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## DEVELOPMENT AND EFFECTIVENESS OF TPACK-BASED TEACHING TOOLS FOR FUNGAL BIOECOLOGY LEARNING

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### ABSTRACT

Fungal biology is often perceived as a challenging topic because many of its concepts are abstract, microscopic, and difficult to relate to ecological processes and real-world environmental issues. This study aimed to develop and evaluate TPACK-based teaching tools integrated with fungal bioecology to support students' higher-order learning outcomes. The teaching tools were developed using the 4-D model, consisting of define, design, develop, and disseminate stages. The evaluation employed a quasi-experimental design involving 90 Grade XI students from three secondary schools in Ambon, Indonesia. Students' learning outcomes were assessed in terms of critical thinking, creative thinking, conceptual understanding, and environmental literacy. Data were analyzed using appropriate inferential statistical procedures to examine differences between students learning through TPACK-based and conventional teaching tools. The findings indicated significant differences in the selected learning outcomes between the two instructional conditions, demonstrating the potential contribution of the TPACK-based teaching tools to fungal biology learning. The integration of technological representations, pedagogical activities, fungal biology content, and bioecological contexts provided students with opportunities to visualize abstract concepts, investigate ecological relationships, analyze biological phenomena, and engage in problem solving. These findings suggest that TPACK-based instructional design can provide a meaningful framework for connecting fungal biology concepts with ecological and environmental contexts. The study contributes an integrated TPACK fungal bioecology 4-D framework that extends the application of TPACK beyond technology-supported visualization by emphasizing the alignment of technology, pedagogy, content, and ecological context. Further research involving larger and more diverse samples and more rigorous experimental designs is recommended to establish the generalizability and causal effects of the developed teaching tools.

**Keywords:** TPACK, Teaching Tools, Fungal Bioecology, Biology Learning.

## 1 INTRODUCTION

21st-century biology education requires students to develop not only disciplinary knowledge but also critical thinking, creativity, collaboration, communication, digital literacy, scientific literacy, and environmental literacy (Thornhill-Miller et al., 2023). These competencies require learning environments in which students actively interpret information, investigate phenomena, construct explanations, and apply biological knowledge to authentic contexts. In this context, teachers need to integrate content, pedagogy, and technology rather than treating technology merely as an additional instructional tool. The Technological pedagogical content knowledge (TPACK) framework provides a theoretical basis for this integration by emphasizing the relationship among technological knowledge, pedagogical knowledge, and content knowledge in designing meaningful learning experiences (Thyssen et al., 2023). Accordingly, the development of teaching tools should consider not only what students need to learn but also how the content can be represented pedagogically and technologically in ways that support meaningful learning.

Fungal biology represents a particularly challenging area of biology education because many of its essential concepts are microscopic, structurally complex, and difficult to observe directly. Structures such as hyphae, mycelium, spores, sporangia, and asci are difficult for students to visualize without appropriate representations (Lee et al., 2022). Consequently, students may memorize scientific terms without developing an adequate conceptual understanding of fungal structures and functions (Bani Melhem & Bani Khalaf, 2026). The problem is compounded by limitations in laboratory facilities and instructional media, including the limited availability of specimens, microscopes, three-dimensional models, and digital simulations (Shambare & Jita, 2025). In addition, fungal classification is conceptually demanding because students must distinguish groups based on morphological, reproductive, and other biological characteristics that are not always directly observable (Hyde et al., 2024). These conditions can make fungal biology learning predominantly theoretical and reduce opportunities for students to connect fungal concepts with phenomena in their everyday environment.

The constructivist perspective suggests that these difficulties should be addressed through learning experiences that enable students to actively construct knowledge from meaningful observations, problems, and contexts. Thus, technological media can serve an important representational function by making invisible or microscopic biological structures more observable. Interactive videos, three-dimensional animations, augmented reality, digital microscope slides, and other visualization technologies have been proposed to support students in understanding biological structures that are difficult to observe directly (Mnguni, 2014; Hansen & Richland, 2020). Similarly, mind maps, conceptual representations, and simplified determination keys can help students organize complex classification concepts (Liu & Lee, 2013). Contextual learning through cases related to food, medicine, biotechnology, disease, and environmental processes can further help students recognize the relevance of fungi beyond their common association with food spoilage or disease (Hendriyani et al., 2025). These approaches indicate that the challenge of fungal biology is not simply a lack of information but a need to provide appropriate representations, pedagogical experiences, and contexts through which students can construct and apply biological knowledge.

Pedagogical approaches such as problem-based learning also provide opportunities to move fungal biology beyond memorization toward higher-order thinking. Through investigations of fungal diversity and their roles in the school environment, for example, students can classify organisms while simultaneously analyzing their benefits, risks, ecological functions, and potential applications. Such activities can encourage students to identify problems, evaluate evidence, compare explanations, and propose solutions, thereby supporting critical and creative thinking (Orozco & Yangco, 2016; Yanto et al., 2026). Previous studies have reported that problem-based learning can improve critical thinking and conceptual understanding (Leasa et al., 2023; Rengkuan et al., 2026), while interactive digital media can facilitate the visualization of microscopic biological structures (Zhang, Li, et al., 2025). These findings suggest that combining appropriate pedagogy with technological representations may provide a stronger response to the conceptual and practical challenges of fungal biology learning than relying on conventional textual materials alone.

In addition to its potential for conceptual learning, fungal bioecology provides an important contextual dimension for biology education. Fungi play essential roles as decomposers in ecosystems and are associated with food production, medicine, biotechnology, human health, and environmental processes (Corbu et al., 2023). Connecting fungal concepts with these ecological and real-world functions can help students understand that fungi are not merely organisms to be classified but components of interconnected biological systems. Fungal bioecology can therefore provide authentic contexts for students to investigate ecosystem processes, evaluate the benefits and risks of fungi, and develop environmental awareness. Previous work has suggested that integrating fungal bioecology into biology learning can promote environmental literacy, ecological awareness, creativity, and understanding of the role of fungi in maintaining ecosystem balance (Green et al., 2019). This contextual dimension is particularly relevant to 21st-century education because environmental literacy requires students to connect scientific knowledge with environmental problems and responsible action.

The integration of TPACK and fungal bioecology is theoretically relevant because each component addresses a different but interconnected dimension of the learning problem. Fungal bioecology provides meaningful content and context, while TPACK provides a framework for selecting and integrating appropriate pedagogical approaches and technologies to represent and investigate that content. Through TPACK, technologies such as videos, simulations, interactive applications, and digital visualizations can be selected according to the characteristics of fungal concepts rather than being used merely for technological purposes. At the same time, pedagogical strategies such as inquiry, investigation, contextual problem solving, and collaborative learning can transform these technologies into learning experiences that require students to analyze and apply biological knowledge. Thus, the integration is expected to make abstract fungal structures more accessible, simplify complex classification concepts, increase contextual relevance, and provide opportunities for higher-order thinking. Previous studies have emphasized that TPACK can support meaningful learning through the integration of technology, pedagogy, and content, while its effectiveness is influenced by contextual factors such as teacher readiness, technological resources, and students' prior experiences (Nguyen et al., 2024).

