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Project-based learning in biotechnology: A profile of senior high school students' 21st-century 4Cs in South Labuhanbatu Regency

Hasmi Syahputra Harahap, Sri Rahayu Lestari*, Ibrohim, Sofia Ery Rahayu
Doctoral Program in Biology Education, Faculty of Mathematics and Natural Sciences, Universitas Negeri Malang, Jl. Cakrawala No. 5, Sumbersari, Lowokwaru, Malang, East Java, 65145, Indonesia
*corresponding author: srirahayulestari@um.ac.id

ABSTRACT

Twenty-first-century education requires students to develop critical thinking, creativity, collaboration, and communication (4Cs) to address increasingly complex scientific and societal challenges. This study aimed to profile senior high school students' 21st-century skills in South Labuhanbatu Regency, North Sumatra, through the implementation of Project-Based Learning (PjBL) in biotechnology instruction. A descriptive cross-sectional survey design was employed involving 157 twelfth-grade students. Data were collected through self-assessment questionnaires, peer-assessment questionnaires, observation rubrics, and documentation of PjBL activities. Descriptive statistical analysis was used to examine students' 4Cs. The findings revealed that the overall mean score of students' 4Cs was 67.33, indicating a moderate level of proficiency. Self-assessment results showed mean scores of 67.73 for critical thinking, 64.25 for creativity, 65.76 for collaboration, and 67.74 for communication. Similarly, peer-assessment results indicated mean scores of 66.07, 64.34, 74.87, and 67.91 for critical thinking, creativity, collaboration, and communication, respectively, all within the moderate category. Collaboration achieved the highest score, particularly in peer assessment, whereas creativity consistently obtained the lowest score across both assessment methods. The consistency between self- and peer-assessment results suggests that collaboration and communication were the most developed competencies among students. Although variations in students' skill profiles may be influenced by pedagogical, contextual, and social factors, the findings were obtained from biotechnology learning activities implemented through PjBL involving investigation, discussion, problem-solving, and scientific presentation. These findings describe students' 21st-century skill levels in a PjBL-based biotechnology learning context and provide empirical information that may inform future instructional strategies aimed at supporting 4C development.

Keywords: Biotechnology, descriptive cross-sectional survey design, project-based learning, South Labuhanbatu Regency, 21st-century 4Cs

INTRODUCTION

Twenty-first-century education requires students to develop critical thinking, creativity, collaboration, and communication (4Cs) to respond effectively to rapid advances in science, technology, globalization, and the increasing complexity of contemporary societal challenges. These competencies are widely recognized as essential learning outcomes because they enable learners to solve problems, make informed decisions, collaborate across diverse contexts, and communicate scientific ideas effectively (Partnership for 21st Century Learning, 2019; Trilling & Fadel, 2009). Their importance has become even more pronounced in the era of the Fourth Industrial Revolution and artificial intelligence, where higher-order thinking, innovation, digital literacy, and collaborative problem-solving are indispensable for future workforce readiness (OECD, 2019). Consequently, educational systems worldwide are increasingly shifting from content-oriented instruction toward competency-based learning that promotes 21st-century skills (UNESCO, 2021). Recent studies have shown that technology-enhanced learning environments, active learning strategies, and information literacy-oriented instruction contribute to the development of students' 4Cs (Kurniawan et al., 2024; Papagiannis & Pallaris, 2024).

Biology education provides an authentic context for developing twenty-first-century competencies by engaging students in scientific inquiry, evidence-based reasoning, data interpretation, and problem-solving through real-world biological phenomena (Markula & Aksela, 2022; Semilarski & Laius, 2021). Recent studies have emphasized the importance of literacy-oriented biology instruction (Husamah et al., 2024), scientific literacy in inclusive science education (Lenzer et al., 2024), and the integration of scientific literacy and critical thinking as key competencies in science learning (Mujriati, et al., 2025). Evidence from STEM-based inquiry learning demonstrates that authentic and inquiry-oriented learning experiences can significantly enhance students' critical thinking skills (Pahrudin et al., 2021).

Among contemporary instructional approaches, PjBL has been widely recognized as one of the most effective pedagogical models for promoting students' 21st-century skills because it actively involves learners in investigating authentic problems, designing solutions, making collaborative decisions, and producing meaningful products. Rather than emphasizing knowledge acquisition alone, PjBL encourages students to integrate conceptual understanding with 4Cs throughout the learning process (Bell, 2010; Kokotsaki et al., 2016; Beckett, 2023). Numerous empirical studies have demonstrated that PjBL significantly improves students' critical thinking, creative thinking, scientific communication, collaboration, and digital literacy across various science learning contexts (Khafah et al., 2023; Guo et al., 2020; Chen et al., 2021). Furthermore, recent studies have highlighted the need for biotechnology PjBL-STEM programs to better prepare students for contemporary scientific and technological challenges (Utari et al., 2024). These findings highlight the potential of PjBL to foster students' 4C skills in biology learning.

In biology education, PjBL is frequently implemented through authentic contexts such as environmental issues, health, and biotechnology, enabling students to connect scientific concepts with real-world applications (Jiménez-Gaona & Vivanco-Galván, 2024). Biotechnology-based projects provide opportunities to investigate authentic biological problems, analyze scientific data, identify biological variables, and develop evidence-based solutions to contemporary societal challenges (Semilarski et al., 2021; Utari et al., 2024). Previous studies have demonstrated that project-based activities in science education significantly enhance students' scientific reasoning, argumentation, evidence evaluation, and inquiry skills by engaging them in practical scientific investigations (Guo et al., 2020; Markula & Aksela, 2022). Furthermore, biotechnology-oriented PjBL has been reported to improve students' creativity and problem-solving abilities (Amalia et al., 2022), while also demonstrating a positive relationship with creative thinking skills (Husna et al., 2023). Accordingly, biotechnology offers an effective context for PjBL to develop higher-order thinking and key twenty-first-century competencies (Akiri et al., 2025; Guo et al., 2020; Markula & Aksela, 2022.

Critical thinking, creativity, collaboration, and communication (4Cs) are integrated competencies that underpin effective learning and problem-solving in the twenty-first century. Critical thinking enables students to analyze information, evaluate evidence, and make informed decisions, and has been consistently associated with scientific literacy and meaningful learning (Abrami et al., 2015; Listiani et al., 2022; Lubis et al., 2025; Franco-Mariscal, 2025). Creativity complements critical thinking by enabling learners to generate original ideas and innovative solutions through authentic inquiry and project activities (Choi et al., 2019; Husna & Handayani, 2023; Khafah et al., 2023). In addition, collaboration and communication are equally essential, as PjBL engages students in teamwork, discussion, negotiation, and knowledge sharing to accomplish common goals. These competencies are strengthened through meaningful social interaction, authentic project experiences, and technology-supported collaboration, consistent with the principles of social constructivism (Baran et al., 2021; Fleer, 2020; Iftanti et al., 2025; Sari et al., 2024; Yani et al., 2026).

