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Exploring Students' Mental Models of Photosynthesis: A Five-Tier Diagnostic Case Study in Senior High School

Alfyn Abdan Nurahman, Ari Widodo*, Sariwulan Diana
Universitas Pendidikan Indonesia
Jl. Dr. Setiabudhi No. 229 Bandung 40154, Indonesia
*Corresponding author: widodo@upi.edu

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ABSTRACT

Understanding students' mental models is essential to identify conceptual and representational challenges in learning intricate biological processes such as photosynthesis. This study explores senior high school students' mental models of photosynthesis using a five-tier open-ended diagnostic test that integrates conceptual and visual understanding. A qualitative case study was conducted with 27 students in Bandung, Indonesia. The results revealed that only 22.8% of students demonstrated scientific understanding of the light reaction, and just 16.0% did so for the dark reaction. The majority of students exhibited initial or synthetic models, indicating fragmented knowledge, misconceptions, and difficulties in depicting key photosynthesis processes. Visualization results further highlighted students' limited ability to construct accurate scientific representations, especially for the dark reaction. These findings suggest a need for model-based teaching strategies, multimodal representations, and formative assessments to enhance students' conceptual and visual understanding of photosynthesis.

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INTRODUCTION

Photosynthesis is a central concept in biology education that serves as a gateway for understanding the flow of energy and cycling of matter within ecosystems. Its foundational role in connecting molecular biology, plant physiology, and environmental science makes it a critical topic in secondary science curricula worldwide. Beyond its biological importance, photosynthesis underpins students' understanding of broader global issues (Jančaříková & Jančařík, 2022) such as sustainability, carbon sequestration, food security, and climate change. Therefore, fostering a scientifically accurate comprehension of photosynthesis is not only fundamental for advancing biological literacy but also for cultivating environmentally responsible citizens (Eriksson et al., 2023; Georgiou, 2023).

However, despite its curricular importance, numerous studies have shown that students at various educational levels (e.g Ayunda et al., 2019; Diana, 2019; Diana et al., 2021), including senior high school, frequently struggle to understand the process of photosynthesis in a scientifically coherent manner (Vančugovienė et al., 2024). Senior high school students frequently make errors in comprehending the relationship between photons and light reactions, as well as in identifying chemical reactions in photosynthesis (Almualimah et al., 2024). These difficulties persist even as student progress through their education, with older students developing misconceptions (Barrutia & Díez, 2021; Vančugovienė et al., 2023) such as believing oxygen is produced in the Calvin cycle at night (Radanović et al., 2015). Several concepts in photosynthesis material that tend to be misunderstood by students include the definition of photosynthesis, the time when photosynthesis occurs, chlorophyll and chloroplasts, the stages of light and dark reactions, and the function of water photolysis (Machshunah & Yuliani, 2019; Rusydiana et al., 2016). These difficulties stem from several factors: the abstract and invisible nature of photosynthetic processes, the requirement to integrate knowledge across multiple scales, such as molecular, cellular, organismal, and ecological (Akçay, 2017; Zangori et al., 2017). The presence of competing everyday experiences or intuitive beliefs that can conflict with scientific explanations. Common misconceptions persist even after formal instruction (Jančaříková & Jančařík, 2022; Métioui et al., 2016), suggesting that traditional teaching approaches may not adequately support conceptual change.

In addressing these learning difficulties, the construct of mental models offers a valuable theoretical and methodological framework. Mental models are not static, they are dynamic cognitive representations that individuals construct based on a broad spectrum of factors, including prior knowledge, sensory input, and crucial instructional experiences (Holtrop et al., 2021; Körhasan, 2021; Körhasan et al., 2015). These models are dynamic, often partial or inconsistent, and serve as the basis through which learners interpret new information (van Ments & Treur, 2021). Investigating students' mental models thus provides deep insight into their conceptual structures, including both scientifically accurate understandings and persistent alternative conceptions (Conrad & and Libarkin, 2022). Unlike standardized assessments that capture only surface-level knowledge, mental model analysis enables researchers and educators to uncover how students visualize, reason about, and mentally simulate complex biological processes like photosynthesis, making it essential to explore how both internal and external factors influence their formation and transformation

Although extensive research has been conducted on misconceptions in photosynthesis (e.g (Lian & Peng, 2021; Lim & Poo, 2021; Machshunah & Yuliani, 2019) relatively few studies have examined how students construct and revise mental models of photosynthesis in context-rich, qualitative settings. Most existing studies rely heavily on quantitative instruments, such as multiple-choice tests, which often fail to capture the nuanced, dynamic, and evolving nature of students' cognitive representations. Moreover, detailed case-based investigations that trace the formation and transformation of mental models within authentic instructional contexts remain scarce. This gap is particularly significant given the complexity of the photosynthesis process, which involves intricate and multi-step biochemical mechanisms requiring both conceptual understanding and representational competence (de Freitas Zômpero & Laburú, 2016).

