

Enhancing Creative Thinking in High School Biology Education: A Systematic Literature Review

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Abstract: This study aimed to examine approaches to enhance critical and creative thinking skills in biology education in senior high schools in Indonesia. This study was conducted using the Systematic Review and Meta-Analysis (PRISMA) method. Bibliometric analysis was employed to understand the research patterns and trends in this topic. The search yielded 214 articles that met the inclusion criteria. Data visualization using VOSviewer revealed connections between creative thinking skills and other factors such as students' critical thinking skills, motivation, educators, and intelligence. These findings highlight the importance of integrating teaching approaches that foster creative thinking skills, such as inquiry-based, project-based, and problem-based learning, to enhance students' learning experiences and outcomes. This study provides valuable insights for improving science education in Indonesia and preparing students for a successful academic and professional future in science, technology, engineering, and mathematics (STEM) fields.

Keywords: biology education, critical thinking skills, creative thinking skills, science education, senior high school

INTRODUCTION

Indonesia's rapidly evolving educational landscape underscores the need to foster both fundamental and innovative thinking skills among students, particularly in high-school science education (Muchson et al., 2024; Permanasari et al., 2021). These skills are crucial for

comprehending complex biological concepts, engaging meaningfully with the subject matter, and preparing students for the demands of higher education and future careers in the Science, Technology, Engineering, and Mathematics (STEM) fields (Faisal and Martin, 2019; Sari and Juandi, 2023).

Critical thinking skills enable students to question assumptions, evaluate evidence, and synthesize data to draw informed conclusions (Pamungkas et al., 2018). This approach allows students to engage in curiosity and precision with biological concepts, leading to a deeper and more significant understanding of the material (Vieira and Tenreiro-Vieira, 2014; Zuhra et al., 2021). Consequently, students develop the ability to analyze and interpret scientific data, which is an essential skill for both academia and industry (Hunaepi et al., 2021).

Conversely, creative thinking fosters innovation and the generation of novel ideas and solutions (Daud et al., 2012). In science education, innovative thinking empowers students to explore biological concepts and enriches their learning experiences. This skill is crucial for navigating the complexities of cutting-edge science and contributes to scientific advancement (Sucilestari et al., 2023).

Over the past few years, developing critical thinking and creativity in biology has been one of the urgent needs demanding attention from high schools. Literature reveals that applying innovation in pedagogic features such as inquiry-based learning (IBL), project-based learning (PjBL), and problem-based learning (PBL) greatly enhances students' cognitive skills, including their abilities to think critically or creatively through science (Sari et al., 2024; Mulyono et al., 2023). This kind of pedagogy encourages active student involvement and application of learned skills in the solving of real-life situations, which is necessary for understanding complex biological concepts. Also, the incorporation of STEM (Science, Technology, Engineering, and Mathematics) education and digital devices has reinforced these approaches, affording diverse learning opportunities to bridge theoretical concepts with practical applications (Febaliza et al., 2023). Hence, modern educational strategies will fit into grooming the next generation of scientific minds endowed with much more than knowledge but skills to create as well as check global challenges.

Recent research continues to enhance the learning models that it has recently evidenced in improving the high school students' creative thinking abilities. This was evident in the recent studies of McLure et al. (2024) and Sucilestari et al. (2023) that deal with project-based learning and inquiry-driven activities effectiveness in promoting creativity and problem-solving in science education. The innovations in educational technologies including virtual laboratories and interactive simulations were found to promote the development of critical and creative

thinking enhancement (Candido et al., 2022; Sari et al., 2024). The same goes for the new research on digitizing biology education as carried out by Eliaumra et al. (2022) and Febliza et al. (2023) which showed how students could take full advantage of digital tools in interacting and exploring biological phenomena in more innovative ways to create greater innovative output. This continues to broaden evidence towards understanding how educational approaches would be tailored to learning needs in the 21st century.

It brings a new addition: a systematic review of new approaches for creative thinking enhancement in high school biology education, particularly within the Indonesian context. This study highlights important gaps and chances to improve the incorporation of creative thinking abilities in science education by combining recent developments in inquiry-based, project-based, and problem-based learning approaches. The study also provides useful insights for teaching methods in the digital age by highlighting the role of educators and the importance of motivation in encouraging creative thinking. An inventive framework for enhancing biology education results is offered by the emphasis on the interaction of cognitive abilities, instructional strategies, and digital tools—not just in Indonesia but also internationally.

Despite the potential challenges, integrating critical and creative thinking into high school science curricula is essential. A systematic literature review (SLR) provides an in-depth overview of the current state of research on this topic within the Indonesian educational context. This review aims to contribute to ongoing efforts to enhance science education and prepare students for a successful future by identifying practical approaches and areas for further exploration.

METHODS

Data were collected through a systematic literature review of sources related to creative thinking skills in high school biology education. These data were obtained from reputable scientific databases such as Scopus, using targeted keywords such as “creative thinking,” “high school,” and “biology education” from 2019 to 2024. This study was developed using the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) 2020 guidelines to investigate creative thinking skills in high school biology education. Further analysis employed bibliometric analysis to understand the development of educational models for enhancing creative thinking and research directions, utilizing the VOSviewer software.

The selection criteria included studies that presented evidence-based methods to improve creative thinking in high school biology education. The initial search retrieved several relevant

articles for an in-depth analysis. The predefined inclusion and exclusion criteria were used to assess the quality and relevance of the selected studies. Additionally, we examined each study's methodologies, study designs, sample sizes, and outcomes to ensure their robustness and applicability in the Indonesian educational context. Data extraction and synthesis were conducted using Microsoft Excel to identify common themes and patterns among studies.

Finally, the review analyzed various teaching strategies and interventions, such as inquiry-based learning, project-based learning, Problem-Based Learning (PBL), the STEM approach, interactive simulations, and educational technologies. Teacher attitudes and student engagement were also considered to be influential factors in enhancing creative thinking skills. Through this structured approach, the systematic literature review (SLR) aims to provide a comprehensive overview of current practices and potential future directions for fostering creative thinking in high school biology education.