Contemporary education emphasizes the integration of scientific knowledge, creativity, digital literacy, and problem-solving skills to prepare students for increasingly complex global challenges. Accordingly, PjBL and problem-solving approaches have been widely recognized as effective pedagogical strategies for promoting 21st century competencies by engaging learners in authentic, inquiry-based, and collaborative learning experiences (Guo et al., 2020; Tarigan, 2025; UNESCO, 2021; Zhang & Ma, 2023). Despite these educational priorities, evidence from international assessments and recent studies indicates that many students continue to demonstrate insufficient critical thinking, creativity, collaboration, and communication skills in authentic science learning contexts (Franco-Mariscal, 2025; OECD, 2019). In biology education, classroom instruction also remains largely focused on conceptual knowledge acquisition, providing limited opportunities for scientific inquiry, evidence-based reasoning, and collaborative knowledge construction, particularly in biotechnology learning where students are expected to solve authentic socioscientific problems (Markula & Aksela, 2022; Semilarski et al., 2021; Utari et al., 2024). Consequently, evidence describing students' actual 4Cs competencies in biotechnology learning remains limited, highlighting the need for comprehensive studies that can provide contextual evidence to support instructional improvement and curriculum development.

Although numerous studies have demonstrated the effectiveness of PjBL in improving students' critical thinking, creativity, collaboration, and communication skills, most investigations have primarily evaluated intervention outcomes rather than profiling students' twenty-first-century competencies (Busnawir et al., 2025; Chen & Yang, 2019; Zhang & Ma, 2023). Furthermore, research has predominantly been conducted in general science or STEM contexts, whereas studies examining students' 4Cs profiles in biotechnology learning at the senior high school level remain limited (Markula & Aksela, 2022). Recent evidence also suggests that the relationships among 4Cs, biological literacy, and biology learning outcomes are still rarely examined simultaneously (Franco-Mariscal, 2025; Yudhistian & Cintamulya, 2026). Biotechnology offers an authentic context for fostering and assessing twenty-first-century competencies through PjBL (Sapitri et al., 2024; Semilarski et al., 2021). Nevertheless, empirical evidence describing students' actual profiles of 4Cs during biotechnology project activities remains scarce, limiting efforts to identify students' strengths, learning needs, and appropriate instructional interventions (OECD, 2023; Zhang & Ma, 2023).

To address these limitations, a more comprehensive profiling approach is required. Nevertheless, empirical evidence describing students' actual 4Cs profiles in biotechnology learning at the senior high school level remains limited, particularly within specific local educational contexts (van Laar et al., 2020). Baseline information regarding students' critical thinking, creativity, collaboration, and communication competencies is still insufficient, as previous studies have primarily focused on measuring learning outcomes following instructional interventions rather than documenting students' existing competency profiles (Care & Kim, 2018). Moreover, many investigations have relied on a single assessment approach, despite evidence suggesting that combining self-assessment and peer assessment provides a comprehensive and valid representation of students' twenty-first-century competencies by integrating self-perceptions with observable peer evaluations (Panadero et al., 2016; Yan et al., 2022). Recent studies emphasize that authentic twenty-first-century skills assessment requires multiple evidence sources, including self-, peer-, and performance assessment, observations, and project artefacts to assess higher-order thinking and collaborative performance (Care & Kim, 2018; Papagiannis & Pallaris, 2024; Zhang & Ma, 2023). Therefore, profiling students' 4Cs through multiple assessment sources in biotechnology-based PjBL is essential for generating contextual baseline evidence that can inform biology instruction, assessment practices, and curriculum improvement in South Labuhanbatu Regency.

This study aims to profile senior high school students' twenty-first-century 4Cs skills in biotechnology learning implemented through PjBL. Unlike previous studies that have primarily examined the effects of PjBL on specific outcomes, such as creative thinking, problem solving, and ecopreneurship (Achmad et al., 2024; Husna et al., 2023), this study focuses on students' actual levels of critical thinking, creativity, collaboration, and communication. Using multiple data sources, including self-assessment, peer assessment, classroom observation, and project documentation, this study provides a comprehensive profile of students' 4Cs competencies through authentic, multi-source assessment approaches that integrate multiple forms of evidence to evaluate complex twenty-first-century competencies (Brandt et al., 2025; Zhang & Ma, 2023). Given the limited empirical evidence regarding students' 4Cs profiles in biotechnology-based PjBL, particularly in developing countries, this study contributes baseline evidence to support future instructional improvement, assessment development, and curriculum refinement (Busnawir et al., 2025; Romero, 2026). Accordingly, this study addresses the following research question: What is the profile of senior high school students' twenty-first-century 4Cs in biotechnology-based project-based learning?

This study contributes to the literature on 21st-century skills and PjBL by providing empirical evidence of students' 4Cs profiles in biotechnology learning. Practically, the findings offer insights for biology teachers, curriculum developers, and policymakers to strengthen the integration of critical thinking, creativity, collaboration, and communication within secondary biology education.

METHOD

This study employed a descriptive cross-sectional survey design (Creswell, 2022) to profile senior high school students' 21st-century skills in biotechnology-based PjBL. This design is suitable for examining students' characteristics, perceptions, and competencies at a specific point in time using standardized data collection procedures.

Data were collected through self- and peer-assessment questionnaires, observation rubrics, and project documentation to provide a comprehensive profile of students' 4C skills. This design was selected to describe the current status of students' 4Cs in biotechnology-based project learning rather than to explore their lived experiences in depth.

The research participants consisted of 157 students involved in biotechnology project implementation across five senior high schools in South Labuhanbatu Regency: SMA Negeri 1 Kampung Rakyat (33 students), SMA Negeri 1 Sei Kanan (29 students), SMA Negeri 1 Silangkitang (30 students), SMA Negeri 2 Kotapinang (31 students), and SMA Negeri 2 Torgamba (34 students). Self- and peer-assessments were used as complementary data sources to triangulate students' 4Cs by comparing self- and peer perceptions. The participants were selected using purposive sampling based on three inclusion criteria: (1) participation in the complete biotechnology-based PjBL program, (2) active involvement in project activities under teacher supervision, as confirmed through attendance records and classroom observations, and (3) completion of all self-assessment, peer-assessment, and observation instruments. These criteria ensured that participants had sufficient project experience and complete assessment data to provide valid and relevant information for profiling their 21st-century 4Cs.

