those goals, and establishing effective teaching strategies. Subsequently, the development phase brings the plan to life, with activities like crafting engaging STEM-based AR learning activities for plant identification and constructing AR-powered multimedia learning materials in various formats like .exe, printable, and Android versions. These multimedia resources incorporate a wealth of information, including plant identification guides, relevant images and animations, video clips from popular media for real-world connections, references, developer profiles, and interactive quizzes with automated scoring. This meticulous design process ensures the creation of high-quality AR-based learning tools that effectively integrate ethnobotanical knowledge into the Plant Physiology curriculum.

Develop Stage

The learning media developed in this study was integrated into the Plant Physiology course using a Project-Based Learning (PBL) model. Validator assessment of the media indicated its suitability and validity for educational purposes. Validation was assessed using Cohen's kappa, which measures the level of agreement among validators regarding the media's quality. The results demonstrated that all media attributes fell within the valid category, with an average kappa value exceeding 0.70, indicating substantial and perfect agreement (Table 10).

Table 10. Validity Results from the Expert Team

Attribute	ND	AS	TS	Cohan's Kappa			Cat. Agreement
				Po	Pe	κ	
Media Accuracy							
Material Relevancy	5	4.00	48	0.80	0.17	0.76	Substantial
Task and assessment in learning media	2	4.25	17	0.85	0.52	0.69	Substantial
Accuracy	6	4.25	51	0.85	0.17	0.82	Perfect
Completeness and systematics	9	3.93	59	0.80	0.12	0.77	Substantial
Suitability of presentation	5	4.10	41	0.82	0.20	0.77	Substantial
Material presentation method	5	3.80	15	0.76	0.32	0.64	Substantial
Average		4.06		0.81	0.25	0.74	
Appropriate Design							
General display	6	4.17	25	0.84	0.17	0.81	Perfect
Specific feature display	3	4.00	37	0.80	0.04	0.79	Substantial
Picture, video, and animation	4	4.00	16	0.80	0.25	0.73	Substantial
Average		4.06		0.81	0.15	0.78	
Language and Readability							
Readability	10	3.90	39	0.78	0.10	0.75	Substantial
Conformity to language rules	4	4.25	24	0.80	0.28	0.72	Substantial
Communicativeness	4	4.00	16	0.80	0.25	0.73	Substantial
Average		4.05		0.79	0.21	0.74	
Total Average Cohan's Kappa						0.75	Substantial

Note: ND. = total number of descriptors per validation attribute; AS = average score; TS = total score; P_o = relative observed agreement among validators; P_e = hypothetical probability of chance agreement; and κ = Cohan's kappa or validation score; Cat = category of Cohan's kappa. The media stated that it was valid if the κ score is above 0.41 and the minimum expected by Cohan's kappa category is moderate.

Based on Cohen's Kappa values, the validators agreed on the validity of the AR-based media, with a total average kappa value of 0.75, indicating a substantial or valid category with revisions of less than 30% (minor revision). Furthermore, the AR-based learning media with a STEM approach appears promising in supporting ethnobotany learning, with Cohen's Kappa scores exceeding the benchmark for the moderate category. This suggests a high agreement among validators regarding the media's effectiveness in achieving its learning objectives. According to the media learning accuracy attributes, which assess how well the AR media presents ethnobotanical information accurately and scientifically, the average value reached 0.74, indicating substantial agreement. Additionally, the validators agreed that the developed learning media accurately presents the learning material, with a value of 0.82, falling within the perfect category.

The design suitability attribute, which evaluates the completeness and organization of the AR media content, had an average kappa value of 0.78, indicating a substantial category. This encompasses how well the media covers the intended ethnobotanical aspects (completeness) and how logically the information is presented (systematics). The Cohen Kappa score in this category also falls under substantial, demonstrating strong consensus among validators regarding the media's completeness and systematic approach. Specifically, validators also assigned an average kappa value of 0.81, falling within the perfect category for the overall media presentation, indicating high media acceptability.

The language and readability attribute, which assesses how the AR media communicates ethnobotanical information, had an average value of 0.74 and fell under the substantial category. This indicates the use of clear and straightforward language, ensuring that the material presentation is well-received by users. Based on validator feedback, refinements and optimizations were made to the AR-based learning media with a STEM approach, rendering it suitable for small-scale and large-scale pilot testing (Figure 1). Despite some limitations, the overall findings suggest that this approach holds promise as a valuable resource for ethnobotany education.

