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Enhancing Conceptual Understanding of Photosynthesis through Integrated 5E Inquiry-Based and Cooperative STAD Learning: A Case Study in Thailand

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Abstract. Photosynthesis is widely regarded as a conceptually complex topic in biology that many students find difficult to understand. Nonetheless, there has been limited research to explore how inquiry-based and cooperative learning can be systematically integrated to support students' understanding. This study aimed to investigate the effects of an integrated 5E inquiry-based learning model and Student Teams Achievement Divisions (STAD) cooperative learning approach on students' conceptual understanding of photosynthesis, cooperative learning behaviors, and learning satisfaction. A one-group pretest–posttest quasi-experimental design was employed with 62 Grade 11 students at a public secondary school in Thailand. The intervention was implemented over eight instructional hours. Research instruments included a Photosynthesis Conceptual Understanding Test, a cooperative learning behavior observation rubric, and a learning satisfaction questionnaire. Data were analyzed using paired-sample t-tests, effect size (Cohen's d), normalized gain (g), and descriptive statistics. The results showed a significant improvement in conceptual understanding, with a very large effect size ($d = 1.88$) and a medium-to-high normalized gain ($g = 0.62$). Students also presented high levels of cooperative learning behaviors and very high learning satisfaction. The results indicate that embedding STAD within the 5E inquiry cycle can potentially support both cognitive and social dimensions of learning as well as provide a practical framework for teaching complex biological concepts. This research supports SDG 4 (Quality Education) and SDG 13 (Climate Action) by promoting effective, student-centered learning through inquiry and cooperation, while enhancing students' understanding of photosynthesis and its role in climate change, and developing the skills needed to address future sustainability challenges.

Keywords: Cooperative learning; 5E model; Inquiry-based learning; Photosynthesis; STAD

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INTRODUCTION

Photosynthesis is a fundamental concept in biology, describing the basic biochemical processes of producers that create the primary products of ecosystems. It is widely recognized as a key concept, playing a vital role in helping students connect broader biological concepts such as cellular energy, matter cycles, ecosystem products, and global carbon balance (Mostan, 2024; Page & Parry, 2025). Therefore, a correct and clear understanding of photosynthesis is necessary for students' comprehension of important current social and scientific issues, including climate change mitigation, sustainable agriculture, and ecosystem resilience (Baslam et al., 2020).

Despite its importance, students often experience difficulties in learning and understanding photosynthesis conceptually rather than procedurally at both secondary and early tertiary levels (Aprianti et al., 2025; Lim & Poo, 2021). Most students can memorize basic equations or reactions, but fail to explain causal relationships between light absorption, electron transport, ATP and NADPH synthesis, and carbon fixation. This reflects difficulties in incorporating scientific ideas at various organizational levels (Scott et al., 2018). Moreover, photosynthesis is particularly challenging because it requires connecting ideas of molecular processes with organelle functions and system-level outcomes (Bilbis et al., 2026). Common misconceptions such as confusing photosynthesis with respiration or misunderstanding the origin of plant biomass tend to persist after instruction (Aprianti et al., 2025; Lim & Poo, 2021).

To address these challenges, inquiry-based learning (IBL) has been widely recommended. IBL promotes active knowledge construction through questioning and exploration, and its effectiveness has been supported by recent studies (Öztürk et al., 2022; Sam, 2024). The 5E instructional model (Engage, Explore, Explain, Elaborate, and Evaluate) is a well-established IBL framework that supports conceptual change and has shown better outcomes than traditional teaching (Joswick & Hulings, 2024; Rosadi et al., 2018). The model has been shown to improve students' scientific reasoning and problem-solving abilities in biology instruction (Susilowati & Anam, 2017). There is also evidence that guided inquiry within the 5E framework is more effective than minimally guided approaches for teaching complex scientific topics (Lazonder & Harmsen, 2016).