Acknowledging the limited number of detailed case-based investigations on the formation and transformation of mental models, this study adopts a qualitative case study approach to explore senior high school students' mental models of photosynthesis. This study utilizes a five-tier open-ended diagnostic test that integrates both levels of understanding and levels of visualization according to Kurnaz & Eksi (2015), offering a comprehensive lens to capture the structure and quality of students' mental models. This instrument allows for a deeper analysis of how students mentally construct, articulate, and depict their knowledge of light and dark reactions in real classroom settings, thereby responding to the critical need for richer, more explanatory research in science education. However, despite existing studies on students' misconceptions, few have qualitatively examined students' mental models using integrated conceptual and visual diagnostics. This study aims to fill that gap by exploring how senior high school students construct and represent their understanding of light and dark reactions in photosynthesis.

RESEARCH METHODS

This study employed a qualitative case study approach to explore senior high school students' mental models on the concept of photosynthesis. Case studies are a key component of qualitative descriptive research that emphasize deep observation and interpretation of a specific case within its real-life context (Morgan et al., 2016; Stephen et al., 2015). This method was selected because it enables researchers to investigate complex, tentative scientific understandings and uncover context-specific problems, particularly how students conceptualize abstract biological processes.

This study involved 27 senior high school students aged 16–18 years, all of whom were enrolled in the same public school located in Bandung, Indonesia. Participants were selected using purposive sampling based on their prior completion of the photosynthesis topic. A key characteristic of the participants' learning experience, which is particularly relevant to this study, is that the majority of them had never conducted laboratory experiments or practical work on photosynthesis. Their learning was primarily based on a teacher-centered approach, predominantly through one-way lectures. This specific learning background is crucial for understanding the formation of their mental models. The focused sample allowed for an in-depth observation and analysis of students' mental models through diagnostic tests, which were specifically designed to analyze the forms and structures of their mental models and to identify the level of misconceptions present. This approach, coupled with a consistent instructional background, ensures the comparability of their conceptual understanding. Ethical approval and informed consent were not required for this study, as it involved minimal risk and used data collected within regular classroom activities with full permission from the school administration. All participants were informed about the study's purpose and voluntarily agreed to participate.

To investigate students' mental models of photosynthesis, this study employed a five-tier open-ended diagnostic test designed to elicit students' conceptual understanding and reasoning regarding the light-reaction and darks-reaction reactions. The diagnostic test was developed based on the mental model framework proposed by Kurnaz & Eksi, (2015), which categorizes students' mental representations into three levels: initial, synthetic, and scientific. To establish inter-rater reliability, Data were analyzed using thematic content analysis. Student responseses were independently coded by two raters using the Kurnaz & Eksi (2015) framework. The level of agreement between the two coders was calculated using Cohen's Kappa (0.85). Any initial discrepancies were resolved through discussion until a consensus was reached, ensuring the consistency of the analytical process for the remaining data.

Each item in the instrument consisted of five tiers: (1) a content-based open-ended question assessing core conceptual understanding, (2) a confidence rating for the selected answer, (3) an open-ended justification probing students' reasoning, (4) a confidence rating for the justification, and (5) an open-ended drawing task to capture students' visual representations of the concept. The summary of the rubric of understanding and visualization are presented in Table 1, Table 2 and Table 3.

Table 1. Students' Level of Understanding (Tier 1-4)

Level of Understanding (LU)	**Level**	**Answer Criteria** **Tier-1**	**Tier-2**	**Tier-3**	**Tier-4**
Sound Understanding (SU)	4	True	Sure	True	Sure
Partial Understanding (PU)	3	True	Sure	True	Not Sure
		True	Not Sure	True	Sure
		True	Not Sure	True	Not Sure
		True	Sure	False	Sure
		True	Sure	False	Not Sure
		True	Not Sure	False	Sure
		True	Not Sure	False	Not Sure
		False	Sure	True	Sure
		False	Sure	True	Not Sure
		False	Not Sure	True	Sure
		False	Not Sure	True	Not Sure
Partial Understanding with	2	False	Sure	False	Not Sure
Alternative Conception (PU-AC)		False	Not Sure	False	Sure
Alternative Conception (AC)	1	False	Sure	False	Sure
No Understanding (NU)	0	False	Not Sure	False	Not Sure
		Blank Answer			