Procedure

The procedure was carried out in several stages:

- Select the database: Data were obtained through reputable scientific databases such as Scopus.
- Define the search concept: Keywords were generated to include in the search process. These words include creative thinking, creative thinking skill, enhancing creative thinking, biology education, creative thinking in science education, and project-based learning.
- Generate the search equations: Based on the keywords, the following equations were prepared: (“creative thinking” OR “creative AND thinking” OR “creative thinking skill*” OR “creative AND thinking AND skill*” OR “enhancing creative thinking” OR “enhancing AND creative AND thinking” OR “biology education” OR “biology AND education” OR “creative thinking in science education” OR “creative AND thinking AND in AND science AND education” OR “project based learning” OR “project AND based AND learning”). These equations were applied to find publications that included any of these terms in their titles.

Study screening

The initial search yielded 2,580 articles that were evaluated based on their titles and abstracts, resulting in 2,268 unique articles. However, 1,476 articles were deemed ineligible and excluded during the initial screening phase. Further analysis excluded papers that did not

meet the specified criteria, ultimately resulting in 214 unique articles that were included in a detailed review, as shown in Figure 1.

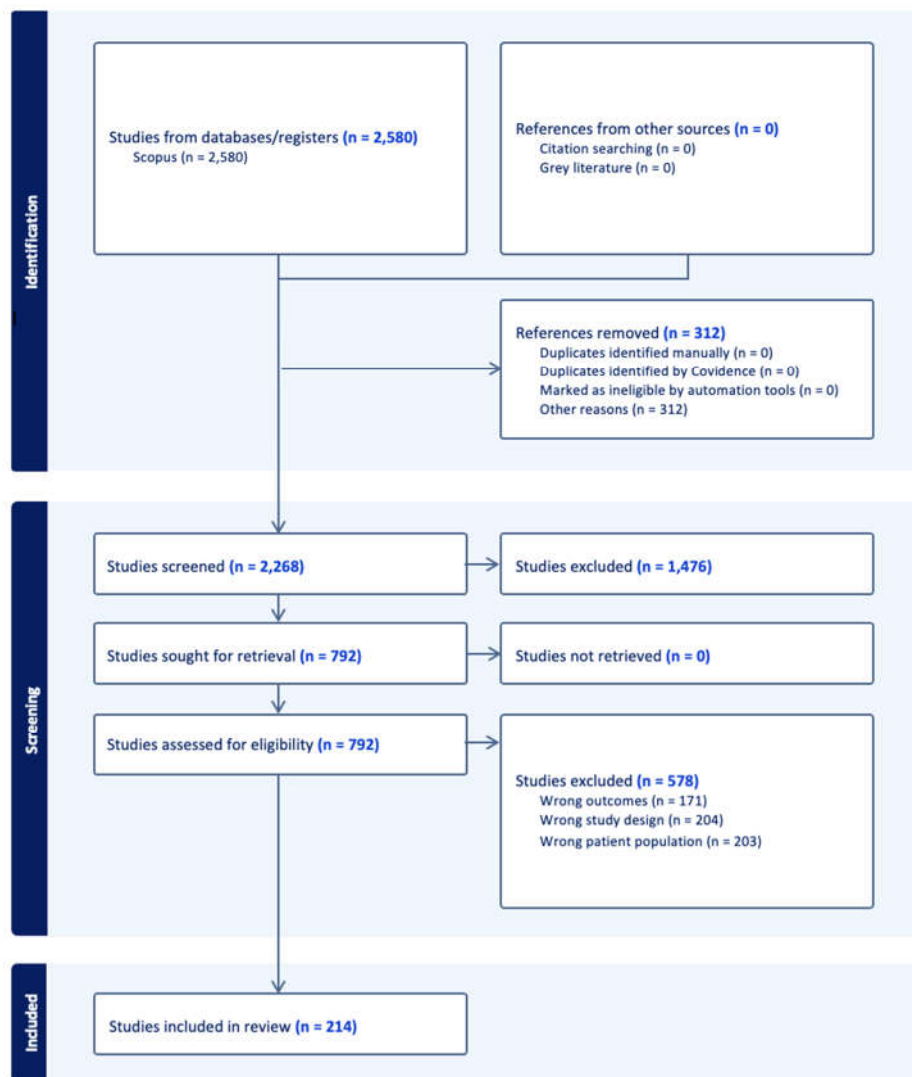


Figure 1. PRISMA flowchart protocol, 2019-2024

RESULTS

Bibliometric Analysis

Bibliometric analyses provide a comprehensive overview, helping identify research trends over time and develop a conceptual understanding of research patterns (Ingale and Paluri, 2022). A visualization of a conceptual network related to various educational and learning concepts created by VOSviewer is shown in Figure 2.

The primary keyword, "creative thinking skills," has several connections to other clusters, indicating that this is a central area of study in the field. This topic also has a substantial correlation with education, motivation, and IQ, indicating the significant aspects that impact students' creative growth. This demonstrates the relationship between education, motivation, intelligence, and technology and the study of creative thinking abilities. The creativity of students is greatly influenced by teachers and methods of instruction. Digital literacy and technology play a part in fostering creative thinking abilities, particularly in STEM fields, such as physics.

The visualization of the VOSviewer data results using the keyword “creative thinking skill” is shown in Figure 3. This image illustrates the relationship between the various educational concepts and skills. Surrounding these core skills are a variety of related terms and ideas, such as “student creative thinking skill,” “motivation,” “educator,” “physics,” “intelligence,” “grade,” “measure,” “mathematical problem,” “team,” “risk,” “learning style,” “academic,” and “ecological literacy.” Visual representation uses colored nodes and interconnected lines to depict the complex network of associations between these different elements.