Although inquiry-based learning can enhance cognitive engagement, it does not ensure effective peer interaction. Cooperative learning—especially Student Teams Achievement Divisions (STAD)—can enhance achievement, motivation, and collaboration in biology classes (Chophel et al., 2023; Togatorop & Dito, 2023). This learning technique emphasizes group heterogeneity, individual accountability, and peer explanation, which help students articulate reasoning, address misconceptions, and build common understanding (Puspitasari & Fatikhah, 2023). The integration of inquiry and cooperative learning is supported by social constructivist theory, originally proposed by Vygotsky, and by the ICAP framework, which highlights the importance of interactive engagement for deeper learning (Chi et al., 2018; Gillies, 2020; Siew & Chai, 2024). Additional studies with combined approaches have reported improvements in academic achievement, communication skills, teamwork, and student engagement (Bunpradit et al., 2026; Pholphuet et al., 2018).

While both approaches are effective, they have typically been studied separately. Studies on the 5E model tend to focus on learning outcomes without exploring how structured peer interaction affects conceptual development (Joswick & Hulings, 2024). On the contrary, STAD-focused research frequently reports achievement gains without analyzing how cooperative mechanisms function within specific phases of inquiry (Chophel et al., 2023; Puspitasari & Fatikhah, 2023). As a result, there is limited empirical evidence on how STAD can be systematically integrated into the 5E inquiry cycle to improve conceptual understanding of photosynthesis. This gap is especially clear in real classroom settings that use practical quasi-experimental designs, which are common in school-based research but less represented in international literature.

Due to limited empirical evidence on how STAD can be systematically embedded within the 5E inquiry model to enhance conceptual understanding of photosynthesis, particularly in authentic classroom settings, addressing this gap is important for improving both classroom practice and scientific literacy. Therefore, this study proposes an integrated instructional framework in which the 5E inquiry-based model provides the cognitive learning sequence, while STAD functions as a cooperative mechanism intentionally embedded within the Explore, Explain, and Elaborate phases. This integration is designed as a unified approach rather than a simple combination of methods. It aims to support conceptual understanding, cooperative learning behaviors, and students' overall learning experience in photosynthesis. The objectives of this study are 1) to examine changes in students' conceptual understanding of photosynthesis following instruction using an integrated 5E inquiry-based and STAD cooperative approach, 2) to investigate students' cooperative learning behaviors during inquiry-based activities supported by STAD, and 3) to explore students' learning satisfaction with the integrated 5E–STAD instructional model.

METHODS

Research Design

This study employed a one-group pretest–posttest quasi-experimental design to examine changes in students' learning outcomes following an instructional intervention. This design was chosen due to practical constraints in real classroom settings, where random assignment or the use of control groups is often not possible. The one-group pretest–posttest design allows researchers to closely examine instructional effectiveness within a single group of students while maintaining ecological validity in a real classroom environment. Although such designs have inherent methodological limitations, they are frequently employed in classroom-based educational research to explore instructional innovations implemented under authentic conditions (Cohen et al., 2018). Accordingly, this design was considered appropriate for the present study, as the primary purpose was exploratory—

to investigate the effectiveness of an integrated inquiry-based and cooperative instructional approach—while ensuring instructional equity for all participating students.

Participants

Participants were 62 Grade 11 students (aged 16–17) enrolled in a biology course during the 2025 academic year at a public secondary school in northern Thailand. All students participated in the study as part of regular classroom instruction. Participants had prior exposure to basic biological concepts but had not received formal instruction on photosynthesis at the time of data collection.

Conceptual Framework of the Integrated 5E Inquiry-Based and STAD Learning

The conceptual framework of this study integrates the 5E inquiry-based learning model with the Student Teams Achievement Divisions (STAD) cooperative learning strategy to address both cognitive and social dimensions of learning (Figure 1). In this framework, the 5E model serves as the cognitive learning sequence (Polanin et al., 2024) guiding students through progressive stages of conceptual construction, while STAD functions as a structured social mechanism that supports peer interaction, shared meaning-making, and cooperative engagement (Togatorop & Dito, 2023).