Table 2. Students' Level of Visualization (Tier 5)

Level of Visualization (LV)	**Level**	**Criteria**
Correct Depicting (CD)	4	Drawing reflects all components of scientific representation
Partial Correct Depicting (PCD)	3	Drawing reflects several components of scientific representation
Correct Drawings Reflecting Also Non-scientific Depicting (CD-ND)	2	Drawing reflects scientific or partially scientific representation but also includes non-scientific elements
Incorrect Depicting (ID)	1	Drawing reflects entirely non-scientific representation
No Depicting (ND)	0	No drawing provided

Following the in-depth analysis of students' conceptual understanding from Tiers 1-4 and their visualization abilities from Tier 5, the next crucial step in this case study is to integrate these two dimensions of data to holistically interpret students' mental models. The verbal and visual representations captured by our five-tier diagnostic instrument collectively provide comprehensive insights into students' internal cognitive structures concerning the concept of photosynthesis. Table 3 presents the synthesized interpretation of students' mental models, categorizing them based on the combined evidence from their conceptual understanding and visual depictions, according to the framework proposed by Kurnaz & Eksi, (2015).

Table 3. Students' Mental Model Categorization

Mental Model	***Content***	***Level of Understanding***
Scientific	Perceptions that are consistent with scientific knowledge: responses at Level 3 (PU or PCD) or Level 4 (SU or CD).	Combination of LU and LV between 3 and 4
Synthetic	Perceptions that are partially aligned or inconsistent with scientific knowledge. All mixed combinations other than those categorized as Scientific or Initial.	All other possible mixed combinations
Initial	Perceptions that are inconsistent with scientific knowledge: combinations of responses at Level 0 (NU or ND), Level 1 (AC or ID), or Level 2 (PU-AC or CD-ND).	Combination of LU and LV between 0, 1, and 2

RESEARCH RESULT

Students' Understanding Level

The distribution of students' levels of understanding of the photosynthesis topic, particularly between the light and dark reactions, reveals a varied yet concerning pattern of conceptual mastery. As depicted in **Figure 1**, the overall student understanding tends to be low, with a marked disparity in comprehension between the light and dark reactions. **Sound Understanding (SU)**, which represents students who correctly answered the diagnostic items, provided appropriate scientific reasoning, and demonstrated high confidence, was observed in only 22.2% of students for the light reaction and dropped significantly to 12.3% for the dark reaction. For instance, **Student 12** accurately detailed light reaction's water photolysis: *"Water will later be broken down by photons through the process of water photolysis, producing 2 hydrogen, 2 electrons, and oxygen. Electrons are used to create ATP, and hydrogen is used to produce NADPH. Meanwhile, oxygen is released into the water, forming oxygen bubbles."* Similarly, **Student 14** precisely articulated the dark reaction's dependence on light reaction products: *"The dark reaction will proceed using energy produced by the light reaction. If there is no light from the beginning, the light reaction will not occur, and ATP and NADPH, which are the energy used in the dark reaction, will not be formed."* These examples underscore the SU students' holistic conceptual integration, despite their low overall proportion.