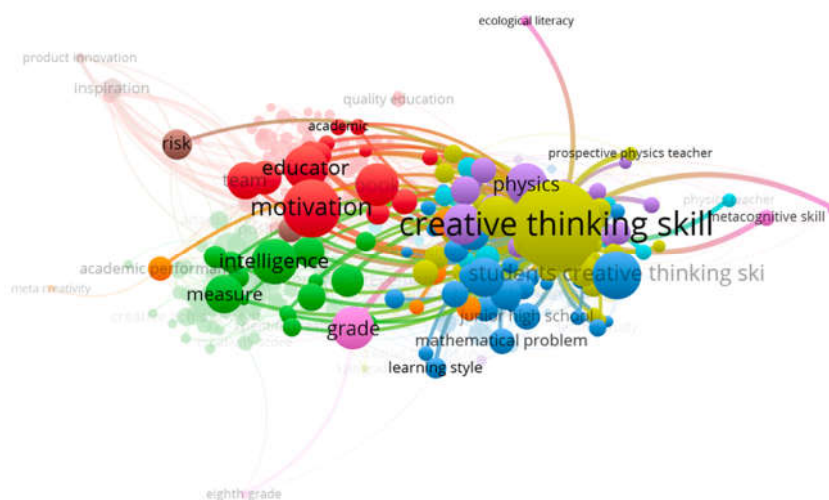


Figure 3. Correlation subject by creative thinking skill based on enhancing creative thinking approach, 2019-2024

Creative thinking skills in an educational context indicate a need for motivation. This implies that creative thinking skills are interrelated with other educational approaches, technologies, and learning outcomes such as science education and student development. The visual structure shows that these concepts and skills are not isolated, but interrelated, with each influencing and being influenced by others. The diversity of terms and their relationships

emphasize the multifaceted nature of education and the need for a holistic and integrative approach to cultivate essential skills. This figure provides an exciting representation of the complex landscape of educational concepts and their interdependence, focusing on cultivating students' creative thinking skills.

Keywords with high frequency are illustrated in the treemap, which can be seen in Figure 4(A). The size of the rectangle is proportional to the keyword frequency. The larger the rectangle, the more frequently a keyword was used. Keywords can provide more detailed information regarding an author's keyword analysis. These images were marked with different colors covering a variety of topics, including students (12%), creative thinking (7%), creativity (6%), humans (5%), and education (4%), which were the most popular keywords. Titles with high frequencies are illustrated in Figure 4(B). These images were marked with different colors covering a variety of topics, including thinking (12%), creativity (11%), students (8%), and learning (8%).



Figure 4. Word Treemap, 2019-2024; (A) Based on keywords and (B) Based on title.

Color coding and the image layout make it visually appealing and easy to navigate. Overall, this visualization offers a holistic perspective on the educational landscape, highlighting the interconnectedness and interdependence of various concepts and related metrics. It is used for analysis, comparison, or decision making in educational or academic settings, providing stakeholders with a comprehensive understanding of the factors at play.

The graph in Figure 5 depicts the values of “MeanTC per article” and “MeanTC per year, from 2019 to 2024. This graph can be used as a measurement or a numerical indicator for tracking and analysis. The overall trend displayed in the graph indicated a significant increase in the MeanTC value per article over time. The graph started at a relatively low level in 2019, with a MeanTC per article of approximately 200. However, from 2019 to 2024, there was a steady and significant increase in the MeanTC per article, reaching a peak of 998 in 2024. The MeanTC value increased yearly and was substantial. The graph began at a relatively low level in 2019, with an annual MeanTC value of approximately 39. However, from 2019 to 2024, there was a steady and significant increase in the annual MeanTC, reaching a peak of 998 in 2024.

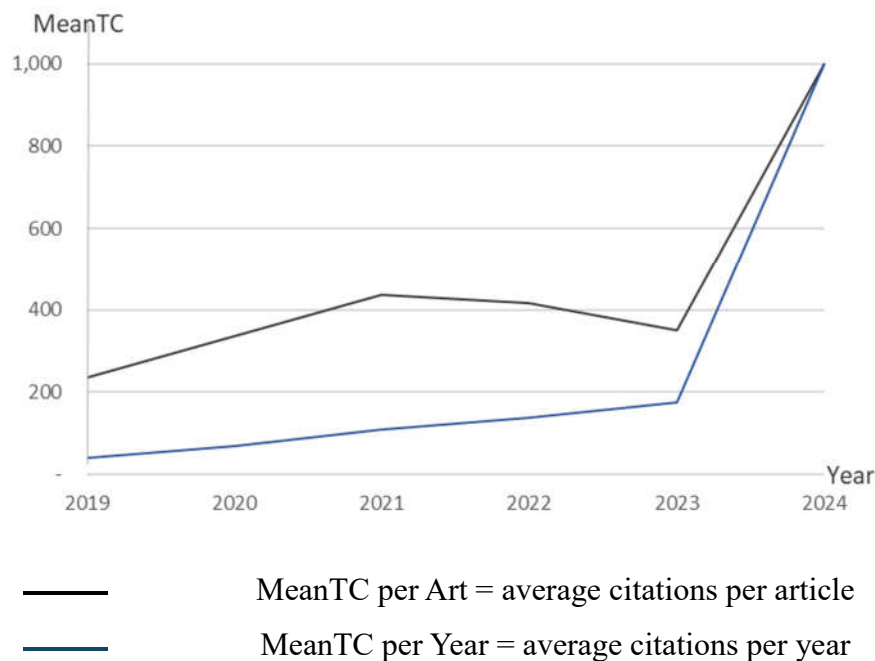


Figure 5. Total MeanTC per article/year against year 2019-2024

These data are used by researchers, analysts, and decision makers to understand trends and patterns related to the average citations per article and average per year to improve critical and creative thinking in high school biology education.

Scientific Performance and Production

Figure 6 shows the number of publications on creative thinking from 2019 to 2024 (A), the number of publications by subject area (B), scientific language used (C), and most of the publications on creative thinking from 2019 to 2024 (D).