In the 5E instructional model, the Engage phase aims to activate students' prior knowledge and stimulate curiosity, mainly through individual or whole-class activities. STAD cooperative structures are intentionally integrated into the Explore, Explain, and Elaborate phases. During these stages, students work in heterogeneous teams to carry out inquiry tasks, share ideas, explain their thinking, and apply concepts to new situations, which are key characteristics of inquiry-based and cooperative learning environments (Shengqiang et al., 2025). In the Evaluate phase, both individual assessment and team-based improvement scores are used. This approach maintains individual accountability while also strengthening positive interdependence among students, both of which are essential elements of effective cooperative learning (Gillies, 2016). Through this integrated design, learning is seen as a combination of inquiry-driven cognitive processes and cooperative social interaction. This combination is expected to improve conceptual understanding, strengthen cooperative learning behaviors, and increase students' learning satisfaction.

Based on this framework, the study focused on three types of learning outcomes: conceptual understanding, cooperative learning behaviors, and learning satisfaction. These outcomes were aligned with the research instruments used in the study.

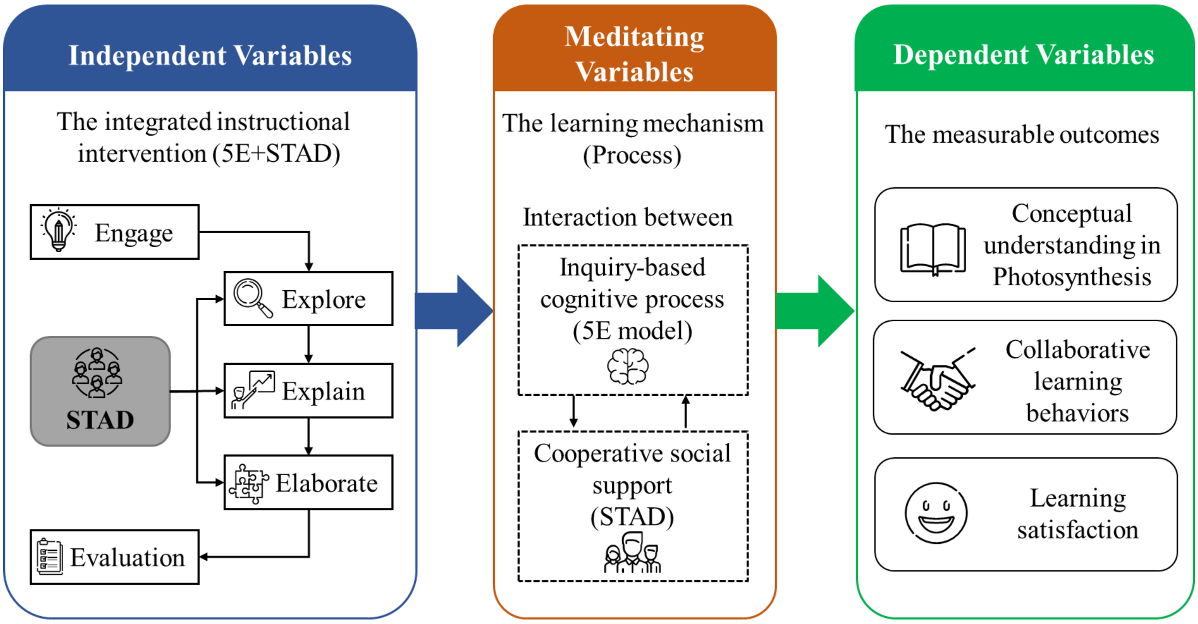

Figure 1. Conceptual framework of 5E-STAD integration

Table 1. Eight-hour instructional plan based on the integrated 5E inquiry-based and STAD cooperative learning model

Hour	5E Phase	Core Content	Learning Activities	STAD Integration
1	Engage	Overview & importance of photosynthesis	Eliciting prior knowledge; analyzing images/videos; questioning	No STAD (whole class)
2	Explore	Light-dependent reactions	Inquiry activity on light reactions; group discussion	STAD group inquiry and peer explanation
3	Explain	Mechanism of light-dependent reactions	Group explanation and teacher clarification	STAD peer tutoring and individual accountability
4	Explore	Calvin cycle	Problem-based inquiry on CO_2 and NADPH	STAD cooperative problem solving
5	Explain	Connection between light reactions and the Calvin cycle	Conceptual discussion and teacher synthesis	STAD team discussion
6	Elaborate	C3, C4, CAM adaptations	Case study analysis and comparison	STAD cooperative product
7	Elaborate	Application of photosynthesis concepts	Solving applied problems and presentations	STAD shared responsibility
8	Evaluate	Overall synthesis and reflection	Posttest and learning reflection	Individual score contributes to the team score

