



Augmented Reality-Based Fungi Encyclopedia: Validity and Practicality as a Biology Learning Media

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Article Info	Abstract
Article history: Received: April 8, 2026 Accepted: June 7, 2026 Published: June 13, 2026	Biology learning on the topic of macrofungi is often hindered by the abstract nature of the concepts and the reliance on static textbook illustrations. This condition is considered insufficient to represent the complexity of the three-dimensional morphology of fungal structures, resulting in low student engagement and limited conceptual understanding. To address this issue, this study aimed to develop FUNGARIA, an Augmented Reality (AR)-based macro fungi encyclopedia, and to evaluate its validity and practicality as a learning aid for promoting environmental literacy. The research employed the ADDIE development model (Analysis, Design, Development, Implementation, and Evaluation). Data were collected through validation by three experts (subject matter, media, and instructional design) using a 15-item four-point Likert scale instrument, as well as a practicality assessment conducted by experienced biology teachers through a 21-item questionnaire. FUNGARIA achieved an overall validity score of 83.33% (Highly Valid), confirming the product's feasibility in terms of mycological concept accuracy, alignment with Learning Outcomes, and the quality of the AR interface. In the practicality assessment, the media obtained a score of 95.44% (Highly Practical) across four evaluation dimensions: operational ease (94.79%), usability (95.42%), visual appearance and readability (95.83%), and educational benefits (95.83%). The novelty of this study lies in integrating the stability of printed guidance materials with immersive AR-based digital visualization to overcome limitations in device availability within schools.
Keywords: Augmented reality Encyclopedia Fungi Validity and practicality	
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INTRODUCTION

Twenty-first-century education requires the mastery of the 6C skills—Critical Thinking, Citizenship, Character, Communication, Collaboration, and Creativity—as essential competencies in the learning process. The development of these skills is closely related to preparing future generations to face global challenges, particularly in the context of environmental education, which is guided by the principle of "think globally, act locally." Environmental education promotes lifelong learning to foster awareness and knowledge as fundamental components of sustainable development. One approach to incorporating environmental education content is by integrating it into classroom instruction through the

development of teaching materials, such as digital handouts, algae-based learning media, and digital student worksheets, which are used in biology education at both the higher education and senior high school levels (Ain et al., 2024; Ayuningtyas et al., 2022; Putra et al., 2021; Trinajah et al., 2024).

Biology education should contextualize theoretical concepts within local ecological realities, such as wetland ecosystems, which are rich in biodiversity but highly vulnerable to environmental degradation. However, this biodiversity wealth has not been accompanied by a comprehensive level of environmental awareness among university students, with only 15.48% categorized as having a high level of awareness and 84.52% falling within the moderate category. Furthermore, studies on senior high school students have shown that wetland-based problem-solving skills integrated with science process skills remain limited, particularly in the areas of communication and inference, which were identified as the lowest-performing competencies compared with other science process skills (Cahayani & Utami, 2025; Utami et al., 2021). These findings suggest that declining environmental awareness among both students and university learners may become more pronounced if it is not supported by comprehensive and well-designed instructional materials.

One of the important biological components of wetland ecosystems is the presence of macrofungi, which play a crucial role as decomposers. The morphological characteristics of fungi are commonly identified based on the color and shape of the fruiting body, as well as the characteristics and color of their spores. The study of macrofungi is included within the topic of biodiversity in biology education. Most macrofungi found in wetland environments belong to the phyla Basidiomycota and Ascomycota, particularly polypore fungi that are commonly associated with decaying wood substrates (Ferliana et al., 2025; Sayuti et al., 2023). Ecologically, fungi play an essential role in nutrient cycling, especially in environments with limited nitrogen and phosphorus availability. In addition, macrofungi contribute to carbon sequestration through their extensive underground networks, making them an important component of environmental conservation and climate change mitigation efforts (Stuart & Plett, 2020).