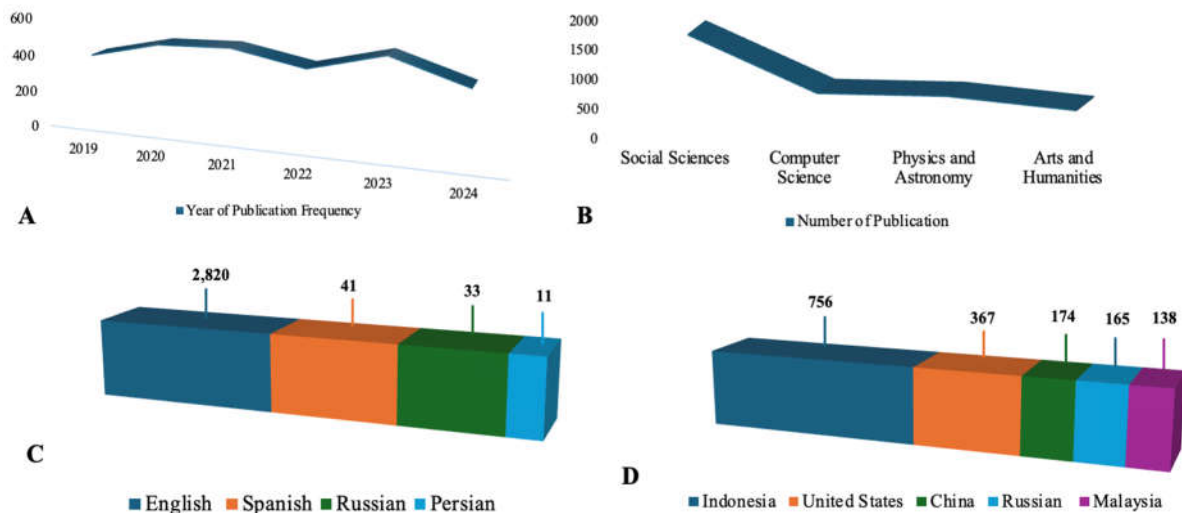


Figure 6. (A) Publication frequency, (B) Number of publications by subject area, (C), Scientific language used, and (D) Most prolific country.

Figure 6A shows the number of publications on creative thinking published from 2019 to 2024. Publication has reached its peak in 2023 with 511 journals, then in 2021 with 486 journals, in 2020 with 473 journals, in 2022 with 412 journals, in 2019 with 385 journals, and at least in 2024 (July) with 313 journals and still continuing.

Based on the subjects provided on Scimagojr.com, we categorized earlier research and found that the social sciences (1,566) comprised the greatest number of subject categories. The remaining topic area exhibits a lower production volume: computer science with 575 journals, physics and astronomy with 525 journals, and arts and humanities with 284 journals (Figure 6B).

Studies on creative thinking have primarily been conducted in English. Although Spanish, Russian, and Persian appear on the list, their production volumes are very small compared with English (Figure 6C). The most significant number of scientific languages used were English with 2,820 journals, Spanish with 41 journals, Russian with 33 journals, and Persian with 11 journals.

The country with the most scientific articles related to creative thinking is Indonesia, with 756 journals. The remaining countries produced far fewer products: the United States with 367 journals, China with 174 journals, Russia with 165 journals, and Malaysia with 138 journals (Figure 6D).

Structural and Thematics Development

In this research, two periods (2019-2021 and 2022-2024) are used as references. The volume of keywords gathered over each time is displayed via the keyword continuity analysis. In this case, in the first period (2019-2021), there were 47 keywords, while in the second period (2022-2024), there were 77 keywords. This is normal, considering that production volumes vary from year to year. The number of keywords not used in the following period is indicated by the up arrow. The downward arrow points to recently added keywords to the project-based learning in scientific research sector. Using this information along with the volume of keywords for the first period (2019-2021) and the second period (2022-2024), the keyword matching percentage between the two periods is determined. The horizontal arrow indicates the 98% match percentage. This demonstrates that there is already a research line in the area of creative thinking in high school biology education, even though it is a new scientific trend currently being produced (Figure 7).

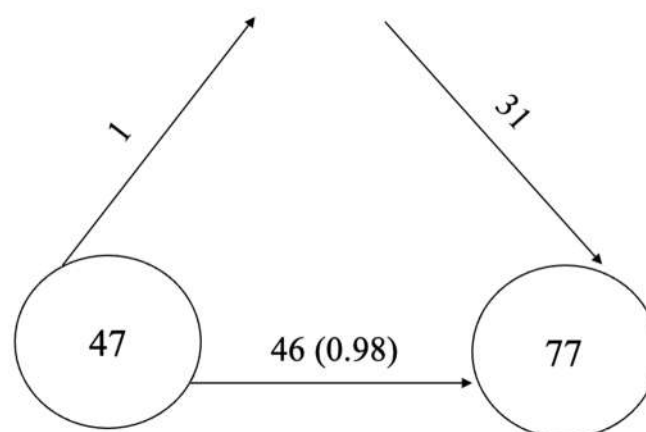


Figure 7. Keyword continuity between contiguous intervals.

Each theme's degree of importance is displayed in the strategic diagram of topics that emerged from the co-word analysis. Figure 8 shows the strategic diagram by h-index of instagram as a catalyst for consumer behavior. Figure 8 is the result of the analysis using Sci-MAT, which displays the Strategic Diagram based on the H-index related to creative thinking in biology education in secondary schools. This diagram uses two main axes, namely the X axis

(Centrality), which shows the relevance and connectedness of a theme to the primary research field, and the Y axis (Density), which shows the level of development and internal cohesion of a theme in the literature.

In 2019-2021 (Figure 8A), the main topic with high centrality and density was "CREATIVE-THINKING-SKILLS," indicating that this is a developing and important theme in research. "PRE-SERVICE SCIENCE TEACHERS" and "EMOTIVE" have more separate positions with low density, indicating their weaker connection in academic discussions. In 2022-2024 (Figure 8B), "CREATIVE-THINKING-SKILLS" remains the main topic, but its position has shifted more to the upper right quadrant, indicating that this theme is increasingly consolidated and relevant. "EDUCATIONAL ROBOTS" emerged as a new theme, indicating a new trend in applying technology to enhance creative thinking. "PRE-SERVICE TEACHERS" remained, but with lower centrality, indicating that while still relevant, its importance may have decreased slightly compared to the previous period.