Instructional Intervention

The instructional intervention consisted of eight hours of instruction on photosynthesis. The 5E inquiry-based instructional model was used to develop the lessons (Joswick & Hulings, 2024). STAD cooperative learning was incorporated during the Explore, Explain, and Elaborate phases of instruction. Students were grouped into heterogeneous teams of four to five members based on prior academic achievement, following recommended practices in cooperative learning (Gillies, 2016). Instructional activities included inquiry tasks, peer discussion, and cooperative problem solving related to light-dependent reactions, the Calvin cycle, and photosynthetic adaptations in C3, C4, and CAM plants. Table 1 summarizes the eight-hour instructional plan and the relationship between the 5E inquiry phases, photosynthesis content, classroom learning activities, and the integration of STAD cooperative learning structures.

Research Instruments

Photosynthesis Conceptual Understanding Test (PCUT)

The Photosynthesis Conceptual Understanding Test (PCUT) was developed to assess students' conceptual understanding of photosynthesis, emphasizing causal relationships, process integration, and application of knowledge rather than factual recall (Scott et al., 2018). The instrument consists of 20 items covering key content areas, including light-dependent reactions, the Calvin cycle, and photosynthetic adaptations in C3, C4, and CAM plants. As presented in Table 2, the items were distributed across major conceptual focuses to ensure balanced coverage of fundamental processes, interconnections between photosynthetic stages, and reasoning in novel or context-based situations.

Each item was designed to elicit students' explanations of how and why changes in internal processes or environmental conditions influence photosynthesis, thereby capturing deeper levels of conceptual understanding aligned with inquiry-based learning principles. Content validity was established through expert review by three specialists, yielding Index of Item-Objective Congruence (IOC) values ranging from 0.67 to 1.00. The internal consistency reliability of the PCUT, calculated using the KR-20 coefficient based on data from the main study, was 0.82, indicating acceptable reliability for measuring students' conceptual understanding of photosynthesis.

Table 2. Example structure and sample items of the Photosynthesis Conceptual Understanding Test

Conceptual focus/ learning objective	Sample conceptual test item	Weight/ proportion
Role of light-dependent reactions	A plant is exposed to high light intensity but water availability becomes limited. How would this condition affect the light-dependent reactions of photosynthesis, and why?	20% (4 items)
Relationship between light-dependent reactions and the Calvin cycle	If the production of NADPH during the light-dependent reactions decreases, how would this affect carbon fixation in the Calvin cycle?	25% (5 items)
Role of CO_2 in photosynthesis	Why does increasing the concentration of carbon dioxide enhance the rate of photosynthesis only up to a certain point?	15% (3 items)
Comparison of C3, C4, and CAM plants	Why are C4 and CAM plants more effective than C3 plants in minimizing photorespiration under high-temperature conditions?	20% (4 items)
Application of photosynthesis concepts to new contexts	If a CAM plant is transferred to an environment with abundant water and low temperature, how might its stomatal behavior and carbon fixation process change?	20% (4 items)
Overall assessment of conceptual understanding across all domains		100% (20 items)

Group Cooperation Observation Rubric

A five-dimensional observation rubric was used to assess students' cooperative learning behaviors, comprising participation, idea exchange, shared responsibility, peer support, and group presentation. Inter-rater reliability was examined through independent scoring by two observers, yielding a satisfactory intraclass correlation coefficient (ICC = 0.86). Classroom observations were conducted during the Explore, Explain, and Elaborate phases of each instructional session across the eight-hour intervention. The two observers recorded students' cooperative behaviors at regular intervals throughout these phases to ensure consistency and comprehensive coverage of group interactions.

Learning Satisfaction Questionnaire

A 10-item Likert-scale questionnaire was used to examine students' satisfaction with instructional activities and the learning environment. The questionnaire demonstrated good internal consistency (Cronbach's alpha = 0.89).