The research instruments comprised rubrics, self-assessment and peer-assessment questionnaires, and observation sheets to assess students' 4Cs. The 4Cs instrument was developed based on established 21st-century skills frameworks. Critical thinking was assessed using the FRISCO indicators (Focus, Reason, Inference, Situation, Clarity, and Overview); creativity through fluency, flexibility, originality, and elaboration; collaboration through working productively, demonstrating respect, compromise, and shared responsibility; communication through oral communication, receptive communication (listening, reading, and viewing), discerning intent, using communication strategies, communicating clearly for a purpose, and presentation skills. The study used self- and peer-assessment questionnaires with 84 and 20 close-ended items, respectively. All items were rated using a four-point Likert scale ranging from 1 (strongly disagree) to 4 (strongly agree). Representative questionnaire items included: “I can identify the key issue or main question underlying a problem” (critical thinking), “I am able to elaborate my ideas into a well-developed and comprehensive plan” (creativity), “I work collaboratively with my group members to complete group tasks efficiently” (collaboration), and “I communicate my ideas clearly and appropriately in different situations” (communication). Scores for each construct were summed, converted into percentages, and interpreted using predefined criteria. Observation sheets were used to record students’ participation and interactions during project activities, while project documentation, including presentations and final products, provided supporting evidence for assessing students’ 4Cs.

Data were collected through observations conducted three times during biotechnology-based PjBL, covering the planning, implementation, and presentation–reflection stages, with each session lasting approximately 90 minutes. The observations were carried out directly in the classroom by trained observers using structured observation sheets. During each session, observers recorded students' observable behaviors related to the 4Cs, including how they identified problems, generated ideas, collaborated in groups, communicated during discussions, and presented project outcomes. The observers did not intervene in the learning process but focused on documenting students’ participation, interactions, and performance during project activities. Questionnaires were administered upon project completion. All instruments were reviewed and validated by experts in biology education and educational assessment for content relevance, clarity, and alignment with the 4Cs constructs. Reliability analysis of the self-assessment instrument yielded Cronbach’s alpha coefficients of 0.860 (critical thinking), 0.797 (creativity), 0.891 (collaboration), and 0.878 (communication), indicating acceptable to good internal consistency. Teacher interviews supported data triangulation and strengthened the credibility of the findings.

Data were analyzed using descriptive statistical techniques appropriate for a descriptive cross-sectional survey design (Creswell, 2022). Responses from the self-assessment, peer-assessment, and observation sheets were first checked for completeness and consistency. Incomplete or invalid responses were excluded from the analysis. The remaining responses were coded, scored according to the four-point Likert scale, tabulated, and converted into percentage scores for each 4Cs dimension. Mean scores and percentages were then calculated and classified into three categories based on the criteria adapted from Siregar (2017): low (0–60), moderate (61–80), and high (81–100). Observation records and teacher interviews were used to triangulate and support the interpretation of the quantitative findings. Results were presented in tables and figures to describe students' profiles of critical thinking, creativity, collaboration, and communication.

RESULTS AND DISCUSSION

Classroom observations indicated that students participated in biotechnology project activities and demonstrated elements of 4Cs during the learning process. Students were generally able to work in groups, discuss project-related tasks, share responsibilities, and communicate their ideas during group discussions and presentations. However, the level of participation varied among students, with some showing active involvement while others tended to rely on more dominant group members. During problem-solving activities, students were able to identify problems and propose possible solutions, although their arguments and justifications were not always supported by comprehensive scientific reasoning. Similarly, while students contributed ideas during project development, many of these ideas were adaptations of existing examples rather than highly original or innovative solutions.

Teacher interviews provided further insights into students' 4Cs during project implementation. Teachers reported that project-based learning encouraged students to become more engaged in learning activities and increased opportunities for interaction, discussion, and teamwork. Students appeared more willing to express opinions, ask questions, and participate in group tasks than in conventional classroom instruction. Nevertheless, teachers observed that some students still experienced difficulties in evaluating information critically, generating creative ideas independently, and communicating scientific concepts in a clear and convincing manner. Teachers also noted that students' collaboration skills were generally more evident than their creativity and critical thinking skills. Overall, the observation and interview findings suggest that students demonstrated the four 21st-century skills during biotechnology project activities; although their performance remained at a moderate level and required further instructional support for development.

The interview results also indicate that students' communication skills develop through presentations, discussions, debates, question-and-answer sessions, and role-playing activities. The researcher also observed an increase in some students' confidence in expressing their opinions; however, significant barriers remain, including fear of making mistakes, embarrassment when speaking in front of the class, and a learning environment that is not yet fully conducive to this. These conditions contribute to unequal participation, in which only certain students are verbally dominant. Interview findings revealed that biotechnology projects implemented in the sampled schools primarily resulted in posters, presentation slides, simple reports, and conceptual models. Teachers reported that these products mainly emphasized information presentation and content understanding, while activities involving data analysis, evidence-based decision-making, and evaluation of alternative solutions were still limited.

Findings from classroom observations and teacher interviews were used to complement and triangulate the quantitative results. The observations and interviews generally indicated that students demonstrated the four 21st-century skills during biotechnology project activities, although their performance varied across skill domains and remained at a moderate level overall. The following research findings present a comparison of the percentages of 21st century skills assessed through students' self-assessments and peer assessments across four main skill domains: critical thinking, creativity, collaboration, and communication. Overall, a relatively consistent pattern is observed between the two types of assessments, although notable differences appear in certain skill aspects.

Critical thinking skills

In the critical thinking skills domain, students' self-assessment yielded a score of 67.73%, which falls into the moderate category, while peer assessment results were slightly lower at 66.07%, also categorized as moderate. This relatively small difference indicates that students' perceptions of their own critical thinking abilities were generally consistent with those of their peers. The findings indicate moderate abilities in analysis, information evaluation, and problem-solving. These findings are consistent with previous studies showing that PjBL improves students' critical thinking, although the extent of improvement depends on the quality of inquiry tasks, teacher scaffolding, and opportunities for evidence-based reasoning (Facione, 2015; Guo et al., 2020). According to social constructivist theory, authentic problem-solving activities encourage learners to construct knowledge through investigation and reflection (Vygotsky, 1978). The moderate level of critical thinking observed in this study suggests the need for instructional strategies that provide more structured scaffolding and richer opportunities for higher-order thinking, as illustrated in Figure 1.