The study of macrofungi is included in the biodiversity topic of the senior high school curriculum. Although research on wetland macrofungi and environmental education has progressed independently, a significant research gap remains due to the lack of specialized instructional materials that explicitly integrate these two fields. In particular, there is a need for learning resources that combine the morphology of wetland macrofungi with an environmental literacy-oriented pedagogical approach and three-dimensional visualization technology based on Augmented Reality (AR). Previous studies on encyclopedia-based learning media have shown that students prefer materials presented through images and narratives, as these formats facilitate the retention of biological concepts. Furthermore, 81.3% of students reported increased learning motivation when using image-based media supported by comprehensive information (Azhari et al., 2025). The development of encyclopedias that are both valid and practical has also been shown to support various aspects of students' thinking skills, including cognitive abilities (Dewanti & Ilmi, 2022; Kartika & Ibrahim, 2020). In addition, numerous studies have demonstrated that the integration of Augmented Reality can enhance students' thinking skills and promote more engaging learning experiences (Arsyad et al., 2026). These findings provide a strong rationale for incorporating AR into the proposed encyclopedia, particularly because mycology learning materials are still predominantly presented in two-dimensional formats and rarely connect biological objects with the development of environmental literacy, especially in the context of wetland fungal anatomy and morphology.

These limitations have hindered the integration of biological concepts with environmental education frameworks, particularly in the visualization of the anatomy and

morphology of wetland fungi. This pedagogical disconnect represents a critical research gap that remains largely unaddressed in biology education. To bridge this gap, the present study introduces FUNGARIA, an innovative Augmented Reality (AR)-based encyclopedia that integrates field-based visualizations of macrofungi with a structured pedagogical orientation toward environmental literacy and wetland conservation. This strategic combination positions FUNGARIA as a novel educational resource that connects biological knowledge with ecological awareness through immersive learning experiences. Therefore, this study aims to evaluate the validity and practicality of FUNGARIA as an instructional medium for promoting environmental literacy and fostering ecological awareness among biology students.

METHODS

This study employed a Research and Development (R&D) approach using the ADDIE development model, which provides a systematic framework for analyzing learning needs and for the iterative design, development, implementation, and evaluation of instructional materials (Branch, 2009). In the present study, the primary focus was placed on the Development phase as an adaptation of the ADDIE process. This stage involved validating FUNGARIA for its use in biology learning, particularly as a tool for promoting environmental conservation, as well as evaluating teachers' responses to the use of FUNGARIA as prospective end users of the instructional media.

The participants were selected using a purposive sampling technique based on specific criteria to evaluate the validity and practicality of the product. The validation process involved three expert validators representing the fields of media, subject matter, and instructional design to ensure a comprehensive evaluation. The experts were required to hold at least a master's degree (M.Ed. or equivalent) in Biology Education, Science Education, or Educational Technology and to have experience in teaching or conducting research within their respective areas of expertise. The practicality assessment (user response) was conducted on a limited scale and involved ten biology teachers who had 5–15 years of teaching experience, held a bachelor's degree in Biology Education, and were currently teaching or preparing to teach the topic of biodiversity. Data were collected using a structured validation instrument designed to evaluate FUNGARIA, as presented in Table 1.

Table 1 Dimensions and indicators of the FUNGARIA validity instrument

No	Dimension	Indicator
1	Concept Accuracy	Accuracy and correctness of macro fungi concepts in wetland ecosystems. Alignment of the content with the learning objectives. The depth of the material is appropriate to students' characteristics. The content is presented in a logical, coherent, and well-structured manner. FUNGARIA is able to attract students' attention and promote environmental conservation awareness.
2	Product Appearance	Attractive and consistent cover design and layout. Appropriate typography (font type and size) and clear, readable illustrations in FUNGARIA. Clarity of language, terminology, and AR usage instructions. Effective integration between the AR features and the encyclopedia content.
3	Media Quality	Application stability, responsiveness, and ease of AR marker detection. Ease of navigation and user interaction with AR objects and buttons. AR visualization helps clarify abstract concepts.

Then, the practicality of FUNGARIA was evaluated based on user responses. This evaluation aimed to identify potential improvements for the development of FUNGARIA when used by its intended users, namely biology teachers. The practicality instrument used in this study is presented in Table 2.

Table 2 Dimensions and indicators of the user practicality instrument

No	Dimension	Indicator
1	AR Usability	The usage instructions (in the handbook/application) are clear and easy to understand. The AR application is easy to install on a smartphone. The markers in the handbook are easily recognized and scanned by the camera. The AR content (3D objects/animations) appears smoothly, without lag or errors, and is visually engaging. The text displayed on the AR screen is clear and easy to read. The buttons or navigation features within the AR application (if available) are easy to use.
2	Product Appearance	The language and terminology used in both the handbook and AR application are easy to understand. The sequence of the learning materials presented in the handbook and AR application is logical and easy to follow. The presentation of information is clear. The combination of the encyclopedia and AR features helps users understand the concepts. The amount of information presented is appropriate and not excessive. The integration of the written content and the AR display is harmonious and mutually supportive. The language and terminology used in both the handbook and AR application are easy to understand.