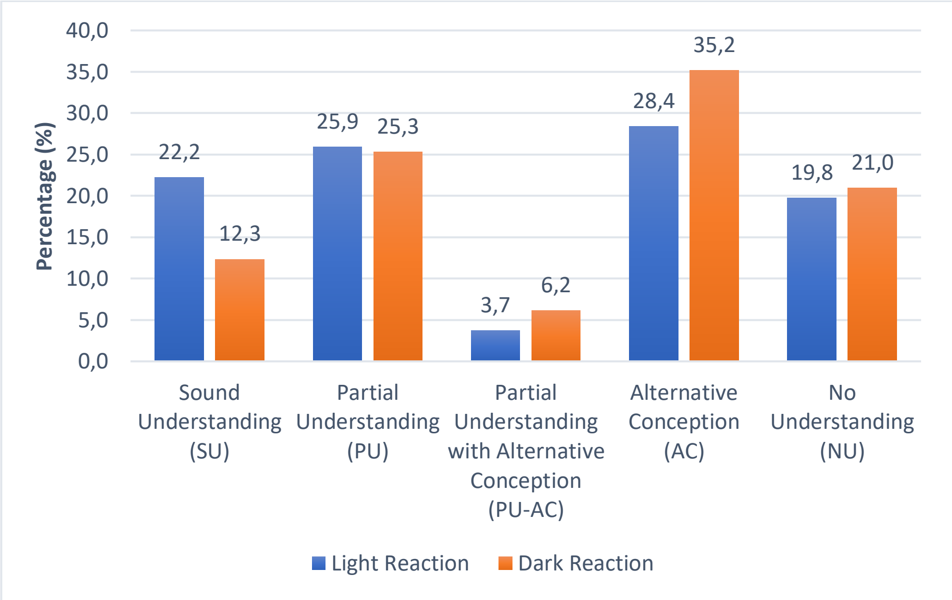

Figure 1. Distribution of Students' Level of Understanding

The **Partial Understanding (PU)** category where students selected correct answers but failed to justify their reasoning or expressed low confidence recorded the most balanced proportion between both reactions, at 25.9% (light) and 25.3% (dark). This suggests that a notable portion of students possess fragmented scientific knowledge that lacks full integration with coherent conceptual reasoning, reflecting superficial understanding not yet solidified into robust mental models. Meanwhile, **Partial Understanding with Alternative Conceptions (PU-AC)** was relatively low in both contexts 3.7% in the light reaction and 6.2% in the dark reaction indicating a smaller group of students transitioning between scientifically accepted ideas and entrenched misconceptions. It highlights students integrating some correct understanding with clear misconceptions, often stemming from faulty inferences. For instance, regarding adding baking soda ($NaHCO_3$) to the Ingenhousz experiment, **Student 18** provided a striking PU-AC response:*"When the plant is given baking soda, it will expand, and 'expand' here means oxygen. So, I assume more oxygen will appear because water mixed with baking soda will expand and produce oxygen."* This student failed to identify that the primary function of baking soda in the photosynthesis experiment was as a source of carbon dioxide (CO_2), which would increase the rate of photosynthesis (and therefore, the production of oxygen as a byproduct). Instead, Student 18 incorrectly inferred that "expanding" was a direct indicator of oxygen production, reflecting a partial understanding of oxygen as "bubbles" but with a completely non-scientific mechanism.

A more critical finding is observed in the **Alternative Conception (AC)** category. A substantial 28.4% of students in the light reaction and a markedly higher 35.2% in the dark reaction exhibited strong misconceptions. These students not only answered incorrectly but also reasoned incorrectly and did so with confidence, suggesting that these misconceptions are deeply rooted and possibly reinforced through prior instruction or everyday experiences. Several critical areas of alternative conception were identified, notably concerning the photolysis of water, the interconnection between light and dark reactions, photorespiration, and the unique mechanisms of C3, C4, and CAM plants. Regarding water photolysis, students exhibited fundamental misunderstandings. Student 9, for instance, articulated a misconcept that conflates water's role with carbon fixation and the Calvin cycle:*"the water obtained by the plant undergoes fixation, so after the Calvin cycle, Oxygen will be produced as the final product"*. This response erroneously suggests water undergoes fixation, a process typically associated with CO_2, and incorrectly places oxygen production as an outcome of the Calvin cycle, demonstrating a significant conceptual confusion between the roles of water and CO_2, and the distinct phases of photosynthesis. Another vivid example comes from Student 19, who simplified the process to mere evaporation: *"water exposed to sunlight will evaporate and produce oxygen"*. This misconceptualizes oxygen release as a physical process of evaporation rather than a biochemical breakdown of water molecules. The interconnection between light and dark reactions also proved to be a major source of AC. Student 18's response highlights a common misbelief about the dark reaction's independence:*"the dark reaction/Calvin cycle can produce starch without light but requires air/oxygen to carry out the dark reaction"*. This student correctly identifies the output (starch/amilum) but critically misunderstands the energy source, asserting independence from light while erroneously introducing atmospheric oxygen as a requirement for the Calvin cycle. This firmly held misconception about light-independence reinforces the challenge posed by the term "dark reaction" and the abstract nature of ATP/NADPH as energy carriers. Photorespiration concepts also revealed deep-seated ACs. Student 10's reasoning exemplifies a reversal of key understanding:*"high temperatures are not very good for plants because plants will find it difficult to absorb oxygen for photosynthesis"*. This student incorrectly believes oxygen is an *input* for photosynthesis, especially under high temperatures where photorespiration actually *consumes* oxygen and produces CO_2. This indicates a failure to differentiate between respiration and photosynthesis, and a lack of understanding of the detrimental effects of photorespiration.