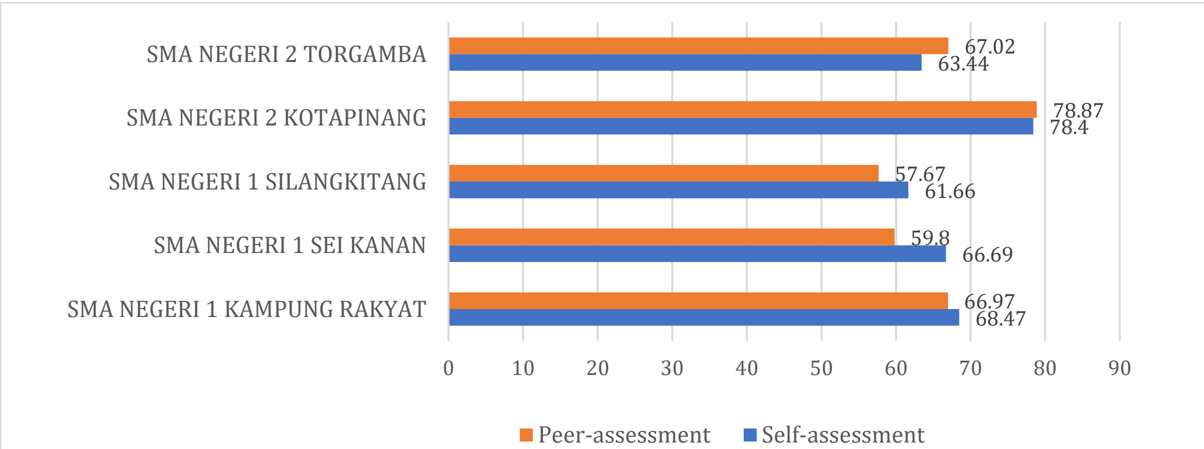

Figure 1. Average of students' critical thinking skills.

Creativity skills

In the aspect of creativity skills, a relatively stable condition is observed between the self-assessment score of 64.25%, categorized as moderate, and the peer assessment score of 64.34%, also categorized as moderate. These nearly identical values indicate a consistency in perceptions regarding students' ability to generate new and innovative ideas, as well as their imaginative capacity in completing assignments. This percentage indicates a moderately good level of creativity. Creativity develops when students are provided with opportunities for divergent thinking, experimentation, and autonomy during project work (Beghetto, 2020). Consistent with previous studies, PjBL enhances creativity when projects require students to design original solutions rather than reproduce existing products (Guo et al., 2020; Kokotsaki et al., 2016; Priani et al., 2025; Sapitri et al., 2024). However, the results suggest that students' creativity has not yet reached its full potential, indicating the need for learning experiences that provide greater opportunities for experimentation, exploration, and creative production, as illustrated in Figure 2.

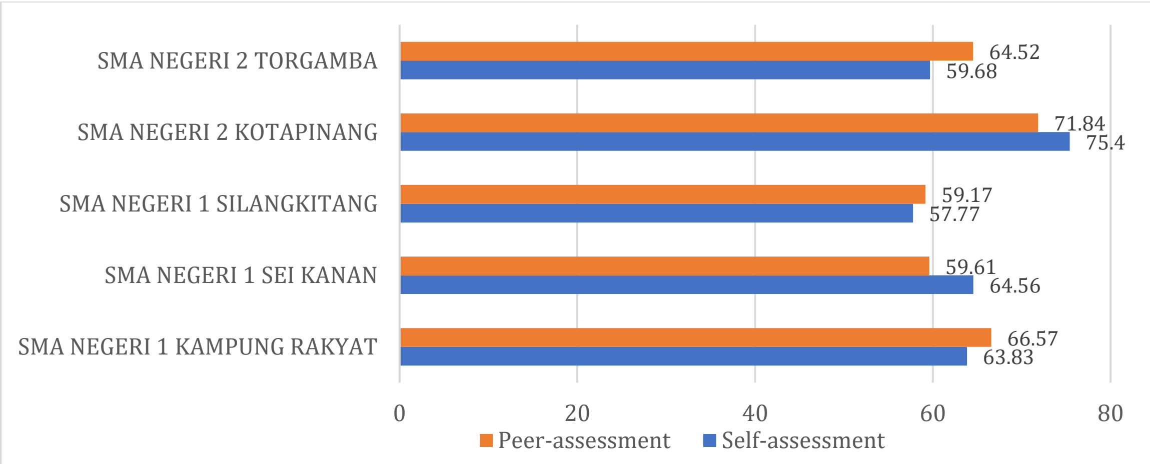

Figure 2. Average of students' creativity skills

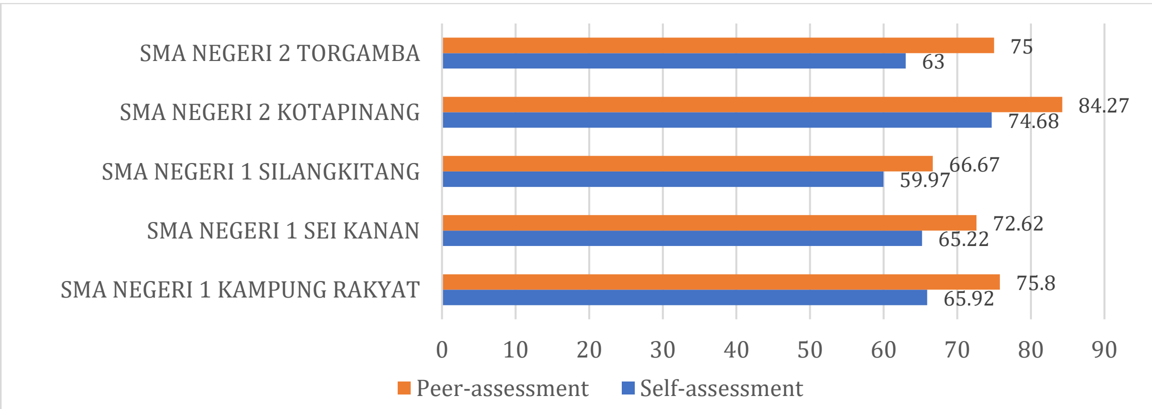

Figure 3. Average of students' collaboration skills

Collaboration skills

The aspect of students' collaboration skills shows the most striking difference between self-assessment and peer assessment. Students rated themselves at 65.76%, categorized as moderate, whereas peer assessment reached 74.87%, which is the highest percentage among all other skill aspects. This finding suggests that students tend to underestimate their collaborative abilities, whereas their peers perceive these skills as very good. This pattern is consistent with social interdependence theory, which emphasizes that collaborative learning promotes positive interdependence, shared responsibility, and mutual accountability among group members (Shimizu et al., 2022).These results indicate a tendency toward self-underestimation within a positive collaborative learning culture, as illustrated in Figure 3.