Pilot Testing of Research Instruments

Prior to the main implementation, all research instruments were pilot tested with 28 Grade 11 students from a comparable public secondary school who were not included in the main study. The purpose of the pilot testing was to examine item clarity, item quality, and the reliability of the instruments.

For the PCUT, item difficulty indices (p) ranged from 0.42 to 0.78, and discrimination indices (r) ranged from 0.31 to 0.62. Items that did not meet acceptable criteria were revised before final administration. The observation rubric and learning satisfaction questionnaire also demonstrated satisfactory reliability during pilot testing, supporting their use in the main study.

Data Analysis

Data were analyzed using paired-sample t-tests to examine differences between pretest and posttest scores. Effect size (Cohen's d) and normalized gain (Hake's g) were calculated to assess the magnitude of learning improvement. Descriptive statistics (mean and standard deviation) were used to summarize cooperative learning behaviors and students' learning satisfaction. Prior to inferential analysis, assumptions for parametric testing, including normality of score distribution, were examined to ensure the appropriateness of the statistical procedures. In addition, the interpretation of effectiveness was based not only on statistical significance (p-values) but also on the magnitude of effect sizes and normalized gain, allowing for a more comprehensive evaluation of instructional impact. Given the one-group pretest–posttest design, the analysis emphasizes within-group improvement trends rather than causal comparison, and the results are interpreted as indicative of instructional potential under authentic classroom conditions.

RESULTS AND DISCUSSION

Conceptual Understanding of Photosynthesis

Students demonstrated substantial improvement in conceptual understanding following the integrated 5E inquiry-based and STAD cooperative instruction. As shown in Table 3, posttest scores (M = 16.84, SD = 2.31) were significantly higher than pretest scores (M = 9.21, SD = 2.75), $t(61) = 14.82$, $p < .001$, with a very large effect size (Cohen's d = 1.88). The normalized gain (Hake's g) of 0.62 further indicates a medium-to-high level of instructional effectiveness for a conceptually demanding topic.

Table 3. Descriptive statistics and inferential analysis comparing pretest and posttest scores on the Photosynthesis Conceptual Understanding Test (PCUT)

Test	Mean	SD	t	Effect size (d)
Pretest	9.21	2.75		
Posttest	16.84	2.31	14.82**	1.88

**p<.001

The significant improvement in students' conceptual understanding aligns with contemporary research demonstrating the effectiveness of the 5E inquiry-based instructional model in biology and science education contexts. Recent studies indicate that the 5E model supports conceptual change by engaging students in a structured cycle of exploration, explanation, and application, thereby facilitating deeper understanding of abstract scientific concepts (Balta & Sarac, 2016; Joswick & Hulings, 2024; Negerie et al., 2026). In the present study, students not only participated in inquiry activities but were also guided to construct explanations and apply their understanding across multiple representations of photosynthesis—an essential process for overcoming persistent misconceptions in this domain.

The magnitude of the observed learning gains, however, is larger than those reported in many studies employing inquiry-based learning alone. One explanation could be the planned use of structured cooperative learning, using the STAD model, in critical inquiry stages. Recent research on cooperative learning shows that STAD can improve students' conceptual understanding through peer explanation, individual accountability, and positive interdependence, especially in science classes with students who possess heterogeneous ability levels (Chophel et al., 2023; Puspitasari & Fatikhah, 2023). These mechanisms likely contributed to the cognitive benefits of inquiry-based learning found in this study.

During the Explore and Explain phases of the 5E learning cycle, students participated in small-group discussions that required them to articulate reasoning, evaluate peers' explanations, and negotiate alternative conceptions of photosynthesis processes. Such dialogic interactions are known to promote deeper conceptual understanding by making students' thinking explicit and encouraging metacognitive reflection (Chi et al., 2018; Gillies, 2016). These peer-mediated explanations are especially useful for abstract biochemical processes such as the light-dependent reactions and carbon fixation, because they help learners connect molecular-level mechanisms to system-level outcomes.