Finally, C3, C4, and CAM plant mechanisms were widely misunderstood. The majority of students failed to correctly identify examples like rice (C3), corn (C4), and cactus (CAM) and more importantly, *the answers did not focus on the distinct photosynthetic mechanisms (i.e., carbon fixation pathways)*. Instead, their justifications gravitated towards superficial morphological or ecological adaptations:*"focused on thick leaves, coated with waxy substances, corn's better heat resistance than rice, and cacti having thorn-shaped leaves to reduce evaporation."*. This pattern reveals that while students might recognize some adaptive features, they fail to connect these features to the underlying biochemical strategies of carbon fixation. This indicates that their mental models of C3, C4, and CAM plants are primarily ecological/morphological, lacking a crucial biochemical understanding. The **No Understanding (NU)** category, comprising students who failed to answer correctly, could not provide any valid reasoning, and lacked confidence, accounted for 19.8% of responses in the light reaction and 21.0% in the dark reaction. These results reveal a significant proportion of students who are entirely disengaged from or unfamiliar with the core concepts, reinforcing the need for remediation efforts at the foundational level.

Students' Visualization Level

Based on the chart presented in **Figure 2**, which illustrates students' visualization levels on the photosynthesis topic assessed through Tier 5 of the diagnostic test, it is evident that most students exhibit significant difficulty in scientifically depicting the processes of light and dark reactions. The findings indicate a dominant presence of non-scientific mental images, suggesting substantial gaps in students' internal representations of the photosynthesis process, especially in translating abstract biochemical phenomena into coherent visual models.

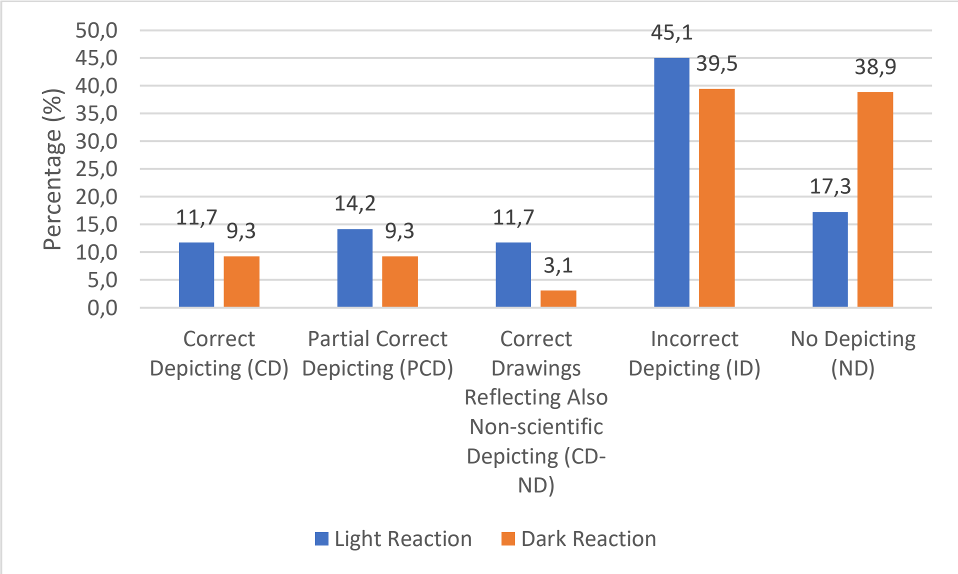

Figure 2. Distribution of Students' Level of Visualization

The most striking result is the high percentage of **Incorrect Depicting (ID)** responses: 45.1% for the light reaction and 39.5% for the dark reaction. These figures imply that nearly half of the students failed to create scientifically meaningful illustrations and instead produced drawings that were irrelevant, conceptually flawed, or based on incorrect interpretations. This trend reflects the lack of accurate mental models, particularly for the light reaction which, despite being more observable and frequently supported by visual aids in textbooks and media, remains challenging for students to represent correctly. One possible reason is the inherent complexity of the light reaction, which includes multiple sub-processes such as the role of light energy and chlorophyll, the photolysis of water, ATP and NADPH production, and electron transport across the thylakoid membrane. Although these processes are central to energy conversion in photosynthesis, they occur at the molecular level and are not directly visible, making them difficult for students to visualize in an integrated and scientifically accurate manner.