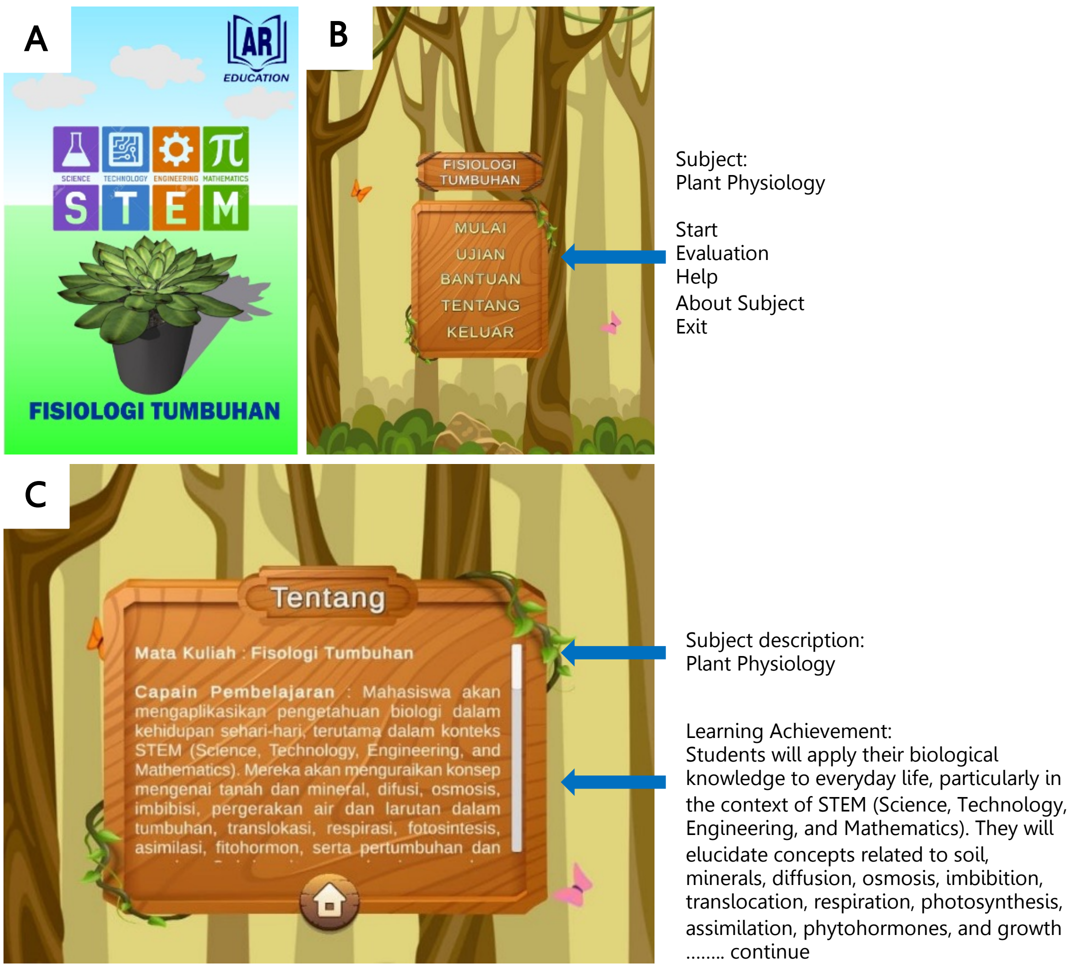
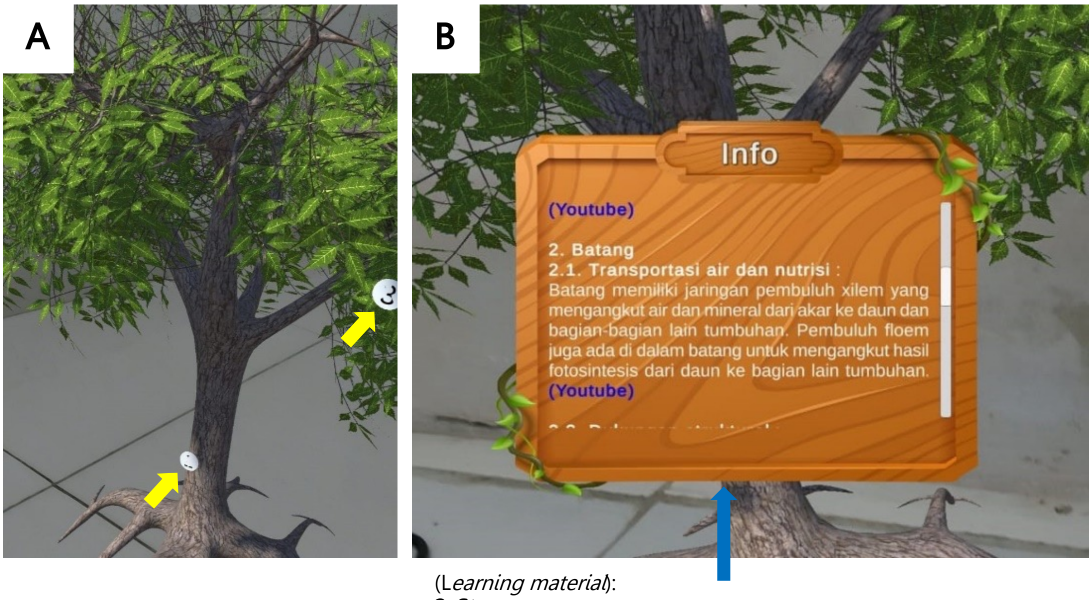