Communication skills

The aspect of students' communication skills shows a very small difference in mean scores between self-assessment and peer assessment. The mean self-assessment score is 67.74%, categorized as moderate, while the peer assessment score is slightly higher at 67.91%, also categorized as moderate. This minimal difference suggests that students' perceptions of their own communication abilities are relatively aligned with those of their peers, although there is a slight tendency for students to rate themselves lower. These findings indicate that students' communication skills are relatively well developed and consistent across the learning environment. This is consistent with studies showing that scientific discourse, presentations, and collaborative dialogue are essential for developing communication skills in inquiry-based science learning (Bell, 2010; OECD, 2019; Partnership for 21st Century Learning, 2019). The comparison of mean scores is illustrated in Figure 4.

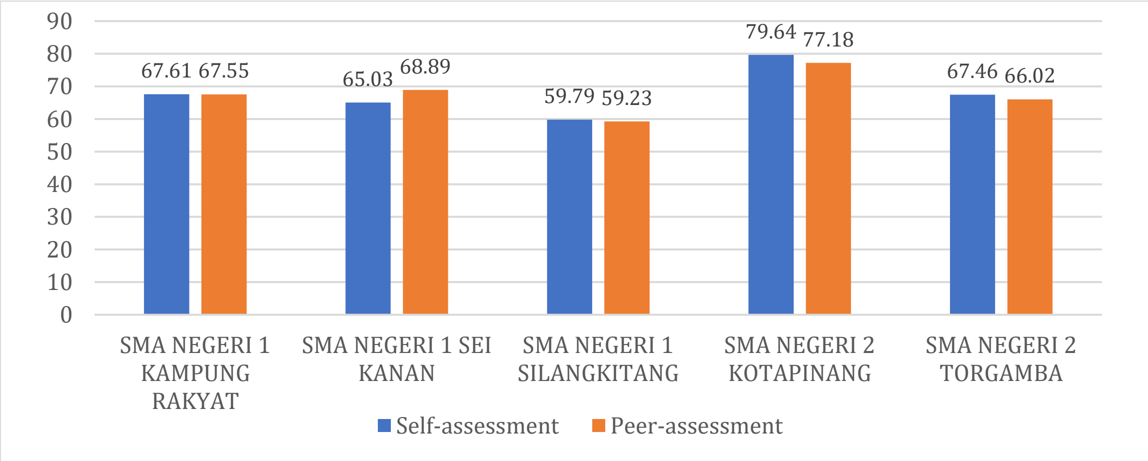

Figure 4. Average of students' communication skills

Project-Based Learning (PjBL) provides a learning environment that systematically promotes the development of 21st-century skills through its six instructional phases: (1) Start with the Essential Question, (2) Design a Plan for the Project, (3) Create a Schedule, (4) Monitor the Students and the Progress of the Project, (5) Assess the Outcome, and (6) Evaluate the Experience (Bell, 2010; Larmer et al., 2015). In biotechnology learning, PjBL begins with authentic scientific problems, such as environmental pollution, food biotechnology, or waste management, which encourage students to identify issues, formulate questions, analyze information, and propose explanations. These activities foster critical thinking through interpretation, analysis, inference, and evaluation (Facione, 2015). Previous studies have shown that authentic inquiry and problem-solving activities significantly enhance students' ability to evaluate evidence and make reasoned judgments (Anazifa & Djukri, 2017; Guo et al., 2020).

During the Design a Plan for the Project and Create a Schedule phases, students collaboratively determine project objectives, select methods, allocate responsibilities, identify required resources, and organize project timelines. These activities foster creativity because students are given autonomy to generate original ideas, design innovative procedures, and propose multiple solutions to scientific problems. The theoretical foundation for this process can be traced to constructivist learning theory, which views knowledge construction as an active and creative process (Erawati & Adnyana, 2024; Piaget, 1972; Vygotsky, 1978). Furthermore, creativity is strengthened when learners are provided with opportunities for divergent thinking and problem solving in authentic contexts. Research conducted in STEM and science education consistently reports that PjBL enhances students' creative thinking through project design, product development, and innovation-oriented tasks (Kokotsaki et al., 2016).

Project implementation, students engage in task distribution, negotiation, collective decision-making, and conflict resolution, reflecting the social constructivist perspective that learning occurs through social interaction (Vygotsky, 1978). These collaborative experiences foster teamwork, communication, leadership, and shared responsibility, while enabling students to exchange ideas and co-construct knowledge. Consistent with previous studies, PjBL promotes collaborative problem-solving and strengthens students' ability to coordinate actions, manage group dynamics, and contribute effectively to team performance, which are essential competencies for 21st-century learning (OECD, 2019).

The assess the outcome and evaluate the experience phases strengthen students' communication skills through presentations, reports, and reflective discussions that require evidence-based reasoning and effective communication of scientific ideas. Consistent with 21st-century learning frameworks, these activities promote scientific literacy while supporting the integrated development of critical thinking, creativity, collaboration, and communication, making PjBL particularly suitable for biotechnology learning and authentic problem solving (Bell, 2010; Guo et al., 2020; Partnership for 21st Century Learning, 2019).

In-depth analysis of the alignment and discrepancies between self-assessment and peer assessment in measuring students' 21st-century 4Cs

The comparing self- and peer-assessments provide valuable insights into students' perceptions of their 21st-century 4Cs skills. The degree of alignment between the two reflects students' self-awareness as well as the social interactions developed during PjBL. In biotechnology projects, where students engage in investigation, discussion, and product development, combining both assessment perspectives offers a more comprehensive understanding of students' demonstrated critical thinking, creativity, collaboration, and communication.