Similarly concerning is the **No Depicting (ND)** category, where 17.3% of students failed to illustrate anything for the light reaction, and this percentage increased dramatically to 38.9% for the dark reaction. The high incidence of non-responses in the dark reaction underscores the abstractness of the Calvin cycle, which lacks direct sensory referents such as light or pigment activity. Students may struggle to visualize how carbon dioxide is fixed, or how ATP and NADPH from the light reaction are utilized in the biochemical synthesis of glucose. Moreover, the dark reaction's abstract interdependency with the light reaction is rarely made explicit in traditional instruction, and the added complexity of processes such as photorespiration and adaptive mechanisms in C3, C4, and CAM plants introduces further cognitive overload.

In contrast, only 11.7% (light reaction) and 9.3% (dark reaction) of students achieved the **Correct Depicting (CD)** level, indicating full alignment with scientific expectations in their drawings. These students successfully visualized essential components and relationships, such as the location and sequence of processes within chloroplast compartments. The **Partial Correct Depicting (PCD)** category, with 14.2% for the light reaction and 9.3% for the dark reaction, suggests some students understood isolated components but lacked the ability to connect them meaningfully, indicating a fragmented or incomplete mental model. The **Correct Drawings Reflecting Also Non-scientific Depicting (CD-ND)** category, comprising 11.7% (light reaction) and 3.1% (dark reaction), reflects transitional thinking, where students attempted to represent scientific elements but were influenced by persistent misconceptions, such as misplacing organelles or oversimplifying reaction pathways.

Students' Mental Model

Based on the graph presented in **Figure 3**, the mental models of senior high school students regarding the photosynthesis process particularly the light and dark reactions were categorized into three distinct types: scientific, synthetic, and initial, derived from a combination of their conceptual understanding (Tiers 1–4) and visualization ability (Tier 5). The results show a predominance of non-scientific mental models, revealing critical gaps in students' internal representations of photosynthesis mechanisms.

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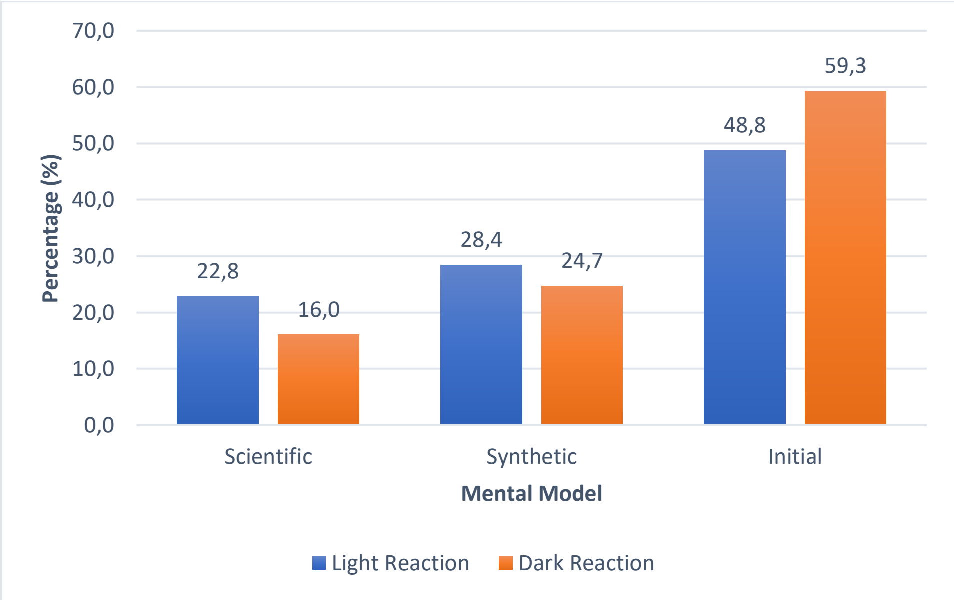

Figure 3. Distribution of Students' Mental Model

The scientific mental model, which reflects students who demonstrated both a sound understanding and accurate scientific visualization, was adopted by only 22.8% of students for the light reaction and dropped further to 16.0% for the dark reaction. These relatively low percentages suggest that few students possess a comprehensive and coherent understanding of the two stages of photosynthesis. The dark reaction, in particular, is poorly represented, likely due to its abstract biochemical nature and students' limited exposure to effective instructional visualization tools for this concept. The synthetic mental model, representing students with partially integrated scientific and non-scientific conceptions (e.g., accurate answers but flawed reasoning or visuals), was seen in 28.4% of students for the light reaction and 24.7% for the dark reaction. These students appear to be in a transitional cognitive state, holding fragmented knowledge that may be shaped by prior misconceptions or instruction lacking clarity. While they show some grasp of key ideas, these ideas are not fully or consistently aligned with scientific representations.