The 4-D development model provides a complementary methodological framework for translating this theoretical integration into usable teaching tools. Rather than treating TPACK as a general conceptual framework, the 4-D model enables the identified learning needs to be systematically translated into instructional products through the stages of define, design, develop, and disseminate. In the Define stage, the abstraction of fungal concepts, media limitations, classification difficulties, curriculum demands, and students' 21st-century competency needs can be identified. The Design stage can then translate these needs into teaching tools that combine fungal content, pedagogical activities, and appropriate technologies. The Develop stage allows the resulting tools to be validated and revised, while the Disseminate stage provides an opportunity for broader implementation. Previous research indicates that 4-D-based teaching-material development can support science literacy, creativity, and learning motivation (Anggraheni & Lutfianasari, 2025), while the integration of content, pedagogy, and technology within a systematic development framework can make learning more interactive and relevant (Arifuddin et al., 2025). Therefore, the 4-D model is not an independent instructional strategy in this study but functions as a systematic development pathway for operationalizing the TPACK–fungal bioecology integration.

Nevertheless, a research gap remains. Although previous studies have demonstrated the potential of problem-based learning, interactive digital media, TPACK, and 4-D-based teaching-material development, these approaches have largely been investigated as separate solutions to particular learning problems. Existing studies have provided evidence for improving visualization, conceptual understanding, science literacy, creativity, or motivation, but limited research has systematically integrated TPACK-based teaching tools with fungal bioecology through a structured 4-D development model. In particular, it remains insufficiently explored how such an integration can simultaneously address the abstraction of fungal concepts, limitations of instructional media, and complexity of classification while supporting conceptual understanding, critical thinking, creative thinking, and environmental literacy. The relationship between fungal bioecology as contextual content and TPACK as a framework for designing technological and pedagogical representations also requires further empirical examination. This gap is important because fungal biology provides a distinctive opportunity to connect microscopic biological concepts with ecological processes and real-world applications, yet such connections are not consistently incorporated into technology-supported instructional development.

The novelty of this study lies in the integration of three complementary components TPACK, fungal bioecology, and the 4-D development model—within a single teaching-tool development and evaluation framework. Unlike approaches that use technology primarily for visualization or focus on a single learning outcome, this study develops TPACK-based teaching tools that combine fungal biology content, fungal bioecological contexts, interactive technological representations, and pedagogical activities designed to engage students in meaningful and higher-order learning. The novelty also lies in evaluating the developed tools not only in relation to students' conceptual understanding but also in terms of critical thinking, creative thinking, and environmental literacy. Through this integration, the study positions fungal bioecology as more than supplementary content: it functions as a contextual bridge connecting fungal concepts to ecosystem processes, everyday applications, environmental issues, and 21st-century competencies.

Although previous studies have explored TPACK-based learning, interactive digital media, problem-based learning, and 4-D-based instructional development in biology education, these approaches have largely been examined separately and have focused on specific learning outcomes or particular instructional problems. Previous research has demonstrated the potential of technology-supported learning to improve visualization and conceptual understanding, while pedagogical approaches such as problem-based learning have supported students' higher-order thinking. However, limited research has systematically integrated TPACK-based teaching tools, fungal bioecology, and the 4-D development model to address the interconnected challenges of abstraction, limited instructional media, and the complexity of fungal classification. Moreover, the effectiveness of such an integrated approach in simultaneously supporting conceptual understanding, critical thinking, creative thinking, and environmental literacy remains insufficiently explored. Therefore, there is a need for an empirically tested instructional framework that connects

technological affordances, pedagogical strategies, fungal biology content, and ecological contexts within a coherent learning design.

The novelty of this study lies in the integrated development and evaluation of TPACK-based teaching tools for fungal bioecology learning using the 4-D development model. Rather than using technology solely to visualize fungal structures or applying a pedagogical model independently, the proposed teaching tools integrate technological representations, pedagogical activities, fungal biology content, and bioecological contexts within a single instructional framework. This integration is designed to transform abstract fungal concepts into contextual and meaningful learning experiences while providing opportunities for students to develop conceptual understanding, critical thinking, creative thinking, and environmental literacy. Thus, the study contributes an integrated TPACK–4-D–fungal bioecology framework for developing and evaluating technology-supported fungal biology learning at the secondary-school level.

Therefore, this study aimed to develop and evaluate TPACK-based teaching tools for fungal bioecology learning using the 4-D development model. Specifically, the study focused on determining the effectiveness of the developed teaching tools in improving students' conceptual understanding, critical thinking, creative thinking, and environmental literacy compared with conventional teaching tools.

## **2 RESEARCH METHOD**

### **2.1 Research Design**

This study employed a research and development (R&D) design using the 4-D development model, consisting of define, design, develop, and disseminate stages. The R&D design was selected to systematically develop and evaluate TPACK-based teaching tools integrated with fungal bioecology in response to the identified challenges in fungal biology learning, particularly the abstract nature of fungal structures, limitations of instructional media, and the complexity of fungal classification. The development process was guided by the integration of technological pedagogical content knowledge (TPACK), fungal bioecology, and 21st-century learning competencies. TPACK provided the theoretical basis for integrating fungal biology content, pedagogical strategies, and appropriate technological representations, while fungal bioecology provided contextual content linking fungal concepts to ecological processes and real-life applications. The 4-D model provided a systematic development pathway for translating these theoretical components into validated and implementable teaching tools.

Following the development process, the effectiveness of the resulting teaching tools was evaluated through a quasi-experimental design by comparing learning outcomes between students using the TPACK-based teaching tools and those using conventional teaching tools. The evaluation focused on students' conceptual understanding, critical thinking, creative thinking, and environmental literacy. This design enabled the study not only to produce a teaching tool based on the identified learning needs but also to empirically examine whether the integration of TPACK and fungal bioecology contributed to improved learning outcomes.

### **2.2 Research Subjects and Setting**

The study was conducted at Rehoboth Christian High School, Kartika-VIII-1 High School, and Pertiwi High School in Ambon, Indonesia. The participants consisted of 90 Grade XI students who participated in the development and effectiveness evaluation of the teaching tools. Biology teachers at the participating schools were involved as practitioners and research collaborators during the needs analysis, implementation, and evaluation stages. The participants were selected to represent the intended context of secondary-school fungal biology learning.

### **2.3 Development Procedure**

The development procedure followed the 4-D model: Define, Design, Develop, and Disseminate. Each stage was designed to address the learning problems identified in the preliminary analysis and to operationalize the integration of TPACK and fungal bioecology into the teaching tools.

#### **2.3.1 Define**

The Define stage involved an analysis of curriculum requirements, teacher and student needs, learning difficulties, and the characteristics of fungal biology content. Particular attention was given to students' difficulties in visualizing microscopic fungal structures, understanding complex classification systems, accessing appropriate learning media, and connecting fungal biology with ecological and everyday contexts. The analysis also considered the need to strengthen critical thinking, creative thinking, and environmental literacy as components of 21st-century learning. These findings served as the basis for determining the content, pedagogical activities, technological features, and assessment components to be incorporated into the teaching tools.