The data analysis technique used to determine the expert validation results was based on calculating the mean score obtained from each expert evaluator.

$$\text{Expert Validation} = \frac{Tse}{Tsh} \times 100 \quad \dots (1)$$

Notes:

Va = Expert validation score

TSe = Total empirical score (validation score obtained from the expert validators)

TSh = Maximum expected total score

After the expert validation process was completed, the scores provided by the experts were aggregated and analyzed using the following formula.

$$\text{Mean validation score} = \frac{\text{Total final score assigned by the validators}}{\text{Number of validators}} \quad \dots (2)$$

The mean validation score was interpreted based on the expert validation criteria presented in Table 3.

Table 3 Expert validation criteria

Percentage Score	Category
$85.00\% \leq \bar{x} \leq 100.00\%$	Highly Valid
$70.00\% \leq \bar{x} < 85.00\%$	Valid
$50.00\% \leq \bar{x} < 70.00\%$	Less Valid
$00.00\% < \bar{x} < 50.00\%$	Invalid

Next, the practicality of FUNGARIA was interpreted based on the user response data. The questionnaire used in this study had a Cronbach's Alpha coefficient of 0.90, indicating that the instrument was highly reliable. The user response questionnaire, which was completed by biology teachers, was analyzed by calculating the mean score and comparing it with the assessment criteria presented in Table 4.

Table 4 User practicality assessment criteria

Percentage Score	Category
$85,00\% \leq K \leq 100\%$	Excellent
$70,00\% \leq K < 85,00\%$	Good
$50,00\% \leq K < 70,00\%$	Poor
$00,00\% \leq K < 50,00\%$	Very Poor

RESULTS AND DISCUSSION

FUNGARIA Expert Validation Results

The development of FUNGARIA to promote environmental literacy is intended to support biology learning in schools. Therefore, this study describes the validity and practicality of FUNGARIA as an instructional medium. The validity assessment was conducted not only to ensure the scientific accuracy of the content but also to evaluate its visual design and user interface, thereby ensuring that the product can effectively support the learning process. A summary of the validation results is presented in Table 5.

Table 5 Summary of expert validation results by the validators

No	Indicator	Validator 1	Validator 2	Validator 3
1	Accuracy and correctness of the content presented.	4	3	3
2	The relevance and depth of the macro fungi content.	4	3	4
3	Alignment of the content with the Learning Outcomes/Learning Objectives (LOs) of biology education.	4	3	4
4	Suitability of the content to the cognitive development level of the learners.	4	3	4
5	The cover design and layout of the handbook are attractive and consistent.	4	3	3
6	The typography (font type and size) and illustrations in the handbook are clear and easy to read.	4	4	3
7	The user interface (UI) design of the AR application is intuitive and easy to understand.	4	3	4
8	The quality of the digital assets (3D objects, animations) and audio is clear and of good quality.	3	3	4

No	Indicator	Validator 1	Validator 2	Validator 3
9	The language, terminology, and usage instructions (in both the handbook and AR application) are clear and easy to understand.	3	3	3
10	The content is presented in a logical, coherent, and well-structured sequence.	3	3	3
11	The integration between the handbook and the AR content is synergistic and mutually complementary.	3	3	4
12	The use of AR visualization helps clarify abstract concepts.	3	3	3
13	The media, as a whole, is able to attract students' attention and enhance learning motivation.	3	3	3
14	The application is stable, responsive, and capable of detecting AR markers easily.	3	3	4
15	Navigation and user interaction with the AR objects and buttons are easy and intuitive.	3	3	3
Total		52	46	52
Percentage (%)		86.67	76.67	86.67
Category		Highly Valid	Valid	Highly Valid

Based on Table 5, two of the three validators (Validator 1 and Validator 3) assigned a score of 86.67% (Highly Valid), while Validator 2 assigned a score of 76.67% (Valid). The overall mean score was approximately 83.33%, indicating that FUNGARIA falls within the highly valid category. These findings suggest that FUNGARIA is suitable for use as a supporting medium in biology learning. Although some variation in perspectives was observed among the validators, this highlights the importance of triangulation and consensus discussions among experts to strengthen and refine the overall evaluation of FUNGARIA.