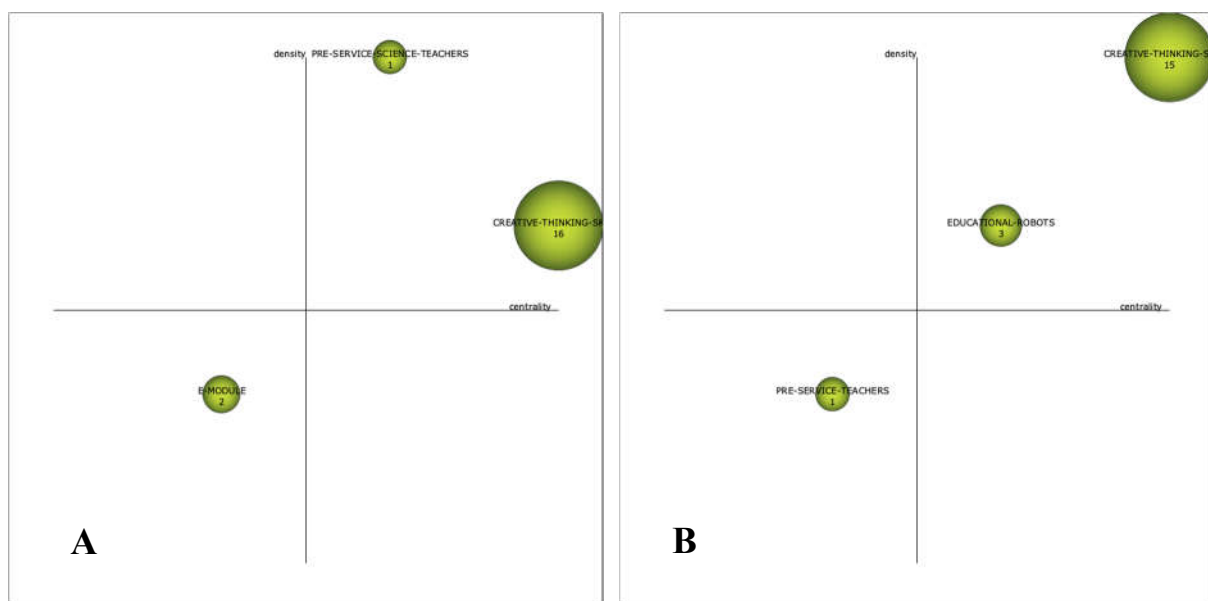


Figure 8. Strategic diagram by h-index of creative thinking in high school biology education.

Note: (A) Interval 2019-2021; (B) Interval 2022-2024.

From Figure 8, it can be seen that from 2019-2021 to 2022-2024, there was a shift in research topics related to creative thinking in secondary school biology education. "Creative Thinking Skills" remained the center of attention, but the approach evolved, with the emergence of "Educational Robots", reflecting the increasing role of technology in education. The focus on "Pre-Service Science Teachers" decreased slightly in relevance, indicating a change in research priorities.

Smaller nodes around the centre indicate various factors that contribute to the development of creative thinking, such as: "LEARNING-MODEL" indicates that learning models play a role in fostering creativity. "MATHEMATICAL-THINKING & SCIENTIFIC-ATTITUDES" relates to scientific and mathematical thinking in building creativity. "STEM-EDUCATION" strengthens the relevance of STEM in supporting creativity in biology education. Creative thinking skills are a key concept in the 2019-2021 study, with broad links to STEM, problem-solving, learning models, and scientific attitudes. The study focuses more on students than other aspects, such as teachers or education policies. STEM and problem-solving have important roles in fostering creativity in biology learning.

Figure 11 shows the Thematic Evolution by h-index of research related to creative thinking in secondary school biology education. This analysis uses Sci-MAT to compare the evolution of research themes between two time periods. The figure shows two time periods, each with a central theme represented by a large circle and supporting themes by small circles. The first period (left) represents research in the early interval. Meanwhile, the second period (right) represents research in a more recent interval.

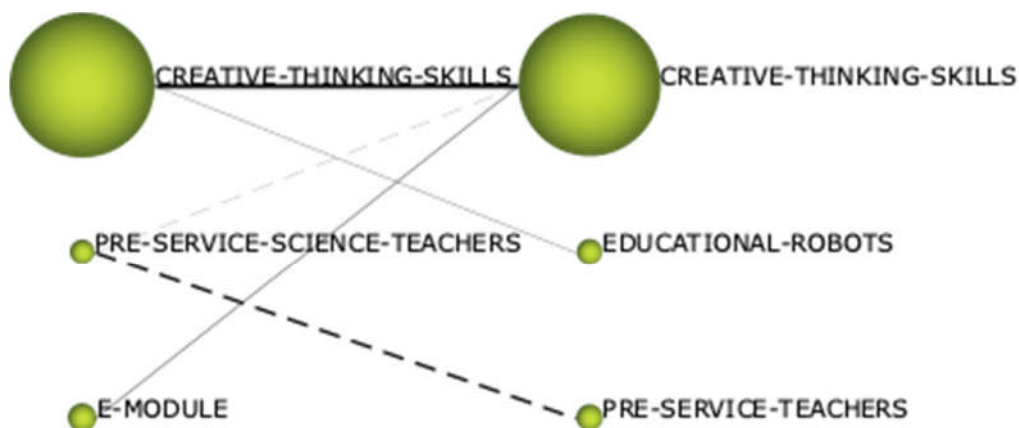


Figure 11. Thematic evolution by h-index of creative thinking in high school biology education.

The central theme remains "Creative-Thinking-Skills," indicating that research on creative thinking skills in biology education remains a significant focus. Several supporting themes persist, indicating the continuity of research on certain aspects. The emergence of new themes indicates changes in research trends and the influence of more developed innovative approaches. The size of the circle indicates the h-index value, which reflects the academic impact of the theme. Larger circles indicate that the theme has more citations and significantly

influences related research. Figure 13 shows that active thinking in biology education continues to evolve, with the central theme remaining relevant but experiencing changes in its approach. The emergence of new themes indicates innovation in applied educational methodologies and theories. The h-index helps identify themes with the highest academic impact, thus providing insight into the most influential research.

DISCUSSION

The systematic literature review revealed various practical approaches to enhance creative thinking in high school science education, focusing on biology education. This discussion synthesizes the key findings of this review, highlights the most effective teaching methods and interventions, and considers their implications in practice and future research.