The Design stage translated the findings from the Define stage into the structure and content of the TPACK-based teaching tools. The content knowledge (CK) component focused on fungal biology and fungal bioecology, including fungal structures, classification, ecological roles, and applications. The pedagogical knowledge (PK) component incorporated contextual, inquiry-oriented, problem-based, and collaborative learning activities designed to engage students in analysis and application of biological concepts. The technological knowledge (TK) component incorporated appropriate digital and visual resources, including videos, animations, interactive media, and other representations intended to make microscopic and abstract fungal concepts more observable. The integration of CK, PK, and TK formed the basis of the TPACK-oriented instructional design. The teaching tools included worksheets, digital learning modules, visualizations, videos, mind maps, and related assessment instruments.

### **2.3.2 Develop**

The Develop stage involved the production, expert validation, revision, and limited testing of the teaching tools. The validation process examined the accuracy and relevance of the fungal biology content, the appropriateness of the pedagogical design, the functionality and relevance of the technological components, the integration of fungal bioecology, language, presentation, and assessment components. Feedback from experts, teachers, and students was used to revise the teaching tools before their effectiveness was evaluated in the field.

### **2.3.3 Disseminate**

The Disseminate stage involved the implementation of the finalized teaching tools in Grade XI biology learning and the communication of the research findings through scholarly dissemination. The dissemination stage was intended to support the broader use of the developed tools in fungal biology learning and provide opportunities for adaptation to similar biology topics.

## **2.4 Effectiveness Evaluation**

The effectiveness of the developed teaching tools was evaluated using a quasi-experimental design. The experimental group used the TPACK-based teaching tools integrated with fungal bioecology, whereas the comparison group used conventional teaching tools. Pretest and posttest data were collected to examine changes in students' learning outcomes. The evaluation focused on conceptual understanding, critical thinking, creative thinking, and environmental literacy. N-Gain analysis was used to determine the magnitude of improvement, while inferential analysis was conducted to examine differences between groups and, where applicable, the interaction between instructional condition and learning outcomes.

## **2.5 Data Analysis**

The data obtained from the research instruments were analyzed using descriptive and inferential statistical procedures. Descriptive analysis was used to summarize students' pretest and posttest scores for conceptual understanding, critical thinking, creative thinking, and environmental literacy. The mean, standard deviation, minimum, and maximum scores were calculated to describe students' performance before and after the implementation of the teaching intervention.

The improvement in students' learning outcomes was determined using the normalized gain (N-Gain), calculated from the difference between pretest and posttest scores. The N-Gain values were interpreted according to the following criteria: high ( $g \geq 0.70$ ), moderate ( $0.30 \leq g < 0.70$ ), and low ( $g < 0.30$ ).

Before conducting inferential analysis, the assumptions of normality and homogeneity of variance were examined. Normality was assessed using the Shapiro–Wilk test, while homogeneity of variance was examined using Levene's test. A significance level of  $\alpha = 0.05$  was used to determine whether the assumptions were satisfied.

To evaluate the effectiveness of the teaching intervention, a two-way analysis of variance (Two-Way ANOVA) was conducted separately for each dependent variable. The analysis used a  $2 \times 3$  factorial design, with teaching tool as the first factor and school as the second factor. The teaching-tool factor consisted of two levels: conventional teaching tools and TPACK-based teaching tools integrated with fungal bioecology. The school factor consisted of three levels: Rehoboth Christian High School, Kartika-VIII-1 High School, and Pertiwi High School.

The Two-Way ANOVA was performed separately for conceptual understanding, critical thinking, creative thinking, and environmental literacy. For each outcome, the analysis examined three effects: (1) the main effect of teaching tool, (2) the main effect of school, and (3) the interaction between teaching tool and school. The interaction analysis was used to determine whether the effectiveness of the teaching tools differed across the three participating schools.

The statistical analysis was based on data from 90 Grade XI students, comprising 45 students who received conventional teaching tools and 45 students who received the TPACK-based teaching tools integrated with fungal bioecology. With three schools and two instructional conditions, the factorial structure consisted of six analytical groups. For each

dependent variable, the total degrees of freedom were 89, with 5 degrees of freedom for the factorial model and 84 degrees of freedom for the error term.

Statistical significance was determined at  $p < 0.05$ . When a significant main effect or interaction was identified, the results were interpreted in relation to the descriptive statistics and N-Gain findings. Statistical analyses were performed using IBM SPSS Statistics 25.

### 3 RESULTS AND DISCUSSION

#### 3.1 Challenges Faced by Teachers in Teaching Fungal Biology, Particularly Related to Concept Abstraction, Media Limitations, and Classification Complexity

Teaching fungal biology in secondary schools often faces complex challenges. One of the main obstacles lies in the material's abstract nature. The microscopic structure of fungi, such as hyphae, mycelium, spores, and specialized reproductive organs like sporangia and asci, is challenging to understand without adequate visualization media (Klees & Piepenbring, 2018). As a result, many students only memorize terms without truly building conceptual understanding (Karakaya et al., 2023). This situation is exacerbated by the limitations of learning media in schools, whether in the form of living specimens that quickly deteriorate, expensive 3D models, or microscopes and digital simulations that are still available (Anyanwu et al., 2012). The results of the researcher's interviews with two biology teachers at Kartika High School. A Yani Ambon, and Rehoboth High School Ambon explain as follows:

##### 3.1.1 First Teacher

*"The challenge I face in teaching fungal biology lies in students' difficulty in understanding and remembering scientific names that feel foreign and are difficult to pronounce, thereby reducing their enthusiasm for learning. Additionally, I experience limitations in practical media, making learning tend to rely on textbooks or virtual materials. Therefore, in my opinion, this situation requires innovation through interactive media, digital simulations, or other creative approaches to make learning about fungi more interesting, easier to understand, and meaningful for students."*

##### 3.1.2 Second Teacher

*I often face challenges when teaching material about fungi. Students often have difficulty imagining their structure and components because the learning is primarily theoretical. I rarely provide hands-on practice due to limited media, preserved specimens, and the availability of very simple light microscopes and live specimens, which make the material feel abstract and far from real experience. Therefore, I need a more creative learning approach, such as simple experiments, the use of digital technology, or projects based on environmental observation, so that students' understanding of fungi becomes more concrete, engaging, and meaningful.*

This statement highlights the need for innovation in mushroom biology education. Teachers are required to employ creative strategies, such as using interactive digital media, 3D visual simulations, educational games based on scientific terms, or augmented reality technology. In this way, abstract concepts can be visualized more concretely, scientific names can be learned in a fun way, and student engagement in learning. The unavailability of resources causes students to lose out on direct learning experiences. Unlike topics such as plants or animals, which are familiar in everyday life, fungi are rarely observed by students in the real world. It makes learning about fungi theoretical, abstract, and even confusing. The variety of fungal reproduction, both asexual and sexual, often adds to the complexity, so that students not only find it difficult to understand the concepts but also lose motivation to explore further.