The validity assessment is an essential step in identifying the weaknesses and limitations of the developed product. Based on the validation results, FUNGARIA is considered suitable to proceed to the implementation stage. However, several targeted improvements are still necessary to further enhance the quality of the product. In subsequent stages, FUNGARIA should progressively incorporate more complex details, greater interspecific variation, and more comprehensive ecological information while continuing to promote and strengthen environmental literacy.

Various studies have reported that instructional media achieving the highly valid category can proceed to subsequent stages of development and implementation, particularly in collaborative biology learning environments. Moreover, validity assessment represents the initial stage in ensuring the sustainability of a developed product, as it provides an expert-based evaluation of the quality and appropriateness of the instructional instrument (Almubarak et al., 2021; Riyana et al., 2022; Utami et al., 2023).

The validators stated that FUNGARIA is suitable for use as a learning medium to support concept mastery in the topic of biodiversity. Based on the validation results from the expert validators, the developed instructional media is aligned with the learning objectives and fulfills the requirements for conceptual accuracy. Nevertheless, the expert validators provided several comments and suggestions for improvement. These recommendations were incorporated through a revision process to further enhance the quality of the product. The revisions included correcting typographical errors, improving the clarity of images, and adding relevant concepts and supporting information.

According to the design validators, the cover design, layout, color scheme, and navigation features of FUNGARIA have met the criteria for usability and aesthetics, making it suitable for use as a learning medium to promote environmental literacy. Although the overall design adheres to established design principles and facilitates user interaction, several improvements are recommended, including enhancing the color contrast of interface elements and optimizing the display of images and fonts across different devices.

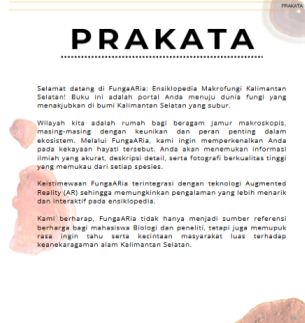
Various studies on instructional media development have reported highly favorable validation results. For example, the development of a website for the Cryptogamae course achieved a mean language aspect score of 3.45, which falls within the highly valid category, indicating that both the content and the design met the required standards. The use of a website-based platform was also found to support independent and contextual learning (Ain et al., 2024). Similarly, the development of image-based media for learning microscopic algae was evaluated as valid, and a trial involving five university students yielded an excellent readability score of 92.2%. These findings suggest that the media is suitable for supporting practical activities in laboratory courses (Amintarti et al., 2019). Both studies demonstrate that the developed instructional media achieved a highly valid level of validation, confirming their appropriateness and quality for educational use.

In general, the validators provided positive responses. This is reflected in the validator's statement such as *"this book is very good and suitable for use in learning because it presents wetland fungi concepts with attractive visualization and is packaged through 3D technology, so that learning feels more contextual, enjoyable, and meaningful."* This appreciation shows a new learning experience that will support Biology learning. Based on the presentation structure, the validators suggested that the discussion flow should start from the general introduction of fungi, followed by classification and species diversity, before focusing in detail on wetland fungi groups as the main focus so that it is in line with a gradual and systematic hierarchical learning structure. This will become input in the development of FUNGARIA. This is also in line with multimedia validation which can support problem-based learning to determine how multimedia validity can train students' critical thinking skills (Agustina et al., 2020).

Based on the supporting components, two validators highlighted the need for improvements in the glossary format, stating that *"the glossary should be organized and presented in bullet-point form to make it easier for readers to distinguish between terms and their explanations."* This feedback emphasizes the importance of readability as a supporting element without reducing user comfort in utilizing the encyclopedia as a whole, especially for users who do not yet have prior knowledge.

In the AR technical aspect, two revision notes were obtained from the trial process. First, the validator reported an issue during AR marker scanning, stating that *"the camera has difficulty focusing to capture the QR code, which slightly disrupts the user experience."* Second, the quality of the 3D object visualization was expected to be improved so that *"the 3D aspects in the AR appear clearer and more complete"* (V5). These two technical inputs became the basis for revisions in AR marker optimization and improvements in 3D object rendering quality in the next development iteration. These suggestions contribute to the enhancement of FUNGARIA, as presented in Table 6.