Figure 1. Presents the validated AR multimedia prototype utilized for small-scale and large-scale pilot testing. It displays the main page (A), the main menu featuring shortcut features (B), and the description of learning objectives for the Plant Physiology course.

This innovative AR-based learning media with a STEM approach using ethnobotanical knowledge of bael overlays interactive 3D plant models onto static diagrams, making complex plant structures easier for students to visualize and understand during lectures. The AR app is user-friendly, allowing students to rotate, zoom in/out, and even dissect the 3D models to examine different plant parts in detail. This creates a more realistic and engaging learning experience compared to traditional methods. Students must point their device's camera at a specific area of the plant diagram (or an actual plant) to see labels with relevant information appear in the AR view. These labels can include the names of the plant parts, their functions, and other essential details (Figure 2).

The improvements made after the validator assessment were then used to prototype AR-assisted STEM approach-based learning media for small and large-scale testing with students. In this development research, both small and large-scale evaluations yielded high positive responses, indicating its acceptability and suitability for educational purposes (Table 10). However, further refinements are still needed to create a more relevant learning medium that effectively addresses student learning needs.

Further analysis of student feedback collected from both small and large-scale test classes revealed a firm agreement on the appropriateness of the AR-based learning media with a STEM approach using ethnobotanical knowledge of bael in interactive learning environments. Across both class sizes, the agreement value exceeded 0.78 points, signifying a high consensus among students regarding using AR learning media. Several aspects even garnered student responses with P_o values exceeding 0.80, indicating significant interest (over 80%) in using the media, particularly for the categories of images, content, and media relevance (Table 11).



(*Learning material*):
2. Stem
2.1. Transport of water and nutrients:
The stem has xylem vessels that transport water and minerals from the roots and leaves to other parts of the plant. Phloem vessels are also present in the stem to transport the products of photosynthesis from the leaves to other parts of the plant.

Figure 2. The AR display's explanation feature provides in-depth information about specific plant organs. The image depicts an animated plant with yellow arrows pointing to numbered organs (A) and detailed explanations of those organs (B).

Disseminate Stage

AR-based Learning Media with STEM Approach Ethnobotanical Knowledge of Bael Improves Naturalist Intelligence.

This research employed student naturalistic intelligence data to assess the most pertinent intelligence type in characterizing ethnobotany-related cognition and knowledge. A large-scale classroom trial evaluated Naturalistic intelligence through pretest and post-test scores. The experimental class significantly improved post-test scores, demonstrating the AR-based learning media with a STEM approach using ethnobotanical knowledge of bael effectiveness in fostering student naturalistic intelligence (Figure 3).