In the aspect of critical thinking skills, a relatively high level of alignment is observed between self-assessment and peer assessment. Students rated their critical thinking abilities at 67.73%, while peers assigned a score of 66.07%. This alignment suggests that students have a relatively objective perception of their analytical and problem-solving skills. Consistent with Rahmadayanti et al., (2022), critical thinking is assessed through observable cognitive processes, including analysis, evaluation, and inference. As PjBL engages students in authentic problem-solving activities, self-assessments tend to reflect abilities demonstrated during information processing, argument construction, and conclusion drawing, resulting in relatively consistent evaluations.

In the aspect of creativity skills, the self-assessment score of 64.25% and the peer-assessment score of 64.34% indicate an almost identical level of consistency in their mean values. Creativity is an aspect that is often perceived subjectively; however, within the context of PjBL, creativity indicators are more readily observable through the project products, alternative ideas, and innovative strategies that students design. In line with the systematic review by Purba et al. (2022), creativity in PjBL is predominantly assessed through project outputs as tangible products that represent students' creative performance. The presence of concrete project artifacts provides a clear and observable basis for evaluation, thereby supporting more consistent judgments when students engage in self-assessment and peer assessment of creativity, particularly in evaluating the product dimension of creativity. Therefore, the alignments observed in creativity skills in this study may indicate that the creativity indicators employed were well understood by students and that the project process enabled a more objective identification of creative contributions.

The most pronounced discrepancy emerges in the aspect of collaboration skills, where the self-assessment score is 65.76%, compared to a peer-assessment score of 74.87%. This nearly 10% difference indicates a tendency toward self-underestimation among students when evaluating their own collaboration abilities. Meanwhile, peers perceive these collaborative contributions as relatively strong. This phenomenon is well documented in the collaborative learning literature. According to Panadero et al. (2017), students often assign lower collaboration scores to themselves due to greater awareness of their limitations, whereas peers evaluate broader aspects of participation and communication, resulting in higher ratings.

Cultural context may partly explain the discrepancy in collaboration assessments. In the Indonesian educational setting, students often evaluate their own collaborative abilities more conservatively due to social norms that emphasize humility and discourage self-promotion. As a result, students tend to assign lower scores to themselves, whereas peers who observe their effort and participation may provide higher ratings. Similarly, Rasooli et al. (2024) found that students' self-assessments in collaborative contexts are influenced by perceptions of fairness, sensitivity to social judgment, and reluctance to overestimate their contributions. These differences may reflect both students' collaboration skills and the cultural and fairness-related factors shaping self-evaluation in group work.

Assessment discrepancies may also be influenced by differences in how collaboration indicators are interpreted. Greenstein (2012) noted that indicators such as working productively, showing respect, compromising, and sharing responsibility are often perceived differently by self- and peer assessors. Students tend to evaluate their collaboration through internal reflection on the quality of their contributions, whereas peers focus more on observable behaviors such as participation and involvement. Similar patterns have been reported in studies of self- and peer assessment, suggesting that differences in assessment outcomes reflect variations in assessment focus rather than differences in collaboration skills alone (Rasooli et al., 2024).

Unlike other 4Cs domains, communication skills showed the strongest agreement between self- and peer-assessments, with scores of 67.74% and 67.91%, respectively. This consistency suggests that communication is more readily observable and objectively evaluated by students. In PjBL, activities such as presentations, discussions, question-and-answer sessions, and report writing provide authentic opportunities for students to develop and demonstrate communication skills. According to the Partnership for 21st Century Learning (P21), effective communication involves expressing ideas clearly through oral, written, and visual forms, while PjBL fosters these competencies through collaborative dialogue, knowledge sharing, and project presentations (Bell, 2010; Kokotsaki et al., 2016). Previous studies have shown that PjBL enhances communication skills by promoting active participation and scientific discourse (Chen et al., 2021; Guo et al., 2020). The close alignment between self- and peer-ratings may reflect their complementary assessment perspectives, as self-assessment emphasizes reflection and self-regulation, whereas peer assessment provides external judgments based on observable behaviors such as participation, responsiveness, and clarity of explanation (Panadero et al., 2016; Yan et al., 2022). Consequently, communication tends to be more easily recognized and appreciated by peers, contributing to the high consistency observed across both assessment methods.

In the context of PjBL, group interaction dynamics also constitute one of the main causes of assessment discrepancies. Processes such as task distribution, group conflict resolution, and decision making are often more visible to other group members than to the individual concerned. In line with the findings of (Ranjbar et al., 2025), students' self-evaluations in group tasks are strongly influenced by their self-efficacy beliefs, particularly in oral or participatory contexts. Students who feel less confident in speaking or participating verbally may underestimate their own performance, even though collaborative settings and peer assessment often reveal that their contributions such as preparation, technical support, or behind the scenes roles are valued and recognized by their peers.

Overall, the comparison highlights the value of multiple assessment perspectives in PjBL. The consistency between self- and peer-assessments in critical thinking, creativity, and communication suggests relatively objective evaluations; differences in collaboration reflect the influence of social and contextual factors. Integrating self- and peer-assessments with reflective activities can therefore provide a more comprehensive evaluation of students' 4C skills and support their continuous development.

Teacher perspectives on factors potentially associated with variations in students' 4Cs achievement

Factors such as project design, teacher facilitation, student engagement, collaborative learning environments, and institutional support contribute significantly to the development of 21st-century skills, while trust, social presence, and peer collaboration shape meaningful learning experiences and competency growth (Joo & Ko, 2025; Suleiman, 2025). Identifying these factors is essential for understanding why certain skills, such as collaboration and communication, develop more prominently, while other aspects, such as creativity and critical thinking in this study, tend to show lower levels of achievement. A comprehensive analysis of these factors provides a strategic foundation for teachers to design learning experiences that are more effective and adaptive to the needs of 21st-century skills development.

Pedagogical factors may help explain variations in students' 4Cs achievement, as suggested by previous studies. Effective PjBL engages students in authentic inquiry, problem solving, collaboration, and reflection, but its success largely depends on teachers' ability to design meaningful projects, facilitate learning processes, monitor progress, and provide constructive feedback (Guo et al., 2020). Variations in 4Cs outcomes are also influenced by the clarity of assessment indicators, as critical thinking is generally easier to demonstrate through structured reasoning tasks, whereas creativity requires open-ended inquiry, explicit instructional support, opportunities for exploration, and authentic innovation, making it more challenging to assess consistently (Beghetto, 2019; Bouckaert 2023). Furthermore, access to adequate learning resources, including digital technologies, scientific literature, and laboratory facilities, enhances students' opportunities to engage in authentic inquiry and develop higher-order thinking skills, whereas limited resources may constrain meaningful learning experiences and creativity development (Suleiman et al., 2025).