Table 6. Suggestions and Follow-up Actions for FUNGARIA

Component	Condition Before Revision	Validator Suggestions	Follow-up Actions	Supporting Image
Cover Design	Title is not prominent; background is not contrasting	Improve the title and background so it is more visible	Update typography, strengthen color contrast, and adjust the cover design	
Writing System	Using the term “Kata Pengantar”	Change the term “Kata Pengantar” to “Prakata” according to scientific book conventions	The term was revised to “Prakata” to match encyclopedia writing standards	
Content	There is no additional information rubric about fungi	Add various fungal facts as supplementary information	Add Fungi Facts, ecological roles, and unique biological characteristics of wetland fungi	
Description	Scientific description is not detailed enough to distinguish between species	Add detailed morphological field notes in nature to clearly show species differences	Add field morphology notes including color, texture, fruiting body size, and growth substrate as comparative descriptions between species	

The revision of the FUNGARIA product encompasses several interrelated components, namely visual design, linguistic refinement, content enrichment, enhancement of augmented reality (AR) features, and strengthening of scientific descriptions. Collectively, these improvements are intended to enhance the quality of the encyclopedia in terms of aesthetic presentation, scientific validity, and technological functionality. The development of FUNGARIA is consistent with the theoretical framework proposed by [Mayer \(2009\)](#).

which posits that human information processing is limited, particularly in relation to the use of instructional media to reduce extraneous cognitive load.

Intuitive navigation, clear typographic layout, and precise visual representations of biological objects are key features of FUNGARIA. Visual representation in biology learning is closely related to interpretive elements that represent contextual components presented in the form of photographs, tables, charts, and diagrams to prevent misconceptions (Sultoni & Suwandi, 2023; Utami, Kaspul, et al., 2021). In addition, this form of content presentation also bridges abstract concepts in anatomy and morphology that cannot be observed without the use of supporting tools.

The presentation of materials in FUNGARIA is designed to stimulate curiosity and foster conservation literacy by connecting abstract ecological concepts with the surrounding environmental context. This enables teachers to facilitate biology learning that is not only focused on knowledge transfer but also on the development of environmental awareness, particularly regarding wetland ecosystems.

Practicality Results of Using FUNGARIA

The practicality of the augmented reality-based fungal encyclopedia was evaluated by 10 biology teachers with 5–15 years of teaching experience as media users. This selection aimed to include teachers with practical experience in lesson planning and classroom management. The 15-year experience threshold was used to ensure that the teachers were capable of adapting to technology, particularly the use of augmented reality. Moreover, teaching experience influences teacher readiness (Bi Hady, 2018). The summary of the indicators and the results of the practicality assessment are presented in Figure 2.



Figure 2 Mean results of user practicality evaluation

The analysis results show that the overall average practicality percentage is 95.43%, which falls within the “Excellent” practicality category (range 81–100%). This achievement indicates that FUNGARIA meets the practicality standards as a learning

support tool used by teachers in classroom instruction. The practicality testing of the FUNGARIA product involved biology teachers as the primary respondents in its use.

Based on Figure 2, it is shown that various aspects, such as operational ease, obtained an average score of 94.79%. This aspect includes the clarity of usage instructions, ease of application installation, the ability of markers to be scanned by the camera, smooth AR content performance, and ease of application navigation. The highest score within this aspect was achieved by the indicator of marker detectability by the camera, at 97.92%. The use of AR enhances narrative memory and improves reading comprehension. One study also reported that children demonstrate increased engagement when interacting with AR books (Billingshurst et al., 2014).

Various findings from the user practicality evaluation highlight several important points, such as the need for additional annotation labels within AR objects to support teachers in providing further explanations. The ease-of-use aspect includes assessments of content flow, clarity of language, clarity of information, and the integration of the encyclopedia with AR in supporting conceptual understanding. The combination of the pocketbook and AR visualization in enhancing concept comprehension obtained the highest score in this aspect, namely 97.92%. This finding is consistent with studies reporting that AR-based instructional materials can achieve practicality levels above 90% (Arsyad et al., 2025; Sahronih et al., 2025). These results indicate that AR usage is considered practical; however, it must be adapted to the characteristics of students who will use it, so that it can be effectively implemented in biology learning contexts.