Table 11. Large-Scale Student Response to Multimedia *Augmented Reality* Biology Learning

Assessment aspects	Bird.	Total	After	Cat.	On	Bird.	Total	After	Cat.	On
Attractive and attractive layout and color display	4.00	40	0.800	Good	0.001	4.06	134	0.812	Excellent	0.001
The image is clear, contrasting, attractive, and high-resolution.	4.00	40	0.800	Good	0.001	3.91	129	0.782	Good	0.001
The actual image fits the concept	4.20	42	0.840	Excellent	0.002	4.18	138	0.836	Excellent	0.001
Images help clarify the material	3.80	38	0.760	Good	0.001	3.94	130	0.788	Good	0.001
Easy-to-read font types and sizes	4.30	43	0.860	Excellent	0.002	4.09	135	0.818	Excellent	0.001
The material is clear, concise, and according to the needs of students	3.90	39	0.780	Good	0.001	4.18	138	0.836	Excellent	0.001
Guided discovery	4.20	42	0.840	Excellent	0.002	4.06	134	0.812	Excellent	0.001
Instructions for working and answering practice questions are clearly described	3.80	38	0.760	Good	0.001	3.88	128	0.776	Good	0.001
Questions according to the learning material	3.90	39	0.780	Good	0.001	4.00	132	0.800	Good	0.001
STEM AR-based bael fruit learning application makes the learning process easier	3.90	39	0.780	Good	0.001	4.12	136	0.824	Excellent	0.001
Augmented reality applications make it easier for students to learn independently	3.90	39	0.780	Good	0.001	3.73	123	0.745	Good	0.001
Augmented reality learning media makes learning more fun.	4.00	40	0.800	Good	0.001	4.15	137	0.830	Excellent	0.001
The language used is straightforward to understand.	3.90	39	0.780	Good	0.001	3.94	130	0.788	Good	0.001
The language used is communicative and persuasive.	4.10	41	0.820	Excellent	0.001	4.18	138	0.836	Excellent	0.001
The sentences used are simple and direct to the point.	3.90	39	0.780	Good	0.001	3.91	129	0.782	Good	0.001
The sentence used represents the content of the message or information that you want to convey.	3.70	37	0.740	Good	0.001	3.91	129	0.782	Good	0.001
Average	4.00	40	0.800	Good	0.001	4.029	133	0.810	Excellent	0.001
Total Standing		1081			0.037		3590			0.037
κ					0.793					0.798
Interpretation	Substantial agreement with < 30% adjustment					Substantial agreement with < 30% adjustment				

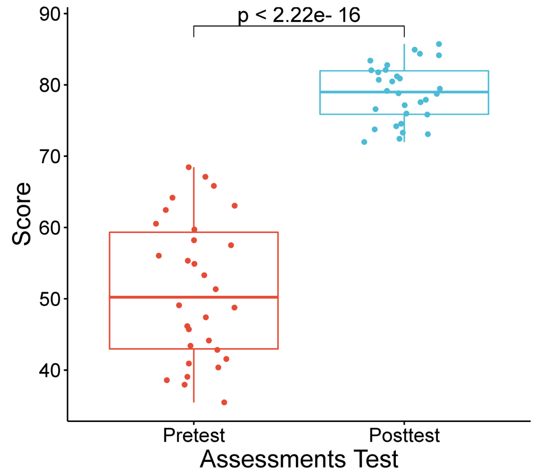


Figure 3. Comparison of pretest and post-test scores of natural intelligences in large-scale tests. The results of the Shapiro-Wilk analysis showed that the two data were normally distributed (p-value *pretest* = 0.310 and p-value *post-test* = 0.274), while the results of the Paired t-test showed that the two groups were significantly different with p-value (2-tailed) = 0.000 (2.22 × 10-16), at a confidence level of 95%.

The average pretest score for the experimental class in the large-scale trial was 50.67 ± 7.22, which significantly increased (p = 0.000) to an average post-test score of 78.93 ± 2.61. This finding indicates that AR-based learning media with a STEM approach to ethnobotanical knowledge of bael can improve naturalistic intelligence. This study's ethnobotanical knowledge, which encompasses plant understanding and utilization based on traditional knowledge and cultural practices, is essential in enhancing cognitive learning and STEM education. Ethnobotanical knowledge, often gained from centuries of observation and interaction with the environment, can be scientifically validated and integrated into STEM-based learning to make it more relevant and engaging for students (Nugraheni *et al.* 2023; Sartika *et al.* 2022b).