The medium-to-high normalized gain (g = 0.62) further validates the effectiveness of integrating inquiry-based instruction with structured cooperative learning. Previous research has indicated that inquiry-based learning environments are more effective in promoting conceptual change when combined with well-designed peer interactions than when these approaches are used in isolation (Morris, 2025; Siew & Chai, 2024). The cooperative inquiry approach is more likely to make conflicting ideas explicit and facilitate their resolution through social negotiation and revision, rather than allowing them to remain unchallenged.

In contrast, previous research has suggested smaller gains when cooperative learning or inquiry-based strategies were used alone or with minimal instructional support. Studies indicate that loosely structured peer interaction may result in uneven participation or superficial discussion, thus limiting conceptual gains (Gillies, 2016; Lazonder & Harmsen, 2016). The stronger results in the present study can be attributed to the intentional integration of STAD within specific phases of inquiry. This ensured that cooperation contributed directly to cognitive processes, which are central to conceptual understanding, rather than functioning as a parallel activity.

Overall, these findings indicate that the integration of the 5E inquiry-based learning model and STAD cooperative structures fosters a synergistic instructional environment that promotes both cognitive engagement and social interaction. The results further suggest that the combined approach has promising potential but should not be interpreted as conclusive evidence that it is superior to other approaches. Instead, the results offer empirical support for instructional designs that intentionally combine inquiry-driven learning processes with structured cooperative mechanisms for addressing the conceptual complexity of photosynthesis in biology education.

Cooperative Learning Behaviors

Observational data indicated a consistently high level of cooperative learning behaviors during inquiry activities (Table 4), with an overall mean score of 4.18 (SD = 0.56). Among the observed dimensions, idea exchange and discussion received the highest ratings, followed by active participation and peer support.

Table 4. Mean scores and standard deviations across five behavioral dimensions

Behavioral dimension	Mean	SD
Active participation	4.22	0.61
Idea exchange and discussion	4.31	0.58
Shared responsibility	4.10	0.55
Peer support	4.19	0.57
Group presentation	4.08	0.61

The high levels of observed cooperative behaviors are consistent with research on cooperative learning, which emphasizes the importance of positive interdependence and individual accountability as conditions for productive cooperation. Recent reviews suggest that students are more likely to engage in sustained and meaningful peer interaction, rather than superficial group work, when the roles, responsibilities, and shared goals of cooperative structures are well defined (Gillies, 2016). This study indicated that the STAD structure effectively facilitated these conditions, as evidenced by frequent peer explanation, questioning, and reciprocal idea exchange among group members.

These interaction patterns suggest that students were involved in socially mediated learning processes that helped understanding through dialogue and peer support. Current socio-cultural perspectives on learning suggest that such dialogue allows students to be in zones of productive struggle where concepts are developed through cooperative reasoning and feedback, not just direct instruction (Daniels, 2016; Gillies, 2020). The prominence of peer support and shared responsibility identified in this study suggests that cooperative learning was a mechanism for scaffolding understanding during inquiry activities.

The findings also align with recent uses of the ICAP framework, which argues that interactive engagement, involving reciprocal dialogue and co-construction of meaning, leads to deeper learning than either active or passive engagement alone (Chi et al., 2018). In this study, cooperative behaviors are not just about organization or tasks. Students used discussion to explain their reasoning, question assumptions, and improve their conceptual understanding through shared sense-making. Such cognitively oriented interaction is particularly important for learning abstract biological processes, such as photosynthetic pathways, that require integration of multiple representations and causal relationships. These findings are further supported by recent empirical research in science education, which demonstrates that structured peer interaction can promote conceptual transformation through cooperative reasoning and dialogue (Michelsen & Groß, 2025). Such evidence suggests that, when students engage in sustained idea exchange and co-construction of meaning, their learning processes align with the interactive level of engagement described in the ICAP framework. Therefore, the high scores observed in idea exchange and discussion in the present study may reflect the successful activation of interactive cognitive engagement facilitated by the STAD structure.

Furthermore, the groups' consistently high levels of cooperative engagement align with recent classroom inquiry research that has shown the beneficial effects of structured cooperative learning models on cognitive engagement and social regulation in inquiry-based science lessons (Gillies, 2016; Siew & Chai, 2024). Loosely organized group work is less effective than cooperative designs that include explicit accountability mechanisms for sustaining equitable participation and preventing social loafing or disengagement.