Overall, FUNGARIA is considered engaging and has strong potential to support biology learning. This is reflected in the positive responses from participants, who stated that the visual design is attractive and the content presentation approaches the standards of a popular scientific book. The practicality assessment also revealed several implementation challenges that require further attention in the continued development of FUNGARIA. Positive responses are influenced by attractive visual presentation, which facilitates students' conceptual understanding (Magdalena et al., 2021; Ridarwati, 2024).

The challenges frequently reported by teachers include limited access to devices and digital infrastructure in schools. Several respondents noted that not all students possess adequate smartphones to access AR features. Moreover, in some boarding school settings, the use of mobile phones is officially prohibited within the school environment; as a result, access to AR features can only be facilitated through school-owned laptops. This condition indicates that reliance on student-owned personal devices may create unequal accessibility gaps across different school contexts (Buditjahjanto & Irfansyah, 2023; Hidayat et al., 2024).

In addition to device-related issues, limited internet connectivity also hinders the smooth use of AR features in classroom settings. Respondents stated that the scanning and exploration of AR objects require considerable additional time, thereby reducing the efficiency of instructional time. This issue is further reinforced by the allocation of time in the SMA X curriculum, where science education is divided into three separate subjects: Biology, Physics, and Chemistry. As a result, the time allocated for a single biology lesson is considered insufficient to fully optimize all features of FUNGARIA. An interactive and enjoyable learning experience is expected to contribute positively to the quality of education (Hidayat et al., 2024).

Respondents expressed appreciation for the usability of the printed version of FUNGARIA. They stated that *"the printed version is more practical for QR code scanning, especially for students who only have one smartphone."* indicating that the printed format remains relevant as the primary medium. In addition, respondents suggested providing a pictorial AR usage guide, offering non-digital content alternatives such as static 3D images

or short videos for schools with limited internet access, and adding student worksheets to each section of the encyclopedia so that teachers can assess student learning outcomes in a more structured manner.

Suggestions for further development also emerged during the practicality testing. Respondents proposed that FUNGARIA be developed into an interactive application platform, such as incorporating quiz features, so that it is not only available in printed form but also in a digital e-book format that is more adaptable to students' learning habits. These inputs emphasize that the development of FUNGARIA should consider multiple platforms, device accessibility, and strengthened interactive components in order to make the product practical, flexible, and applicable across various biology learning contexts in schools. Therefore, future research should be directed toward two main focuses: (1) conducting classroom-scale effectiveness testing to measure the direct impact of FUNGARIA on students' learning outcomes; and (2) expanding the scope of macrofungal species inventory to complete the encyclopedia database and increase species documentation.

CONCLUSION

This study contributes to the development of FUNGARIA, a macrofungi encyclopedia based on Augmented Reality (AR), which has demonstrated strong conceptual and operational robustness, with a very high level of validity (83.33%) and excellent practicality (95.44%). The main contribution of this development lies in addressing the challenge of representing fungal biodiversity, which has traditionally been abstract, by transforming it into interactive and mycologically accurate visualizations. Theoretically, this study strengthens instructional design approaches that integrate local biodiversity potential with immersive technology. Practically, FUNGARIA offers tangible implications as an inclusive and ready-to-use teaching aid for educators. The combination of printed media and AR enables more contextualized content delivery while also bridging the digital infrastructure gap across different school environments.

Although this instrument has been proven to be practical, this study is limited because the evaluation only reached expert validation and teacher practicality testing stages, as well as constraints in the inventory of macrofungal taxa derived from specific field samples. Therefore, future research should focus on conducting classroom-scale effectiveness testing to measure the direct impact of this media on improving student learning outcomes and biodiversity literacy. In addition, further development is strongly recommended to expand the taxonomic database of documented macro fungi to provide a more comprehensive representation of wetland ecosystems. The existence of FUNGARIA can also be utilized in implementing Education for Sustainable Development (ESD).

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS STATEMENT

Conceptualization: APP, NHU, ZSN and MA; methodology: NHU and MA; data collection: APP, NHU, and MA; formal analysis: NHU and MA; original drafting: NHU and APP; reference collection: APP, ZSN and MA.

AI DISCLOSURE STATEMENT

The authors used Grammarly during the preparation of this work to check and correct the grammar used in this article. After using the tool/service, the authors thoroughly reviewed and edited the content as needed and take full responsibility for the publication's content. The authors declare that this technology was used responsibly as a collaborative assistant,

and the core research, data analysis, and conclusions were prepared and written entirely by the human authors.

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