Previous studies suggest that school, social, and cultural contexts may influence the development of 21st-century skills; however, these factors were not directly examined in the present study. Flexible curricula, supportive learning environments, effective group dynamics, and students' self-efficacy promote collaboration, communication, critical thinking, creativity, and active participation in learning (Gillies, 2016; Rasooli et al., 2024; Sahlberg, 2020). In the Indonesian context, cultural norms emphasizing modesty may constrain the expression of original ideas, whereas discussion, idea exchange, and constructive conflict resolution foster interpersonal trust, collaboration, and collective problem-solving.

Overall, variations in students' 4Cs achievement may be associated with pedagogical, contextual, and social factors. Because these variables were not directly measured, they should be interpreted as possible explanations rather than confirmed determinants. Critical thinking, communication tend to develop more readily because their indicators are clearly defined and frequently embedded in project activities, whereas creativity requires stronger pedagogical support and a learning culture that encourages idea expression. Collaboration, meanwhile, strongly influenced by social interactions and cultural values that promote collective work. Consistent with these findings, biology teachers in public senior high schools in South Labuhanbatu Regency reported that critical thinking is fostered through group discussions, case studies, guiding questions, and PjBL linked to real-world problems. However, its development remains constrained by limited instructional time, variations in students' cognitive readiness, and their tendency to passively evaluate information. Therefore, biotechnology learning should incorporate more challenging driving questions, higher-order thinking scaffolds, and reflective formative assessments to strengthen and continuously monitor students' critical thinking processes.

Teacher interviews indicated that students' creativity, collaboration, and communication skills developed through biotechnology project activities; however, their performance remained constrained by limited facilities, technology access, self-confidence, unequal participation, and weak individual accountability. Creativity emerged through experiments, visual products, and contextual tasks, but most ideas remained adaptive rather than innovative. Likewise, collaboration benefited from group work despite frequent dominance and unequal participation. These findings suggest that biotechnology-focused PjBL should incorporate open-ended projects, locally available materials, structured collaborative roles, learning contracts, process-based assessments, and explicit communication strategies, such as evidence-based discussion and role-based presentations, to strengthen creativity, scientific communication, social responsibility, and collective problem-solving as essential components of 21st-century learning.

Implications of empirical findings for strengthening the design of Project-Based Learning (PjBL) to optimize the development of 21st-century skills among senior high school students

The findings indicate that PjBL effectively supports the development of 21st-century skills, particularly communication and collaboration. However, variations in creativity achievement and discrepancies between self- and peer-assessments suggest that instructional design requires further refinement. These results highlight the need for more balanced project structures, authentic assessment practices, and targeted learning support to foster the comprehensive development of critical thinking, creativity, collaboration, and communication. Consequently, the findings provide valuable guidance for teachers, schools, and curriculum developers in designing more effective and responsive learning experiences for the demands of the 21st century. The findings, which show a relatively high level of alignment between self-assessment and peer assessment in the aspects of critical thinking and communication skills, indicate that PjBL activities are sufficiently effective in stimulating students' analytical processes and their ability to articulate ideas. This suggests that the design of PjBL should maintain strong investigative components that encourage students to analyze information, solve problems, and construct well-reasoned arguments.

Project-based learning promotes critical thinking through inquiry, authentic problem solving, and scientific presentations that require students to analyze, justify, and defend evidence-based arguments (Savery, 2015). Effective implementation requires projects that emphasize not only product creation but also data analysis, decision-making, and evaluation of alternative solutions across key PjBL stages (Thomas, 2000). Interview findings revealed that biotechnology projects in the sampled schools primarily produced posters, presentation slides, simple reports, and conceptual models, with limited emphasis on evidence-based reasoning and higher-order decision-making. These findings suggest a need for project designs that require students to analyze data, evaluate alternatives, and justify decisions using scientific evidence.

The findings indicate that creativity achieved the lowest performance among the 4Cs, suggesting that the current PjBL design has not fully provided opportunities for exploration, innovation, and originality. To address this, projects should incorporate open-ended challenges, multiple solution pathways, and greater student autonomy, as these design features encourage creative thinking, idea generation, and authentic problem solving (Condliffe et al., 2017; Thomas, 2000). In biotechnology learning, this may involve designing innovative products, modifying experimental procedures, or creating scientific visualizations, thereby shifting the focus from product completion to the creative process itself and supporting the more effective development of students' creativity.

In addition, the findings related to alignment in the assessment of communication skills carry important implications for strengthening students' scientific literacy. The presentation of project outcomes, structured group discussions, and scientific report writing should be positioned as core components of PjBL. Teachers therefore need to provide explicit guidance on scientific communication, the effective use of digital presentation tools, and evidence-based argumentation. Regular opportunities to present findings, communicate evidence, and respond to feedback enhance scientific communication, argumentation, and reflective thinking skills (Chourio-Acevedo et al., 2024; Guo et al., 2020; Tarr & Alicea-Muñoz, 2024).

Findings related to collaboration skills reveal a notable discrepancy between self-assessment and peer assessment, with peers consistently rating collaborative performance higher than students rate themselves, suggesting that students tend to underestimate their own contributions within group work. This phenomenon underscores the importance of integrating structured collaborative roles into the design of PjBL. Clearly defined role assignments enhance individual accountability and support students in recognizing and valuing their personal contributions to group success. Moreover, role clarity strengthens students' self-perceptions in collaborative assessment by providing explicit expectations regarding responsibilities, task scope, and indicators of successful participation (Gillies, 2019). When collaborative roles are well structured, students are better positioned to evaluate their collaboration skills more objectively. In addition, teachers should incorporate regular group reflection sessions to promote students' self-awareness of individual contributions and group dynamics, thereby fostering more accurate self-assessment and more effective collaboration.

The findings suggest that the development of students' 4Cs is influenced not only by instructional design but also by contextual factors, including learning environments, facilities, and school support. Adequate infrastructure, such as laboratories, digital technologies, internet access, and sufficient time for project work, is essential for effective PjBL implementation and the development of critical thinking and collaboration skills (Savery, 2015). Furthermore, the alignment observed in critical thinking, collaboration, and communication highlights the value of integrating self- and peer-assessment as formative assessment practices that promote reflection, motivation, and learner responsibility (Panadero et al., 2018). The relatively lower achievement of creativity also underscores the need for pedagogical innovation through the integration of digital technologies, STEM, design thinking, maker education, and digital storytelling approaches, which have been shown to enhance creativity and innovation more effectively than traditional PjBL alone (Kokotsaki et al., 2016; Perignat & Katz-Buonincontro, 2019).