Notably, whereas some recent studies have reported persistent challenges in group work—such as dominance by higher-achieving students or uneven contribution—the structured nature of STAD may have mitigated these issues by emphasizing team responsibility and improvement-based scoring (Chophel et al., 2023). This structural feature likely contributed to the uniformly high behavioral ratings observed across groups, supporting the effectiveness of STAD in fostering inclusive, balanced, and cognitively productive cooperative learning environments within inquiry-based biology instruction.

Learning Satisfaction

Students reported a very high level of learning satisfaction with the integrated 5E inquiry-based and STAD cooperative instructional approach, with an overall mean score of 4.41 (SD = 0.51). As shown in Table 5, students expressed particularly positive perceptions of group work experiences (M = 4.49, SD = 0.48) and inquiry-based learning activities (M = 4.45, SD = 0.52), suggesting that the instructional design was perceived as engaging, supportive, and conducive to learning.

Table 5. Students' perceptions across key dimensions of the learning experience

Dimension	Mean	SD	Interpretation
Learning activities	4.45	0.52	Highly satisfied
Group work experience	4.49	0.48	Highly satisfied
Teacher facilitation	4.38	0.54	Highly satisfied
Overall satisfaction	4.41	0.51	Highly satisfied

Note: 1.00-1.80 = Highly dissatisfied, 1.81-2.60 = Dissatisfied, 2.61-3.40 = Moderately satisfied, 3.41-4.20 = Satisfied, 4.21-5.00 = Highly satisfied

The high levels of learning satisfaction in the current study are consistent with previous research indicating that inquiry-based and cooperative learning environments enhance students' motivation, engagement, and affective responses toward science learning (Gillies, 2016; Morris, 2025). Learning activities that promote active participation, cooperative problem solving, and sense-making through inquiry are known to foster students' enjoyment and perceived value of learning (Chophel et al., 2023).

From a motivational perspective, positive learning satisfaction plays an important role in sustaining students' engagement, persistence, and willingness to invest cognitive effort in learning activities. Prior studies suggest that students' affective responses are strongly influenced by perceptions of instructional relevance, autonomy, and social support within the classroom (Fredricks et al., 2016). In the present study, the integration of inquiry-based learning with structured cooperative mechanisms provided opportunities for active involvement and peer support, which likely contributed to students' positive learning experiences.

Although high satisfaction alone does not necessarily guarantee deep conceptual understanding (Lazonder & Harmsen, 2016), the convergence of very high satisfaction levels with substantial gains in conceptual understanding and cooperative learning behaviors strengthens the interpretation that the instructional approach was both affectively engaging and cognitively effective. These findings suggest that the integrated 5E–STAD model can successfully promote positive learning experiences while maintaining a strong focus on meaningful conceptual learning in biology.

Contributions and Limitations

Taken together, this study contributes to the research base in science education by offering empirical evidence that cooperative learning structures can be intentionally integrated in inquiry-based instruction to improve learning in conceptually challenging domains such as photosynthesis. While previous studies have examined inquiry-based learning and STAD separately, the present results show that their effects are synergistic when integrated systematically, with the 5E model facilitating cognitive sequencing and STAD promoting sustained and meaningful peer engagement. This integration is consistent with current socio-cognitive viewpoints that stress the simultaneous involvement of cognitive engagement and social interaction in conceptual learning (Gillies, 2016; Joswick & Hulings, 2024).

The novelty of this research lies in the systematic integration of STAD cooperative learning structures into selected phases of the 5E inquiry-based learning cycle, rather than using the two approaches separately. This study proposes a unified instructional framework in which STAD is purposefully incorporated into the Explore, Explain, and Elaborate phases of the 5E model to promote conceptual understanding of complex biochemical processes, such as photosynthesis. This approach is different from prior research that has considered inquiry-based learning and cooperative learning as separate teaching strategies. Moreover, the design also allows peer interaction to directly support inquiry processes and conceptual construction. It also provides a more coherent pedagogical approach to teaching complex biological concepts.