Inquiry-Based and Project-Based Learning

According to Minister of Education and Culture Regulation number 22 of 2016, inquiry-based or discovery learning must be used to reinforce scientific methods in elementary and secondary education processes. This is consistent with Galili's (2022) assertion that science courses, including biology, are linked to methodically learning about nature. Hence, science courses involve more than just memorizing knowledge expressed as facts, concepts, or principles; they also involve the process of discovery. Knowledge can be gained through observation, comprehension, application, analysis, evaluation, and creation if learning is performed scientifically. Creating issues, developing hypotheses, carrying out experiments, analyzing or interpreting data, arriving at conclusions, and communicating are all processes in the scientific method. These stages are similar to those of investigations conducted by scientists. As Calavia et al. (2021) and Rodriguez et al. (2019) state, encouraging student creativity is a key component of inquiry-based learning.

Research has shown that students' creative thinking skills are greatly improved through inquiry-based and project-based learning (Purnawati et al., 2021). These teaching strategies use practical exercises and real-world problem-solving to support students' active engagement with content, questioning, and exploration of scientific ideas (Rahmi et al., 2019). Students were also shown to have been able to develop their creative thinking skills through this inquiry-based learning method because they presented multiple real-world challenges during the learning activity. The students' strong motivation throughout the learning process may contribute to their significant increase in creative thinking skills. This type of instruction results from the authentic

and contextual learning environment that it offers, which has the power to boost students' drive to learn (Karamustafaoğlu & Pektaş, 2023).

Creative thinking is an intricate cognitive process that helps students advance their thinking abilities. Students who engage in this thought process can develop analytical skills and become proficient problem-solvers, equipping them to tackle real-world issues. Observing, analyzing, evaluating, and producing conclusions or products are just a few of the scientific tasks that science education may use to assist students in developing their creative thinking skills. As a result, teachers might meet this requirement by incorporating the creative process into scientific education through project-based learning methodologies. The advantage of project-based learning is that once a project is finished, students' engagement increases, and they gain a deeper understanding of the material (Putri et al., 2019).

One scientific learning method that allows students to design their own learning activities, work together on projects, and ultimately create goods they can show to others is project-based learning. Project-based learning involves carrying out a project over a set length of time, with processes that include planning and preparation, carrying out the project, reporting, and sharing the outcomes of assessments and activities. To entice pupils to study, project-based learning fosters the development of an inquiry process for the study of real-world subjects. This is further corroborated by research findings that demonstrate how project-based learning approaches can foster creativity and inspire students to study topics found in everyday life (Ngereja et al., 2020; Albar & Southcott, 2021).

In contrast to traditional learning models, project-based learning emphasizes student-centered learning by integrating students in the development of inquiry processes to produce products, acting as a facilitator and motivator for students, and emphasizing proportionate process skills in addition to learning outcomes. This type of learning necessitates the creation of guiding questions for educators and learners. Accordingly, students' learning results and creative levels may be influenced by the project-based learning paradigm. Project-based learning helps students apply scientific ideas in relevant and practical ways while developing their creative thinking abilities (Sukma et al., 2022; Kaharudin and Rosnawati, 2020; Darmuki et al., 2023). Research indicates that project-based learning is frequently used in Indonesia and is beneficial for getting students involved in solving real-world problems and developing their critical and creative thinking abilities (Mirnawati et al., 2021).

Problem-Based Learning (PBL) and STEM Approach

Problem-based learning (PBL) effectively enhances students' creative thinking skills, particularly in biology (Shamdas et al., 2022; Suwono et al., 2021). PBL emphasizes student-centered learning by applying biological concepts to solve complex problems and fostering critical and creative thinking by challenging students to analyze problems, evaluate evidence, and develop novel solutions (Made et al., 2023). Integrating STEM education, which combines science, technology, engineering, and mathematics, further enhances students' ability to think creatively, by providing a multidisciplinary perspective. STEM projects often involve collaborative learning, helping students approach problems from different angles and developing innovative solutions (Aryulina and Riyanto, 2016; Carrió et al., 2016; Thompson, 2019; Madhavia, 2020). A comprehensive literature review of problem-based learning in physics education shows that PBL enhances students' academic performance, attitudes toward learning physics, problem-solving abilities, capacity for creative thought, creation of mental models, and acquisition of science process skills (Nicholus, 2023).

Problem-based learning is widely utilized in Indonesia, supported by research (Sanova et al., 2021; Yanti and Fauzi, 2022), highlighting its effectiveness in developing students' critical thinking, problem-solving, and creativity in high school biology education. It is essential for gifted students to have higher-order thinking abilities. They require support that helps them advance their capacity for problem solving, critical and creative thought, and decision-making. Gifted students can use their curiosity to explore and enhance their abilities through the integrated application of a STEM-based curriculum. STEM integrates science, technology, engineering, and math with other subject areas, benefiting students by providing project-based learning opportunities that require the application of knowledge to solve real-world authentic problems in cooperative settings. According to Abdulrahman et al. (2019), integrated STEM education involves purposefully combining these disciplines to enhance students' learning experience.

Research conducted by Khalil and Osman (2017) revealed the positive outcomes of using integrated STEM to teach students 21st-century skills. The research findings examined digital era literacy, creative thinking, effective communication, high productivity, and spiritual values as elements of 21st-century competencies. Similarly, Sastradika and Defrianti (2020) showed that implementing integrated STEM in learning can improve creative thinking skills.

In conclusion, the search results supported the idea that PBL effectively enhances creative thinking skills in high school biology education. This method encourages students to actively engage with the material, ask questions, and explore scientific concepts through hands-

on activities and real-world problem-solving, fostering creative thinking abilities (Pratiwi et al., 2023). Integrating STEM education and collaborative learning further enhances the development of these skills (Hidayah et al., 2021).