Incorporating indigenous knowledge of medicinal plants into the science curriculum serves a dual purpose: preserving cultural heritage and fostering students' analytical thinking and problem-solving skills (Sumarni *et al.* 2022). Integrating ethnobotanical knowledge with science, technology, engineering, and mathematics has enhanced students' critical and creative thinking, participation, and engagement (Sartika *et al.* 2022a; Sudarmin *et al.* 2022). This integration also facilitates students in connecting new scientific concepts to their prior knowledge, thereby improving cognitive learning outcomes (Sudarmin *et al.* 2019). Moreover, project-based learning incorporating ethnobotanical elements can cultivate entrepreneurial skills and cultural appreciation (Nurhasnah *et al.* 2022). The interdisciplinary nature of ethnobotanical knowledge, encompassing ecological, environmental, and phytogeographical aspects, further enriches STEM education by providing a holistic understanding of human-plant-environment interactions (natural cognition aspect) (Godfrey *et al.* 2022). Additionally, several studies have demonstrated that AR-based media can provide rich and specific botanical learning content, deepening students' understanding and active engagement. Furthermore, ethnobotanical knowledge provides traditional ecological knowledge that can be integrated into the developed AR media.

These findings echo previous research that has established the effectiveness of AR technology in enhancing student understanding and higher-order cognitive abilities in botany, particularly in plant observation (Chien *et al.* 2019). ARR also facilitates the documentation and dissemination of indigenous ecological knowledge, thereby contributing to the preservation and transfer of knowledge developed with community involvement (Kariadinata *et al.* 2023). Furthermore, integrating AR into the learning process can enhance the learning experience by capturing and representing traditional ecological knowledge that might be overlooked (Bohlen & Sujarwo, 2020). Moreover, further development of AR interfaces can automate plant species identification in the field, enabling its use as a field guide that provides virtual and verifiable representations (Chien *et al.* 2019). Additionally, other research has demonstrated that integrating ethnobotanical knowledge and habitats with AR can promote biodiversity conservation and facilitate collaborative studies between the scientific community and indigenous peoples (Ingensand *et al.* 2018). Furthermore, developing digital learning media that integrates ethnoscience with AR has proven valid, practical, and effective in enhancing student understanding of complex scientific concepts (Abraão *et al.* 2008). The synergy between ethnobotanical knowledge and AR enriches the educational experience and promotes cultural heritage and biodiversity preservation and appreciation.

Conclusion

The research findings reveal that ethnobotanical knowledge of bael fruit remains relatively low, with a comprehension range of 0.02 (2%) to 0.58 (58%). This underscores the pressing need for effective ethnobotany learning media. The developed AR-assisted STEM-based ethnobotany learning media, designed using the 4D method, was validated with an average score of 0.75, indicating substantial agreement. Notably, 100% of student feedback from small-scale and large-scale trial classes was positive (good to excellent). The application of this media was also found to be effective and significantly ($p = 0.000$) enhance learning outcomes, increasing the average score from 50.67 ± 7.22 (pretest) to 78.93 ± 2.61 (post-test), representing a remarkable 55.78% improvement. Based on these parameters, it can be concluded that the developed media is valid and appropriate for use in ethnobotany learning at the university level. However, certain aspects still require optimization, particularly in providing more detailed explanations of plant physiological and anatomical processes. Additionally, the proportion of explanations in the media features is still heavily focused on lecture materials. Therefore, it is recommended to incorporate content related to the ethnobotany of plants that discusses their utilization, cultural significance, and accessibility. Furthermore, the AR-based learning media with a STEM approach using ethnobotanical knowledge of bael could be enhanced by incorporating interactive and non-repetitive quizzes and games to engage students further.

Declarations

Ethics approval and consent to participate: This study adheres to strict ethical guidelines and does not employ any personal information of a sensitive nature for data analysis or scientific publications. All participants voluntarily and willingly engaged in the research without compulsion and responded to the questionnaire. All respondent information is kept confidential from the tabulation stage to publication to safeguard participant privacy.

Consent for publication: Not applicable

Availability of data and materials: The data underlying this research is not deposited in a public repository but is available upon reasonable request from the corresponding author for academic and learning purposes. We encourage data sharing to facilitate reproducibility and future research.

Competing interests: There is no conflict of interest in this research.

Funding: Not applicable

Author contributions: This research was constructed by cooperating with the authors. Conceptualization, AR, and WH; instrument and methodology, AR, WH., and SR; validation, PP; formal analysis, AR and SR; investigation, AR, SR and WH; resources, AR; data curation, AR; writing—original draft preparation, AR, WH, SR and PP; writing—review and editing, AR, WH, SR and PP; visualization, AR, and PP; supervision, PP, SR, and WH; project administration, AR; funding acquisition, AR All authors have read and agreed to the published version of the manuscript.

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