Most concerning is the initial mental model, which reflects students who lack both scientific understanding and the ability to visually represent the process. This model was dominant among respondents, accounting for 48.8% of students for the light reaction and a striking 59.3% for the dark reaction. These findings suggest that more than half of the students failed to internalize fundamental principles of photosynthesis, especially for the dark reaction. Their conceptions remain at a rudimentary level, likely relying on everyday experiences or incorrect prior knowledge, rather than scientific reasoning.

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DISCUSSION

The findings of this study reveal a significant challenge in senior high school students' comprehension of photosynthesis, particularly concerning the abstract nature of the dark reactions. The stark decline in conceptual clarity observed from light-dependent to light-independent reactions indicates that the intricate biochemical cycles occurring independently of light pose considerable cognitive hurdles for students. This result aligns with various studies that consistently report student difficulties with these complex biological concepts, especially the dark reaction of photosynthesis (e.g., Vančugovienė et al., 2023). Students, despite providing seemingly correct explanations, often exhibit fragmented knowledge, indicating a superficial grasp rather than a deep, integrated understanding. Unlike previous studies that often rely on a single method, this research contributes significantly to the field by utilizing a open ended five-tier diagnostic tool. This method not only identifies the presence of misconceptions but also provides a robust framework to precisely characterize the forms of students' mental models, ranging from scientifically accurate to fragmented. This nuanced approach offers a deeper insight into the conceptual structures that underpin students' thinking, a level of detail not typically captured by traditional assessments.

This fragmented knowledge is particularly evident in complex topics like light-matter interactions, where students may rely on intuitive reasoning rather than coordinated scientific explanations (Balabanoff et al., 2020). Research on students' misconceptions in science education further corroborates these observations, highlighting that learners frequently hold alternative conceptions that directly conflict with scientifically accepted understanding (Vosniadou, 2020; Wenning & Vieyra, 2020). These misconceptions can be remarkably resistant to change and vary in consistency, often persisting despite conventional instruction. Studies have identified different levels of conceptual understanding, ranging from full scientific understanding to various misconceptions (Didik et al., 2020; Teig et al., 2020; Vančugovienė et al., 2024), underscoring the pervasive nature of these learning difficulties. These level profiles are influenced by factors such as grade level, academic achievement, and epistemic beliefs (Vančugovienė et al., 2024).

Taken together, the dominance of lower-level categories (Partial Understanding with Alternative Conception, Alternative Conception, and No Understanding), especially in the dark reaction component, indicates that current instructional strategies may be insufficient for promoting deep conceptual understanding. The inclusion of complex sub-concepts such as photorespiration, carbon-concentrating mechanisms, and biochemical differentiation among plant types requires greater scaffolding and more nuanced pedagogical approaches. These findings highlight the urgent need for diagnostic-driven pedagogical interventions that specifically focus on reconstructing students' mental models through the judicious use of visual representations, simulations, and multi-representation learning experiences. Furthermore, the effectiveness of multi-tier open-ended diagnostic instruments, as applied in this study, provides valuable insights into students' reasoning processes and levels of conceptual integration, enabling more precise and targeted remediation to address both fragmented knowledge and entrenched misconceptions (Ahzari & Fitri, 2025; Nurahman & Susantini, 2022; Triani & Fahlani, 2024).

The findings on Students' Visualization Level demonstrate that students' visualization skills an essential dimension of mental model construction in biology are generally weak, especially when faced with the abstract and systemic nature of the dark reaction. The significant proportion of students in the Incorrect Depicting and No Depicting categories indicates not only limited conceptual understanding but also difficulties in translating verbal or textual knowledge into spatial and symbolic representations. The Tier 5 diagnostic test, by prompting students to express their understanding through drawings, proves instrumental in capturing students' internalized comprehension beyond verbal reasoning, exposing conceptual gaps that might remain hidden in conventional assessments. Research on students' mental models in science education reveals challenges in conceptualizing complex phenomena. Studies have examined mental models of the greenhouse effect (Liu, 2021), chemistry concepts (Wardah & Wiyarsi, 2020), and quantum physics (Ubben & Bitzenbauer, 2022). These investigations employed various methods, including analyzing student-generated drawings and factor analysis, to uncover underlying mental structures. Findings suggest that students often struggle to form accurate mental models, particularly for abstract concepts. The research highlights the importance of exploring mental models to improve science education. Understanding and addressing students' mental models is crucial for enhancing science learning and developing effective instructional strategies (Ubben & Bitzenbauer, 2022).