Simulations and Educational Technologies

The rapid advancement of information communication and technology in the 21st century has significantly affected human learning. Consequently, the learning management model must be adapted to meet modern world requirements. Owing to swift and continuous developments across many fields, the world has entered a period of globalization and a knowledge-based society (Kwangmuang et al., 2021). Research indicates that integrating theoretical concepts with media features and learning innovations, such as learning environments, skill sets, multimedia, online lessons, and mobile learning, supports higher-order thinking skills, including creative thinking, critical thinking, and problem-solving (Prahani et al., 2020).

It has been suggested that digital technology can significantly enhance students' creativity by providing new tools and environments for both learning and creative expression. Educators worldwide believe that technology can foster creativity and learning (Glăveanu et al., 2019). Research on technology-enhanced improvements has suggested that digital tools can boost creativity. Studies indicate that highly accomplished educators often align their conception of creativity with the literature, possess a wide range of creativity-fostering teaching techniques, and play a crucial role in promoting research-based opinions and approaches among educational stakeholders (Bereczki & Kárpáti, 2021). Numerous studies have proposed theories regarding the use of digital technology to foster creativity and learning. Activities focused on creativity with new technologies combine the qualities of digital technologies, learners' abilities to express higher-order thinking with technology, and creative processes, such as using imagination, pursuing purpose, originality, and judging value (Glăveanu et al., 2019).

Educational technologies enable students to virtually visualize and experiment with scientific concepts, making abstract concepts more concrete and understandable (Candido et al., 2022). Interactive simulations have successfully taught modern biology and enhanced students' creative thinking skills. These simulations provide immediate feedback, allowing students to reflect on their learning and improve their critical thinking processes (Tengku, 2022; Sari et al., 2024; Mukti et al., 2021; Eliaumra et al., 2022).

In conclusion, the search results support the idea that using interactive simulations is a practical approach to enhance creative thinking skills in high school biology education. These

technologies engage students with scientific concepts in a hands-on, interactive manner, providing opportunities for visualization, experimentation, and immediate feedback, which fosters critical thinking and creative problem-solving abilities (Febaliza et al., 2023).

Teacher Attitudes and Student Engagement

The search results demonstrate that teachers' attitudes play a crucial role in fostering an environment that supports creative thinking in students (Azmi et al., 2023). Studies of instructor creativity are becoming increasingly prominent in educational settings. Several experts categorize teacher creativity into three main areas: developing original and novel teaching methods, utilizing a range of strategies, and demonstrating strong dedication to using effective methods to support students' learning progress. Current research on teachers' creativity emphasizes their critical role in fostering student achievement (Arifani & Suryanti, 2019). Chi et al. (2014) showed that teacher creativity positively affects their effectiveness in education. Various perspectives argue that teachers' creativity, beliefs, and personal traits are interconnected factors that characterize their efficacy as educators.

Enthusiastic educators who are open to new teaching methods can motivate students to engage more deeply with the material, thereby promoting a classroom culture that encourages questioning, exploration, and experimentation (Pongračić and Marinac, 2021; Susanti et al., 2020). Although educators are required to fulfill the National Curriculum criteria, this should not restrict the instructional methods used in the classroom. The challenge of making learning appropriate, meaningful, and relevant is that teachers face it daily. Theory-based activities become more engaging and enjoyable when creativity, imagination, and pleasure are incorporated. According to Piaget's cognitive developmental theory of learning, educators must provide students with relevant practical assignments to give them the freedom to explore and create their knowledge. Teachers should carefully select activities for their lesson plans to ensure that they encourage higher-order thinking and knowledge integration. During class activities, students are given the opportunity to apply and investigate their newly acquired knowledge with the help of their teachers and classmates. This teaching strategy has been shown to boost motivation, improve conceptual knowledge, and provide unique opportunities for collaborative learning (Franklin & Harrington, 2019).

For instance, a study examining teacher and student perspectives on creative thinking in a science program for high-ability learners in Singapore revealed a strong correlation between teachers' classroom practices and students' capacities for critical and creative thinking (Slatter, 2009). Another study using story writing to help teachers build their creative thinking

skills identified four major topics: the advantages, difficulties, satisfaction, and enhancement of the Writing Thinking Stories (WTS) program (Preece et al., 2022).

Empirical evidence has indicated that student engagement is essential for highly effective and profound learning. Many teachers recognize that students' levels of engagement during class vary widely. While some students fully participated in the learning activities, others were only moderately engaged. Given the importance of student participation in both current and future successes, fostering student involvement is crucial. General behaviors, such as attending class and participating in school events, constitute student involvement. Conversely, observing student engagement in lessons adopts a more situational focus on students' unique participation within a given session. The three broad types of engagement are behavioral, cognitive, and emotional (Cents-Boonstra et al., 2021).

Furthermore, a qualitative descriptive study aimed at characterizing students' capacities for developing critical thinking found that while problem-posing and problem-solving skills improved, not all aspects of creative thinking capacity improved. The study also emphasized the importance of developing a nonlinear strategic thinking to foster a holistic vision of a scheme, model, or procedure (Butler, 2023). Teachers' attitudes are crucial in fostering an environment that supports students' creative thinking. Enthusiastic educators who are open to new teaching methods can motivate students to engage more deeply with the material and promote a classroom culture that encourages questioning, exploration, and experimentation, helping them feel more comfortable expressing their ideas and taking intellectual risks (Kizilhan and Demir, 2022).

Curiosity and Motivation

Cultivating students' curiosity is vital to increasing their capacity for creative thinking (Suhirman and Ghazali, 2022). Curiosity in Learning Biology: Literature Review” explores how curiosity enhances learning, including raising motivation and interest levels, fostering the growth of critical and creative thinking abilities, and improving academic attainment. According to one study, inquiry, discovery learning, problem-based learning models (PBL), and project-based learning (PjBL) can foster and strengthen student interest (Hunaepi et al., 2021). Engaging a wider sense in the curriculum can encourage and promote curiosity in teaching and learning. The article “Wider-sensory exploration: Fostering curiosity in teaching and learning strategies” examines concrete ways to encourage multisensory participation in the classroom, such as providing teachers with a forum to discuss incorporating multisensory creative provocations in assignment briefs (Manu, 2017).