On the other hand, the ever-evolving classification system of fungi presents new challenges. The differences in characteristics between major phyla, such as Ascomycota and Basidiomycota, require in-depth understanding from teachers and pedagogical strategies that simplify concepts without sacrificing scientific accuracy (Patel & Patel, 2022). Teachers often struggle to balance comprehensive taxonomic presentation with students' need for clear, simple, and meaningful explanations. These challenges indicate that mushroom learning alone is insufficient. Pedagogical innovation is needed to bridge the gap between conceptual abstraction and students' real-world experiences. Digital technology, interactive simulations, inexpensive 3D printed models, and augmented reality-based visualization media can be strategic alternatives to revive mushroom learning in the classroom (Setiawaty & Tjahjono, 2025). Supported by innovative approaches, teachers not only convey information but also foster curiosity, sharpen critical thinking skills, and instill ecological awareness about the important role of fungi in human life and the balance of nature (Khastini et al., 2021). Thus, the challenges in teaching about fungi actually open up opportunities for pedagogical transformation. Through the integration of technology, teacher creativity, and adaptive scientific approaches, learning about fungi can be transformed from mere complex memorization into an inspiring, meaningful, and relevant learning experience for the challenges of the 21st century (Mena-guacas et al., 2025).

### 3.2 Difficulties Experienced by Students in Understanding Mushroom Material, Both in Terms of Visualizing Structure, Classification, and Contextual Application in Daily Life

Fungal material is one of the most challenging subjects for students to learn. Fungal material includes scientific names and Latin terms that students must understand, which is one of the reasons students struggle to learn about fungi. The learning difficulties experienced by students in fungal material can be found based on the results of interviews conducted with one of the students at Rehoboth Ambon High School and Pertiwi Ambon High School, who stated their reflections in a learning journal after learning about fungi, as recorded below:

#### 3.2.1 Student one

*"Learning about fungi is very challenging for me because it is difficult to visualize, the classifications are very diverse, and the benefits are not apparent in everyday life, even though fungi have great potential for life."*

#### 3.2.2 Student two

*"To be honest, I wasn't very interested when learning about fungi. It was very difficult to understand the concepts and issues related to this material. Usually, we only read from textbooks, without much hands-on experience. The section on fungal classification was often confusing, especially since we rarely got to see fungi through a microscope at school. Because of this, I also had difficulty understanding how the fungal reproduction system actually works."*

The student's reflection contains several important points, especially that it is difficult for students to visualize the structure of fungi, such as hyphae or spores, which are microscopic and not easily observed without tools. It makes it difficult for students to understand their shape and function only through explanations or pictures. The world of fungi has many groups (e.g., Ascomycota, Basidiomycota, Zygomycota), each with specific characteristics that are complicated to remember and distinguish. It requires deep understanding, not just memorization. In everyday life, students are more likely to view fungi negatively (e.g., as a cause of disease or spoiled food). However, many fungi are beneficial in food, pharmaceuticals, agriculture, and ecology, though these benefits are often overlooked. Fungi have great potential for life (de Mattos-Shipley et al., 2016; Hamdiyati et al., 2022). Although difficult to study, fungi are actually essential. For example, fungi play a role in recycling substances, producing medicines (penicillin), food ingredients (tempeh, bread, cheese), and even modern technology (industrial enzymes, biotechnology).

Limitations in models or learning media that cannot show the three-dimensional shape and structure of fungi can hinder students' understanding of the actual anatomy of fungi (Yanti, 2024). There are thousands of types of fungi, classified according to their structure and life habits. Students find it difficult to remember and distinguish between different classes and types of fungi. Fungal classification is often based on microscopic or reproductive characteristics that are difficult to observe directly, requiring students to memorize many details (Naranjo-Ortiz & Gabaldón, 2019).

Teachers explain that students still find it difficult to see the relevance of fungi in everyday life, beyond common examples like mold on food. Often, students are unaware of the role of fungi in ecosystems (as decomposers), in the food industry (yeast, tempeh, cheese), in medicine (penicillin), or even as disease pathogens, because their knowledge of these topics is still limited. Fungi are often considered harmful or disgusting organisms, so students are less interested in learning more about their benefits and applications. Learning about fungi is indeed challenging because they are not easily visible, have complex structures, and their benefits are often overlooked. However, behind these challenges lie great opportunities to understand how fungi play a vital role for humans and the environment (Pouris et al., 2024).

### 3.3 The effectiveness of innovative TPACK-based teaching tools and the integration of fungal bioecology on:

#### 3.3.1 Enhancing Students' Critical and Creative Thinking Skills

21st-century education requires students to possess critical and creative thinking skills to address the complexity of global issues (Aldi et al., 2025). Teachers play a crucial role in designing innovative teaching tools that integrate technology, pedagogy, and content (TPACK) (Li et al., 2022). One potential contextual content is fungal bioecology, given its broad role in material cycles, health, the environment, and biotechnology applications. However, many teaching tools still focus solely on delivering cognitive material, without developing higher-order thinking skills. Therefore, this study examines the effectiveness of TPACK-based teaching tools, integrated with fungal bioecology, in improving students' critical and creative thinking skills. The results of the study indicate that the application of innovative TPACK-based teaching tools, integrated with material on fungal bioecology, significantly improves students' critical thinking skills. The N-Gain data for critical thinking skills in three schools are presented in Table 1.

**Table 1: Critical Thinking Skills N-Gain Values**

| Descriptive Statistics                |                     |            |
|---------------------------------------|---------------------|------------|
| Experimental Group                    | N-Gain Score (Mean) | Percentage |
| Rehoboth Christian High School, Ambon | 0.7952              | 79.5       |
| Kartika-VIII-1 High School Ambon      | 0.7440              | 74.3       |
| Pertiwi High School Ambon             | 0.6218              | 62.1       |

The N-Gain scores obtained indicate an increase in critical thinking skills, with high scores at Rehoboth Christian High School Ambon (79.5%) and Kartika-VIII-1 High School Ambon (74.3%), and moderate scores at Pertiwi High School Ambon (62.1%). This improvement is inseparable from the characteristics of the bioecology of fungi, which are rich in real, contextual phenomena close to everyday life. For example, students are invited to analyze the role of fungi in the ecosystem as decomposers, their use in food (such as tempeh and bread), and their impact as pathogens on plants and humans. This situation requires students to identify problems, compare different points of view, evaluate scientific evidence, and construct logical arguments, which are key indicators of critical thinking skills. The integration of fungal material with TPACK-based teaching tools also encourages students to use technology to explore topics, such as observing microscopic images of fungi via digital media, searching for information in online scientific literature, and compiling reports based on observation data. This process connects biology content (fungal bioecology) with inquiry-based pedagogical strategies and technology use, resulting in meaningful learning that strengthens critical thinking skills.

The results of this study also support the theories of Batool et al. (2025), which affirm that TPACK enables teachers to design meaningful learning experiences through the integration of content knowledge, pedagogy, and technology. Stephens-himonides et al. (2025) add that TPACK integration can foster learning that challenges students to connect scientific concepts with real-world practices, thereby encouraging the development of higher-order thinking skills. Furthermore, Wu et al. (2025) emphasize that the success of TPACK implementation is strongly influenced by contextual factors, including teacher readiness, technological resources, and students' prior experiences. It is evident in the differences in achievement between schools: Rehoboth Christian High School in Ambon achieved the highest increase, followed by Kartika-VIII-1 High School in Ambon, while Pertiwi High School in Ambon achieved a relatively lower increase, possibly due to limited facilities or student adaptation.