Practically, the study provides a feasible teaching framework for biology classrooms by integrating two established pedagogical approaches. The 5E inquiry cycle and STAD cooperative structures can enhance conceptual understanding and cooperative learning behaviors, as well as the ecological validity and classroom applicability of the instructional design. These findings provide guidance for teachers interested in designing inquiry-based lessons that move beyond engagement in activities to cognitively and socially productive learning.

Apart from the educational implications, this research also provides benefits to society as it promotes the development of scientifically literate citizens who are able to understand the biological processes that influence food production, ecosystem sustainability, and climate change. A better understanding of the concepts of photosynthesis can help students to make informed decisions associated with environmental issues and the sustainable management of resources. At the same time, the improvement in cooperative learning skills, communication, teamwork, and shared responsibility provides students with the necessary skills for lifelong learning and active involvement in modern society. In terms of the Sustainable Development Goals (SDGs), this research serves SDG 4 (Quality Education) and SDG 13 (Climate Action) by promoting effective, student-centered learning through inquiry and collaboration, while enhancing students' understanding of photosynthesis and its role in climate change, and developing the skills needed to address future sustainability challenges.

Despite these contributions, several limitations must be acknowledged. The use of a one-group pretest–posttest design limits causal inference, and the sample drawn from a single school context may restrict generalizability. Moreover, the relatively short intervention period did not allow for the examination of long-term retention or transfer of learning. Future research should employ comparative and longitudinal designs across diverse contexts to further validate the effectiveness and sustainability of the integrated 5E–STAD instructional approach.

CONCLUSION

The findings demonstrated that students showed significant improvement in their conceptual understanding of photosynthesis following participation in the integrated 5E–STAD instructional program. These results suggest that combining structured inquiry processes with cooperative learning mechanisms can potentially support conceptual change and a deeper understanding of complex biological concepts.

The study also found that students consistently presented high levels of cooperative learning behaviors when participating in inquiry-based activities with the support of STAD. Active participation, exchange of ideas, shared responsibility, peer support, and group presentation were often observed during the learning process. The results further indicate that incorporating cooperative frameworks into inquiry instruction may foster productive peer engagement and promote a learning environment that leads to cognitive engagement and collaborative knowledge construction.

Students likewise reported very high levels of learning satisfaction with the integrated 5E–STAD instructional model. The positive perceptions of inquiry activities, group work experiences, and teacher facilitation indicate that the instructional approach was engaging, supportive, and conducive to learning. The confluence of strong conceptual gains, productive cooperative behaviors, and high learning satisfaction points to the potential of the integrated model for supporting both the cognitive and affective dimensions of learning.

Overall, the results suggest that the integrated 5E–STAD instructional model is a feasible and pedagogically sound approach for teaching abstract and conceptually demanding topics in biology. The model facilitates conceptual understanding, collaborative learning behaviors, and positive learning experiences by deliberately combining inquiry-based cognitive processes with structured cooperative learning. The study contributes to science education by providing evidence for a coherent instructional framework that integrates cognitive and social dimensions of learning. It offers practical implications for biology teachers, curriculum developers, and educators seeking to implement inquiry-based cooperative learning in real classroom contexts. Further research should explore the integration of digital technologies, virtual laboratories, or AI-supported learning environments with the 5E–STAD framework to improve inquiry, collaboration, and conceptual learning in science education.

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AUTHOR CONTRIBUTION STATEMENT

All authors contributed significantly to the work reported in this manuscript. BP conceived and designed the study, served as the research advisor, conducted data analysis, contributed to data interpretation and discussion, and drafted and revised the manuscript. NR carried out the research implementation, developed and validated the research instruments, collected data, and conducted data processing. NP provided scholarly feedback, assisted with statistical data analysis, and contributed to reviewing and revising the manuscript.

ETHICAL CONSIDERATIONS

The study was conducted in accordance with ethical standards for educational research. Participation occurred as part of regular classroom instruction with approval from the school administration. Students were informed of the study objectives, participation was voluntary, and no personally identifiable information was collected or reported.

CONFLICTS OF INTEREST STATEMENT

The authors declare no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

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