The significance of molding creative thinking in students is emphasized in the article “Psychological Foundations of Formation of Creative Thinking of Future Teachers,” which also covers strategies for promoting curiosity, a research-based teaching approach, and question-asking as means of igniting independent and critical thought (Rakhimov et al., 2023). Developing students’ curiosity is crucial to improving their creative thinking capacity. Teachers can foster a supportive learning environment that promotes the development of students’ creative thinking skills by nurturing their innate curiosity through instructional strategies including guided inquiry, discovery learning, and interactive teaching approaches (Pratiwi et al., 2023).

Educators should consider implementing inquiry-based, project-based, and problem-based learning approaches as well as integrating interactive simulations into STEM education to engage students and nurture their cognitive skills. By doing so, students will be better prepared for the complexities of modern biology and their future careers in STEM. Further research should explore the long-term impact of these teaching methods on students’ creative thinking skills and academic success.

Creative Thinking Assessment and Evaluation in Biology Education

The assessment and evaluation of creative thinking in biology education are critical for measuring the effectiveness of employed teaching strategies and technologies applied in the classroom. There are quite a few ways now developed in the direct assessment of students’ creativity in the broad areas of STEM education, including biology.

1. Methods of Assessing Creativity in Biology Education

Creativity assessment within biology education is thus possible by:

- Divergent thinking tests: Measurement of students’ ability to offer multiple solutions to a scientific problem (Bereczki & Kárpáti, 2021).
- Creativity assessment rubrics: The use of originality, flexibility, elaboration, and fluency as indicators to assess project-based tasks or any scientific investigation or research effort (Glaveanu et al., 2019).
- Self- and peer-assessment: Students reflect on their creative thinking process and receive feedback from a peer (Preece et al., 2022).

2. Evaluation of Creativity Pedagogy

Inquiry-based teaching methods and interactive technology stood validated to foster student creativity in biology. However, future research needs to focus on long-term impact effects of such creativity development by comparing:

- Longitudinal settings, where students' creativity is followed over time (Franklin & Harrington, 2019).
- The comparative effectiveness of various approaches, such as PBL, PjBL, and digital simulations (Hunaepi et al., 2021; Candido et al., 2022).
- A mixture of quantitative and qualitative methods in evaluating creative thinking through in-depth interviews, observation in class, and analysis of student portfolios (Azmi et al., 2023; Suhirman & Ghazali, 2022).

3. Implications for Teaching Practice and Educational Policies

- Evaluation of creative thinking in biology education has some insights for the teachers and policymakers on:
- Designing curricula that consciously support creativity and problem-solving in science (Slatter, 2009);
- A teacher training program for teachers to better understand creativity-enhancing teaching strategies (Arifani & Suryanti, 2019);

Therefore, basing evidence-based policies in STEM education for improved student readiness to deal with challenges in the digital age and Industry 4.0 (Abdieva, 2023; Kizilhan & Demir, 2022).

Proposed Solution

Enhancing creative thinking in biology education in high schools can be achieved through teaching methods and integrating new technologies. The following strategies can be employed to foster curiosity, intrinsic motivation, and the development of creative thinking skills among students.

1. Incorporating problem-based learning (PBL) and project-based learning (PjBL) into the curriculum allows students to engage actively with scientific materials, fostering a deep understanding of complex concepts. These pedagogical approaches encourage students to ask questions and explore ideas through hands-on activities and real-world problem solving scenarios. By allowing students to apply their knowledge to meaningful projects and challenges, PBL and PjBL enhance their creative thinking skills and promote collaboration, communication, and independent learning. Through these methods, students develop a more profound appreciation for the scientific process and gain practical experience that prepares them for future academic and professional endeavors (Hunaepi et al., 2021).

2. Interactive teaching methods such as discovery learning and guided inquiry help nurture students' curiosity and enhance their cognitive skills. Discovery learning encourages students to explore scientific concepts independently, thereby guiding them to discover new knowledge through observation and experimentation. These approaches promote active learning and allow students to engage with material at a deeper level, fostering love for exploration and a strong foundation in scientific inquiry. Supporting students' intellectual curiosity and encouraging them to take ownership of their learning can significantly improve their cognitive abilities and academic performance (Slatter, 2009).
3. Virtual reality, augmented reality, and interactive web platforms are examples of new technologies that can be integrated to create immersive and captivating learning experiences that encourage creativity through active learning (Abdieva, 2023). These tools enable students to visualize and interact with complex concepts, thereby enhancing their understanding and ability to think critically. Educators can encourage divergent thinking, curiosity, and exploration among students by incorporating pedagogical strategies aligned with constructivist and socio-constructivist theories. Moreover, fostering a supportive learning environment that emphasizes risk taking and experimentation allows students to freely express their ideas and learn from their mistakes, thus supporting the development of their creative thinking abilities.

CONCLUSION

A systematic literature review on enhancing creative thinking in biology education in high schools highlighted the effectiveness of various teaching methods and strategies in fostering these crucial skills. Methods such as inquiry-based, project-based, and problem-based learning, as well as STEM integration and interactive simulations, offer students dynamic and engaging opportunities to deepen their understanding of biological concepts and to creatively apply their knowledge. These approaches support students in developing strong creative thinking abilities and preparing them for future scientific challenges and opportunities. Teachers are pivotal in creating supportive learning environments that inspire students to embrace curiosity, take intellectual risk, and actively engage with materials. By prioritizing these innovative teaching methods and strategies, educators can equip students with the cognitive tools they need for academic success and future contributions to scientific progress. Further research should explore the long-term impact of these approaches on students' academic

achievement and cognitive development and their potential for broader application across various educational contexts.

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Conflicts of Interest Declaration

There were no disclosed conflicts of interest by the authors.

Author Contributions

Oria Lasmana: Conceptualization, Methodology, Formal analysis, Data curation, Visualization, Writing – original draft, Writing – review & editing. Festiyet Festiyet: Methodology, Validation, Investigation, Supervision, Writing – review & editing. Rahadian Zainul: Visualization, Validation, Supervision, Writing – review & editing. Abdul Razak: Resources, Supervision, Writing – review & editing. Muhyiatul Fadilah: Supervision, Writing – review & editing. All authors have read and approved the final manuscript.

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