Thus, the increase in N-Gain critical thinking skills obtained in the three schools can be explained as the result of the TPACK approach combined with contextual, applicable, and intellectually challenging fungal bioecology material. These results confirm that biology learning with a fungal theme not only enriches students' knowledge of biodiversity but also provides a practical context for developing the critical thinking skills needed in the 21st century.

**Table 2: N-Gain Scores for Creative Thinking Skills**

| Descriptive Statistics                |                     |            |
|---------------------------------------|---------------------|------------|
| School Group                          | N-Gain Score (Mean) | Percentage |
| Rehoboth Christian High School, Ambon | 0.7262              | 72.6       |
| Kartika-VIII-1 High School, Ambon     | 0.6902              | 69         |
| Pertiwi High School Ambon,            | 0.7621              | 76.2       |

The results of this study indicate that the application of innovative teaching tools based on *Technological Pedagogical Content Knowledge* (TPACK) with the integration of fungal bioecology material not only has an impact on critical thinking skills but also provides a significant increase in students' creative thinking skills. The N-Gain data for creative thinking skills in the three schools can be seen in Table 2. The data in Table 2 show that all schools experienced an increase in creative thinking skills, with all skills moving in the high category. The most significant increase was at Pertiwi Ambon High School with an N-Gain score of 0.7621 (76.2%), followed by Rehoboth Christian High School Ambon with 0.7262 (72.6%), and Kartika-VIII-1 High School Ambon with 0.6902 (69%).

These findings confirm that TPACK-based teaching tools are effective in creating learning spaces that support the exploration of ideas, innovation, and students' ability to generate alternative solutions to a problem. The material on fungal bioecology, in particular, provides a rich context for training in creative thinking because it covers aspects of diversity in form, ecological roles, benefits in biotechnology, and negative implications as pathogens. For example, students can be invited to design the use of fungi in functional food products, create models of fungal-mediated waste biodegradation, or develop strategies to control fungal diseases. These activities encourage the emergence of new and original ideas related to real life.

Contextual factors can explain differences in creative thinking skills across schools. Pertiwi Ambon High School, which obtained the highest score, likely has a conducive learning environment that encourages creativity, even though its critical thinking scores were previously in the moderate category. It shows that critical and creative thinking follow distinct developmental trajectories, even though both are components of higher-order thinking skills (Zhang, Tian, et al., 2025).

The results of this study also support the theory that TPACK can enhance creativity, as teachers can design learning experiences that combine technology, inquiry-based pedagogy, and challenging science content (Rahayu et al., 2024). When students are allowed to experiment with new ideas using technology and real biological phenomena, such as fungi, they are encouraged to develop their creative thinking skills more effectively. Overall, these findings confirm that innovative TPACK-based teaching tools incorporating fungal bioecology materials significantly improve high school students' creative thinking skills in Ambon. This achievement is in line with the demands of 21st-century education, which emphasizes the importance of creativity as one of the key competencies for facing global dynamics.

### 3.3.2 Improved Understanding of Fungal Concepts

Biology learning on fungal material often faces various obstacles, particularly regarding the level of conceptual abstraction, limitations in visual media, and classification complexity. In this context, this study involving 90 grade XI Fase F students from Rehoboth Christian High School, Ambon, Kartika-VIII-1 High School Ambon, and Pertiwi High School Ambon aims to analyze the improvement in understanding of mushroom concepts through the use of different teaching tools, namely conventional teaching tools (control class) and TPACK teaching tools based on mushroom bioecology (experimental class). Biology teachers acted as practitioners and collaborators in ensuring the consistent implementation of teaching tools in the field (Dragni & Anderson, 2025).

The results in Table 3 show that students in the experimental class demonstrated a greater increase in conceptual understanding than those in the control class. The use of TPACK-based teaching tools enables stronger integration of content, pedagogy, and technology, so that the previously abstract concept of fungi can be visualized and linked to local bioecological phenomena (Ning et al., 2024). Digital media such as microphotographs, videos of hyphal growth, spore reproduction simulations, and maps of fungal bioecology in the students' environment help them understand the structure-function relationships and adaptive dynamics of fungi more concretely (Wulandari et al., 2024).

Additionally, integrating the bioecological context of local fungi makes it easier for students to relate the material to real-world experiences, such as the appearance of *Auricularia* mushrooms on sago trunks, mold on foodstuffs, and lichen as bioindicators. It fosters the formation of more stable and meaningful concepts. Teachers who act as research collaborators ensure that each phase of TPACK learning exploration, elaboration, and contextualization runs according to the teaching device design and is reflected on during the implementation process (Charania et al., 2024). Conversely, in the control class using conventional teaching materials, student understanding improved, but not as optimally as in the experimental class. The limitations of visual media and the dominance of verbal explanations resulted in some concepts remaining abstract, especially those related to microscopic structure, reproductive cycles, and the principles of mushroom classification. Class discussions were not enhanced by visual examples or local context, so the concepts were less grounded in reality.

**Table 3: Improvement in Mushroom Concept Understanding (Pre-test-Post-test)**

| School   | Group      | n  | Pre-test (M) | Post-test (M) | N-Gain          |
|----------|------------|----|--------------|---------------|-----------------|
| Rehoboth | Control    | 15 | 42.50        | 63.20         | 0.36 (moderate) |
| Rehoboth | Experiment | 15 | 43.10        | 82.70         | 0.70 (high)     |
| Kartika  | Control    | 15 | 40.80        | 61.50         | 0.35 (moderate) |
| Kartika  | Experiment | 15 | 41.60        | 84.20         | 0.73 (high)     |
| Pertiwi  | Control    | 15 | 39.90        | 59.80         | 0.33 (moderate) |

|         |            |    |       |       |       |
|---------|------------|----|-------|-------|-------|
| Pertiwi | Experiment | 15 | 40.20 | 81.40 | high) |
|---------|------------|----|-------|-------|-------|

Overall, this study shows that TPACK-based teaching tools grounded in fungal bioecology are effective in improving high school students' understanding of fungal concepts, particularly by strengthening connections among scientific concepts, environmental phenomena, and the use of technology (Veyis, 2025). It is a relevant strategy for addressing the challenges of material abstraction, limitations in learning media, and the complexity of mushroom classification in modern biology education.

In Table 3, students' pre-test scores were relatively low in all three schools, ranging from 39.90 to 43.10, indicating that fungal material remains abstract for most students. Students had difficulty understanding the microscopic structure, life cycle, and classification of fungi before the learning began. These similar initial scores indicate that students' initial abilities were relatively homogeneous, making the post-treatment comparison valid for measuring the learning model's effect. The control group (conventional learning) experienced *moderate* improvement at all three schools. N-Gain scores of 0.33–0.36 indicate that students gained understanding after receiving explanations, but the improvement was limited. Conventional learning was less effective at visualizing the structure and role of fungi. The absence of digital media made learning less interesting and less contextual.