The analysis identified three main types of mental models: scientific, transitional, and fragmentary/initial. This classification is crucial because it demonstrates that misconceptions do not exist in isolation but are an integral part of students' thinking structures. Fragmentary mental models, the most prevalent among participants, are characterized by profound misconceptions and a lack of logical connections between concepts. This highlights that the primary problem is not a lack of information, but rather students' inability to organize that information into a coherent whole. The most compelling aspect of our discussion concerns the influence of students' learning backgrounds and instructional experiences on the formation of these mental models. The majority of our participants, having never conducted practical experiments and relying primarily on one-way lectures, showed a strong tendency toward fragmented mental models. This suggests that a passive, teacher-centered approach to learning, which lacks direct engagement with biological phenomena, is a crucial external factor in the development of these poor cognitive structures. Students failed to visualize and connect the light and dark reactions because they lacked firsthand experience with the processes. This highlights that effective learning requires active engagement that goes beyond rote memorization, especially for complex and highly visual topics like photosynthesis.

A significant contributing factor to these low understanding levels and prevalent misconceptions, especially within the context of this case study involving students from a specific public school in Bandung, appears to be the predominant reliance on traditional pedagogical approaches. Observations and common teaching practices in the Indonesian education system often involve teachers primarily employing didactic methods, with limited or no visual aids, hands-on practicum, or interactive learning experiences. Instead, instruction frequently leans heavily on textbook content, which may present complex biochemical cycles without adequate contextualization and multi-representation engagement. This teacher-centric approach, devoid of opportunities for visualization and practical application, fundamentally restricts students' ability to construct robust and accurate mental models of abstract biological processes like photosynthesis. Without the experiential and visual scaffolding provided by practical work, simulations, or diverse teaching methods, students struggle to move beyond superficial memorization, leading directly to fragmented knowledge and deeply entrenched misconceptions that are evident in their low understanding levels across all tiers of the diagnostic test.

Furthermore, students' limited exposure to representational learning approaches emerges as another critical contributing factor. For most participants in this study, being asked to visualize mental models as part of a five-tier diagnostic assessment was a novel experience. Discussions with classroom teachers revealed that this lack of prior engagement with representational strategies, such as diagramming or model-based explanations, acted as a major barrier, inhibiting students from producing coherent and scientifically structured drawings. This aligns with broader research indicating that students often struggle with representational strategies in science learning, particularly drawing and diagramming (Park et al., 2020; Uchinokura, 2020). However, studies also demonstrate that explicit instruction in drawing significantly improves students' ability to create accurate diagrams and construct scientific explanations (De Andrade et al., 2020; Wilson & Bradbury, 2021). This collective body of research emphasizes the importance of incorporating explicit instruction in representational practices within science curricula to enhance students' engagement, understanding, and communication of scientific concepts.

Overall, the data unequivocally highlight a critical gap in students' ability to construct and coordinate conceptual and visual knowledge of photosynthesis. The prevalence of synthetic and initial mental models indicates that current instructional approaches may be insufficient in fostering deep learning and scientific model-building. Unlike prior studies relying solely on multiple-choice diagnostics, this study provides a richer, integrated perspective of students' conceptual and visual understanding, offering a significant methodological contribution to biology education research. Educators should consider incorporating explicit model-based instruction, scaffolded visual tools, and iterative formative assessment strategies to promote the development of more scientific and coherent mental models. In particular, emphasis should be placed on helping students visualize and conceptualize the abstract components of the dark reaction, which are often neglected or poorly explained in conventional biology classrooms. Future research could explore the long-term effectiveness of such interventions and their impact on reducing specific misconceptions identified in this study.

CONCLUSION

This study reveals that a majority of students hold fragmented or non-scientific mental models of photosynthesis. Findings reveal that most students exhibited initial-level mental models, with 48.8% and 59.3% of students demonstrating low conceptual and visual understanding. These findings call for the integration of model-based teaching strategies and visual learning tools in biology classrooms. Although limited to a sample of 27 students and not generalizable, the study offers meaningful insights for biology educators to improve instructional design. While limited in sample size and context, this study provides a foundation for future intervention research aimed at improving scientific mental modeling in secondary education.

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