The experimental group showed a *high* increase in all schools with N-Gain values of 0.68–0.73. It means that integrating technology (digital microscopes, fungal ecology videos, life cycle animations) helped students understand previously abstract concepts (Hinostroza et al., 2025). The fungal bioecology approach makes learning relevant to everyday life (edible fungi, pathogenic fungi, fungi in humid environments). Learning becomes more interactive, encouraging students to explore and investigate. It shows that TPACK-based teaching tools grounded in fungal bioecology significantly improve conceptual understanding compared to conventional models.

**Table 4: Comparison of Control vs. Experimental Groups**

| Group        | Average N-Gain | Category |
|--------------|----------------|----------|
| Control      | 0.35           | Moderate |
| Experimental | 0.70           | High     |

Table 4 shows that the overall difference is approximately twofold, indicating the substantial impact of TPACK teaching tools. This finding is consistent with previous research indicating that TPACK can connect content, pedagogy, and technology so that abstract material becomes concrete. Bioecology adds real context and local relevance.

According to Saad et al. (2025), TPACK emphasizes the integration of three main components: (a) Technology (multimedia, simulations, videos, educational applications); (b) Pedagogy (PBL, inquiry, field investigation); and (c) Content (fungal structure, classification, ecology). In this study, the TPACK framework visually presents the structure of fungi (sporangium, hyphae, mycelium), links the function of fungi to the local ecosystem of Ambon, and encourages discussion and group work. It resulted in a significantly higher level of understanding than conventional learning.

Constructivist theory argues that knowledge is actively constructed by students. Visual media and field contexts enhance concept formation. In the mushroom material, students more easily understood the differences between Ascomycota and Basidiomycota fungi, as well as the shapes of mushroom fruiting bodies. Students find it easier to understand the role of fungi in decomposition when they experience it firsthand through supporting technology (Katona et al., 2022). Bioecology-based learning places fungi within the local ecosystem, such as wood-decaying fungi in the school environment, tempeh fungi (*Rhizopus*), and parasitic fungi on garden plants (Vaiana et al., 2026). This relevance enhances meaning-making, thereby significantly improving concept mastery.

### 3.3.3 Main Challenges in Mushroom Learning

Table 1 presents three main challenges faced in teaching fungal material to 11th-grade students. These challenges arise due to the microscopic nature of fungi, the need for strong visual media, and the complexity of their classification. Understanding these challenges is crucial for determining appropriate and effective teaching strategies.

**Table 5: Main Challenges in Teaching About Fungi**

| Challenge                    | Brief Explanation                                                                                                                             |
|------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|
| Conceptual abstraction       | Fungi have a microscopic structure, making them difficult for students to visualize.                                                          |
| Limitations of media         | Conventional learning relies solely on books and lectures, making it less interactive.                                                        |
| Complexity of classification | The abundance of morphological characteristics and scientific terms makes it easy for students to become confused and misunderstand concepts. |

Table 2 shows how TPACK-based teaching tools grounded in fungal bioecology are applied to overcome these challenges. The integration of technology, pedagogy, and content makes learning more concrete, interactive, and ecologically relevant. This TPACK implementation is designed to enhance students' conceptual understanding through visualization, inquiry activities, and reinforcement of the local environmental context (Nisa et al., 2025).

**Table 6: Solutions Through TPACK Teaching Tools Based on Mushroom Bioecology**

| TPACK Components | Form of Implementation                                                                                       | Impact on Understanding                            |
|------------------|--------------------------------------------------------------------------------------------------------------|----------------------------------------------------|
| Technology       | Microscopic structures visualization videos, life cycle animations, and mushroom identification applications | Helps visualization and reduces abstraction.       |
| Pedagogy         | Inquiry, PBL, field observation                                                                              | Enhancing engagement and conceptual understanding. |

The application of TPACK teaching tools based on fungal bioecology can address these three challenges by integrating visual technology, active pedagogical approaches, and content relevant to the local environment. According to Absari et al. (2020) TPACK is effective when technology, pedagogy, and content are harmoniously integrated to produce a richer, more meaningful learning experience. Additionally, constructivist theory (Piaget & Vygotsky) emphasizes that students construct knowledge through direct experience and interaction with the environment, so the use of microscopic structures visualization videos, animations, mushroom identification applications, and field inquiry activities can strengthen the concept formation process (Erawati & Adnyana, 2024). By applying these theoretical principles, learning becomes more concrete, engaging, and contextual, leading in a significant improvement in students' conceptual understanding compared to conventional learning.

TPACK-based teaching tools using fungal bioecology significantly improve students' conceptual understanding compared to conventional methods. The improvement in the experimental group was in the high category, while the improvement in the control group was moderate. The integration of technology, active pedagogy, and local ecological context proved effective in overcoming abstraction, media limitations, and difficulties in mushroom classification.

### 3.3.4 Strengthening students' environmental literacy

Research on strengthening students' environmental literacy found that the application of innovative TPACK-based teaching tools, integrated with fungal bioecology materials, significantly improved students' environmental literacy. The N-Gain data for strengthening students' environmental literacy are shown in Table 7.

**Table 7: N-Gain scores for strengthening students' environmental literacy**

| Descriptive Statistics                |                     |            |
|---------------------------------------|---------------------|------------|
| School Group                          | N-Gain Score (Mean) | Percentage |
| Rehoboth Christian High School, Ambon | 0.7                 | 7          |
| Kartika-VIII-1 High School, Ambon     | 0.7101              | 71         |
| Pertiwi High School Ambon             | 0.7677              | 76         |

Based on Table 3, Pertiwi Ambon High School achieved the most significant increase, with an N-Gain value of 0.7677 (76%), followed by Kartika-VIII-1 Ambon High School (0.7101 or 71%) and Rehoboth Christian High School Ambon (0.7000 or 70%). All values are in the high category, confirming that TPACK-based innovative teaching tools are effective in building students' awareness, understanding, and skills in environmental literacy.

This improvement can be explained by the characteristics of fungal bioecology material, which is directly related to environmental issues. Fungi play an important role in ecosystems as decomposers, organic waste decomposers, and bioremediation agents, but they can also pose threats as plant and human pathogens. Discussions about the dual role of fungi require students to understand human-environment interactions, analyze ecological impacts, and evaluate science-based solutions to environmental problems. Activities such as case studies of soil pollution that can be treated with fungi or innovations in organic waste processing based on fungi encourage students to think reflectively and responsibly about the environment.

Theoretically, these results support the views of Lin & Sah (2025) that environmental literacy encompasses not only knowledge about nature, but also decision-making skills and environmental awareness. The integration of TPACK reinforces this aspect because teachers can use technology (digital simulations, experiment videos, or online literature) to link biology content to real environmental issues (Rizwana Ibrahim & Aslam, 2025) also emphasize that the success of TPACK in building 21st-century literacy depends on the interconnection between science, inquiry-based pedagogy, and relevant technology.

Interestingly, although Pertiwi Ambon High School was only in the moderate category in critical thinking skills in the previous study, this school actually recorded the highest achievement in environmental literacy. It indicates that environmental literacy is not entirely parallel to critical thinking skills but is also influenced by the learning context, student motivation, and direct experience with environmental issues.

Thus, this study shows that TPACK-based teaching tools with the integration of fungal bioecology can be an effective strategy in building environmental literacy among high school students, while also supporting the global agenda of *education for sustainable development*. This is in line with the sustainable development goals (SDG 4.7) target, which emphasizes the importance of education in shaping a generation that is environmentally literate, responsible, and able to participate in maintaining the sustainability of ecosystems (Gacayan, 2025).

### 3.4 Significant differences in students' 4C skills (critical and creative thinking) and environmental literacy scores by teaching tool type (conventional vs. TPACK-based), and an understanding of the interaction between teaching tool type and skill type on these scores.

#### 3.4.1 Differences in 4C Skills, Skill Types, and Environmental Literacy, as well as their Interaction

21st-century education requires 4C skills, particularly critical and creative thinking, as well as environmental literacy, as preparation for facing global challenges (Herlinawati et al., 2024). However, conventional teaching tools, which remain dominant, tend to focus on delivering material, so students are less well trained in developing these skills. As an alternative, TPACK (Technological Pedagogical Content Knowledge)-based teaching tools offer an integration of technology, pedagogy, and content that encourages more interactive, contextual, and challenging learning (Herlinawati et al., 2024).

**Table 8: Two-Way ANOVA Test for Critical Thinking**

| Source                 | Sum of Squares | df | Mean Square | F         | Sig.   |
|------------------------|----------------|----|-------------|-----------|--------|
| Corrected Model        | 1,175.433      | 5  | 235.087     | 4.278     | < .001 |
| Intercept              | 68,546.400     | 1  | 68,546.400  | 1,247.630 | < .001 |
| Teaching Tool          | 589.633        | 1  | 589.633     | 10.732    | .002   |
| School                 | 566.044        | 2  | 283.022     | 5.151     | .008   |
| Teaching Tool × School | 19.756         | 2  | 9.878       | 0.180     | .836   |
| Error                  | 4,615.067      | 84 | 54.941      | —         | —      |
| Total                  | 74,337.000     | 90 | —           | —         | —      |
| Corrected Total        | 5,790.500      | 89 | —           | —         | —      |

$R^2 = 0,394$ . Adjusted  $R^2 = 0,357$

Therefore, this study aims to analyze significant differences in 4C skills (critical and creative thinking) and environmental literacy scores between conventional and TPACK-based teaching tools, and to examine the interaction between the two on student learning outcomes.

The two-way ANOVA results demonstrated a statistically significant difference in students' critical-thinking scores according to the teaching tool,  $F(1,84) = 10.732, p = .002$ . This finding indicates that the type of teaching tool was significantly associated with variation in students' critical-thinking performance. Within the theoretical framework of Technological Pedagogical Content Knowledge (TPACK), this result can be understood through the purposeful integration of technology, pedagogy, and disciplinary content. TPACK does not conceptualize technology as an isolated instructional add on; rather, it emphasizes the dynamic and situated relationship between technological resources, pedagogical strategies, and the specific characteristics of subject matter. A recent second-order review of TPACK research likewise emphasizes that TPACK should be understood as a complex, situated, and dynamic construct and highlights the need for stronger evidence linking TPACK oriented approaches with student learning outcomes (Uçar & Sahin, 2026).

In the context of fungal bioecology learning, this theoretical perspective is particularly relevant because students are required to understand interconnected biological concepts, including fungal characteristics, classification, ecological roles, and relationships between fungi and their environments. The integration of appropriate technological representations with pedagogical activities can provide opportunities for students to observe, compare, analyse, evaluate evidence, and formulate reasoned conclusions. These learning processes are closely associated with the development of critical thinking. Previous research in biology education has similarly reported significant differences in critical thinking performance when TPACK was integrated with PBL, suggesting that technology supported pedagogical designs may create conditions that support analytical reasoning and cognitive engagement with complex biological content (Muhali & Asy'ari, 2026).

The significant main effect of teaching tool does not by itself establish that TPACK-based teaching tools directly caused improvements in critical thinking. Rather, the analysis demonstrates that critical-thinking scores differed significantly according to the teaching tool used in the study. This distinction is important because contemporary TPACK scholarship has identified a need for more rigorous research designs and clearer connections between TPACK-oriented interventions and measurable student outcomes (Scherer et al., 2026). Thus, the present study contributes evidence at the student learning level while maintaining that causal conclusions should remain consistent with the study design and statistical analysis.

A statistically significant difference was also found among the three schools,  $F(2,84) = 5.151, p = .008$ . This result indicates that students' critical-thinking scores varied across the participating schools. Theoretically, this finding is consistent with the situated nature of teaching and learning. Recent research has emphasized that educational contexts may shape how technology, pedagogy, and content are enacted in practice, and contextual knowledge has increasingly been recognized as relevant to understanding technology-integrated teaching. However, because the present study did not directly measure school-level factors, such as technological infrastructure, teacher expertise, prior student experiences, or institutional learning conditions, these factors cannot be identified as the causes of the observed differences. They should instead be regarded as possible contextual considerations requiring further investigation.

In contrast, the interaction between teaching tool and school was not statistically significant,  $F(2,84) = 0.180, p = .836$ . This finding suggests that the statistically observed difference associated with teaching tool did not vary significantly across the three schools. In other words, although school context was associated with differences in critical-thinking scores, the data did not provide evidence that the relationship between teaching tool and critical thinking depended significantly on the school in which the intervention was implemented. This result is noteworthy because recent TPACK research increasingly recognizes the importance of context; however, contextual variation does not necessarily imply that every technology-based instructional approach will interact statistically with every school context (Gatete, 2026).

Overall, these findings support the theoretical relevance of integrating technology, pedagogy, and fungal bioecology content when designing teaching tools intended to engage students with complex biological phenomena. They also extend previous TPACK research by examining student critical-thinking outcomes within a specific biological content domain. A recent systematic content analysis of 90 TPACK studies in science education reported that subject-specific content has received comparatively limited attention and called for greater examination of TPACK within particular science domains and instructional contexts (Schmid et al., 2024). Therefore, the contribution of the present study lies not merely in applying technology to biology instruction, but in investigating how TPACK-based teaching tools can be integrated with fungal bioecology learning and evaluated in relation to students' critical-thinking performance across multiple school contexts.

### 3.4.2 Differences in 4C Skills Types of Skills and Environmental Literacy and their Interactions

The results of the Two-Way ANOVA presented in Table 9 demonstrate a statistically significant main effect of Teaching Tool on students' Creative Thinking. Specifically, the analysis revealed a significant difference among the Teaching Tool groups,  $F(2, 87) = 34.283$ ,  $p < .001$ . This result indicates that students' Creative Thinking scores differed significantly depending on the type of Teaching Tool employed during the learning process. Therefore, the null hypothesis stating that there was no significant difference in Creative Thinking among the Teaching Tool groups was rejected. The magnitude of the  $F$  statistic suggests that the between-group variation associated with Teaching Tool was substantially greater than the within-group or residual variation. Thus, the findings provide robust statistical evidence of a significant main effect of Teaching Tool on Creative Thinking. However, because the Two-Way ANOVA examines more than one factor simultaneously, the interpretation of this main effect should be considered together with the main effect of the second factor and the interaction effect between the two factors.

**Table 9: Two-Way ANOVA Test for Creative Thinking**

| Source          | Type III Sum of Squares | df | Mean Square | F         | Sig.   |
|-----------------|-------------------------|----|-------------|-----------|--------|
| Corrected Model | 5,277.378               | 2  | 2,638.689   | 34.283    | < .001 |
| Intercept       | 169,086.678             | 1  | 169,086.678 | 2,199.611 | < .001 |
| Teaching Tool   | 5,277.378               | 2  | 2,638.689   | 34.283    | < .001 |
| Error           | 6,696.267               | 87 | 76.969      |           |        |
| Total           | 181,060.322             | 90 |             |           |        |
| Corrected Total | 11,973.644              | 89 |             |           |        |

$R^2 = .441$  (Adjusted  $R^2 = .428$ )

The results of the general linear model analysis indicate that the teaching tool factor had a statistically significant effect on the dependent variable. Based on the ANOVA results, an  $F$  value of  $(2, 87) = 34.283$  was obtained, with a significance level of  $p < .001$ . This finding indicates that there were statistically significant differences in the dependent variable across the different types of teaching tools used in the learning process. Therefore, the null hypothesis stating that there were no differences in outcomes among the teaching tool groups was rejected. The relatively high  $F$  value indicates that the variation explained by the teaching tool factor was substantially greater than the residual variation, or the variation that could not be explained by the model.

The explanatory power of the model is further reflected in the  $R^2$  value of 0.441 and the adjusted  $R^2$  value of 0.428. These results indicate that approximately 44.1% of the variance in the dependent variable could be explained by the model incorporating the teaching tool factor. After adjusting for the number of predictors and the complexity of the model, the proportion of explained variance remained at 42.8%. The relatively small difference between  $R^2$  and adjusted  $R^2$  suggests that the model's ability to explain variation in the outcome was relatively stable and was not substantially reduced after accounting for model complexity. Within the general linear model framework,  $R^2$  represents the proportion of variance in the dependent variable explained by the model, whereas adjusted  $R^2$  provides a corrected estimate that takes model complexity into account.

In addition to demonstrating statistical significance, the findings also indicate a substantial effect in practical terms. Based on the Type III Sum of Squares, the teaching tool factor had a sum of squares of 5,277.378, whereas the sum of squares error was 6,696.267. These components resulted in a partial eta squared ( $\eta^2$ ) value of 0.441. This value indicates that approximately 44.1% of the variance associated with the dependent variable, after accounting for error variance in the model, was attributable to the teaching tool factor. Thus, the findings demonstrate not only a statistically significant difference but also suggest that teaching tool made a substantial contribution to the observed variation in the outcome. This interpretation becomes more meaningful when the effect size is considered (Visscher et al., 2025).

The  $\eta^2$  value of 0.441 is considerably higher than the conventional threshold of 0.14, which is commonly used to indicate a large effect in behavioral and educational research. Accordingly, the effect of teaching tool in the present study can be interpreted as large. Nevertheless, this interpretation should be made within the context of the research design because the magnitude of partial eta squared can be influenced by model characteristics, sample size, the number of factors, and the structure of the data. Therefore, the magnitude of the effect should not be interpreted independently of the learning context, student characteristics, types of instructional tools employed, and empirical evidence from previous studies. Reporting effect sizes alongside statistical significance is important because it provides a more comprehensive understanding of the practical meaning of research findings.

From a theoretical perspective, the effect of teaching tool on learning outcomes can be understood through the perspective of media- and technology-based learning, particularly the cognitive theory of multimedia learning (CTML). When the teaching tools used in a study incorporate visual, auditory, video, animation, simulation, or other combinations of information representations, differences in their effectiveness may be explained through the mechanisms of information processing described by CTML. Mayer, (2024) explains that multimedia learning involves active cognitive processing, including selecting relevant information, organizing it into coherent mental representations, and integrating it with learners' existing knowledge.

Nevertheless, the significant ANOVA result does not indicate which specific teaching tool groups differed from one another. The degrees of freedom of 2 for the teaching tool factor indicate that the analysis involved three groups or categories of teaching tools. Therefore, following the significant ANOVA result, a post-hoc analysis, such as the Tukey HSD test, is required to identify which specific pairs of groups differed significantly. Such a follow-up analysis is important because ANOVA only establishes the existence of an overall difference among groups and does not identify which particular groups are significantly different. Consequently, conclusions regarding the superiority of one type of teaching tool over another should preferably be drawn after the post-hoc test results have been examined.

Overall, the findings demonstrate that teaching tool was a factor strongly associated with and contributed substantially to the variation in the dependent variable. The  $F(2,87) = 34.283$  with  $p < .001$  indicates statistically significant differences among the groups, while  $R^2 = 0.441$  and adjusted  $R^2 = 0.428$  indicate that the model explained a substantial proportion of the variance in the outcome. Furthermore, the  $\eta^2 = 0.441$  provides additional evidence that the teaching tool factor had a large effect size. These findings suggest that innovation in the selection and design of instructional tools has the potential to make an important contribution to improving the quality of learning. However, the benefits of such tools depend substantially on their alignment with pedagogical principles, learners' cognitive processes, learning objectives, subject matter characteristics, and the context in which they are implemented.

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## 4 CONCLUSION

This study developed and evaluated TPACK-based teaching tools integrating fungal bioecology using the 4-D development model. The results showed significant differences in students' learning outcomes between TPACK-based and conventional instruction, particularly in critical thinking, creative thinking, conceptual understanding, and environmental literacy. These findings provide empirical support for integrating technology, pedagogy, fungal biology content, and bioecological contexts to facilitate meaningful learning of abstract biological concepts. Through visualization, contextual exploration, analysis, and problem-solving activities, students were able to connect biological concepts with ecological phenomena and environmental issues, consistent with the core principles of TPACK. For biology teachers, TPACK-based tools may provide an alternative resource for teaching fungal biology, particularly concepts that are difficult to observe directly. Technology should be selected according to learning objectives, content characteristics, and students' cognitive needs rather than technological sophistication alone. For instructional developers, coherence among technology, pedagogy, content, and bioecological context is essential to ensure meaningful integration. Several limitations should be considered. The study involved only 90 Grade XI students from three secondary schools in Ambon, Indonesia, limiting generalizability. The quasi-experimental design also does not establish definitive causal effects, while differences in teacher implementation, prior knowledge, school facilities, and technology access may have influenced the outcomes. Future studies should involve larger and more diverse samples, longitudinal designs, and more rigorous experimental or mixed-methods approaches to examine the sustainability and mechanisms of TPACK-based learning. Overall, this study proposes an integrated TPACK fungal bioecology 4-D framework that aligns technological resources, pedagogical strategies, fungal biology content, and ecological contexts. Its main contribution is extending TPACK beyond technology-supported visualization by positioning fungal bioecology as a contextual bridge linking biological knowledge, ecological understanding, environmental issues, and 21st-century competencies. The framework addresses the limited empirical integration of TPACK, fungal bioecology, and the 4-D model and provides a basis for further development and testing in diverse educational contexts.

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## STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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### Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

### Statement of informed consent

Informed consent was obtained from all individual participants included in the study.

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