The high level of collaboration suggests that the cultural value of mutual cooperation can be leveraged to strengthen PjBL through structured collaborative practices, such as role distribution, peer mentoring, and role rotation (Johnson & Johnson, 2017; Rasooli et al., 2024). Overall, the findings highlight the need to enrich PjBL with deeper inquiry, greater opportunities for creativity, scientific communication, and clearer collaborative roles to support the balanced development of critical thinking, creativity, collaboration, and communication in 21st-century learning.

CONCLUSION

This study found that the 21st-century 4Cs of public senior high school students in South Labuhanbatu Regency were generally at a moderate level, with communication and collaboration emerging as the strongest competencies, while creativity remained the least developed. The substantial alignment between self- and peer-assessments in most skill domains indicates a satisfactory level of assessment consistency, although differences in collaboration ratings may reflect variations in students' perceptions and social interactions. The findings describe students' 4Cs profiles within the context of biotechnology-based PjBL and suggest that such learning environments may provide opportunities for students to demonstrate communication, collaboration, critical thinking, and creativity. The results also highlight the importance of strengthening inquiry-based activities, structured collaboration, authentic communication practices, and formative assessment within PjBL. Limited to a single regency and a cross-sectional design, this study has restricted generalizability. Future research should examine innovative STEM-integrated and technology-enhanced PjBL approaches across broader populations and investigate factors associated with variations in students' 4Cs achievement.

REFERENCES

Abrami, P. C., Bernard, R. M., Borokhovski, E., Waddington, D. I., Wade, C. A., & Persson, T. (2015). Strategies for Teaching Students to Think Critically: A Meta-Analysis. *Review of Educational Research*, *85*(2), 275–314. https://doi.org/10.3102/0034654314551063

Achmad, A. A., Zulfiani, & Solihin. (2024). Development of live worksheet based on project-based learning to promote creative thinking and ecopreneurship on biotechnology concepts. *International Journal of STEM Education for Sustainability*, *4*(2), 176–201.

Akiri, E., Lesmes, U., Shpigelman, A., & Dori, Y. J. (2025). Project-based learning outcomes: Chemical knowledge and thinking skills of biotechnology and food engineering undergraduate students. *EURASIA: Journal of Mathematics, Science and Technology Education*, *21*(10), 1–18.

Amalia, G. R., Kurniasih, S., & Jaenudin, D. (2022). Project-based learning on biotechnology materials to enhance high school students' creativity and problem-solving skills. *JSEP (Journal of Science Education and Practice*, *6*(1), 51–64.

Anazifa, R. D., & Djukri. (2017). Project- based learning and problem- based learning: are they effective to improve student's thinking skills? *Jurnal Pendidikan IPA Indonesia*, *6*(2), 346–355. https://doi.org/10.15294/jpii.v6i2.11100

Baran, M., Karakoyun, F., & Maskan, A. (2021). The influence of project-based STEM (PjbL-STEM) applications on the development of 21st-century skills. *Journal of Turkish Science Education*, *18*(4), 798–815. h

Beckett, G. H. (2023). Project-based learning for 21st-century skills: The five C'S for L2 students. *Docens Series in Education*, *5*(May), 40–57.

Beghetto, R. A. (2020). On creative thinking in education: Eight questions, eight answers. *Future EDge*, *1*, 48–71.

Bell, S. (2010). Project-based learning for the 21st century: Skills for the future. *The Clearing House: A Journal of Educational Strategies, Issues and Ideas*, *83*, 39–43.

Bouckaert, M. (2023). *The assessment of students' creative and critical thinking skills in higher education across OECD countries: A review of policies and related practices* (OECD Education Working Papers No. 293). OECD Publishing. https://doi.org/10.1787/35dbd439-en

Brandt, C., Evans, C., & Domaleski, C. (2025). *Assessing 21st century competencies: Guiding principles for states and districts* (Issue January). National Center for the Improvement of Educational Assessment.

Busnawir, Yuniwati, I., Mardiati, & Sitepu, E. (2025). The effectiveness of project-based learning in developing the 21st century skills. *Darussalam: Journal of Psychology and Educational*, *4*(1), 35–50.

Care, E., & Kim, H. (2018). Assessment of twenty-first century skills: The issue of authenticity. *Springer*, 21–39. https://doi.org/10.1007/978-3-319-65368-6

Chen, J., Kolmos, A., & Du, X. (2021). Forms of implementation and challenges of PBL in engineering education: A review of literature. *European Journal of Engineering Education*, *46*(4), 1-26. https://doi.org/10.1080/03043797.2020.1718615

Choi, J., Lee, J.-H., & Kim, B. (2019). How does learner-centered education affect teacher self-efficacy? The case of project-based learning in Korea. *Teaching and Teacher Education*, *85*, 45–57.

Chourio-Acevedo, L., Köhler, J., Coscarelli, C., Gacitúa, D., Proaño-Ríos, V., & González-Ibáñez, R. (2024). *Information literacy development and assessment at school level: A systematic review of the literature*. arXiv. https://doi.org/10.48550/arXiv.2404.19020

Condliffe, B., Quint, J., Visher, M. G., & Bangser, M. R. (2017). *Project-based learning: A literature review* (Issue October). MDRC.

Creswell, J. W. (2022). *A concise introduction to mixed methods research second*. SAGE Publications.

Erawati, N. K., & Adnyana, P. B. (2024). Implementation of Jean Piaget's theory of cognitive development in education. *International Journal of Education and Development*, *5*(3), 394–401.

Facione, P. A. (2015). *Critical thinking: What it is and why it counts*. Insight Assessment. https://www.law.uh.edu/blakely/advocacy-survey/Critical Thinking Skills.pdf?

Fleer, M. (2020). Studying the relations between motives and motivation – How young children develop a motive orientation for collective engineering play. *Learning, Culture and Social Interaction*, *24*(7), 1–20. https://www.monash.edu/education/research/projects/conceptual-playlab/publications/working-papers/2020-Preprint-Fleer.-Studying-the-relations-between-motives-and-motivation-How-young-children-develop-a-motive-orientation-for-collective-engineering-play.pdf

Franco-Mariscal, A. J. (2025). *Critical thinking in science education and teacher training*. Springer Nature. https://link.springer.com/book/10.1007/978-3-031-78578-8?

Gillies, R. M. (2016). Cooperative learning: Review of research and practice. *Australian Journal of Teacher Education*, *41*(3), 39–54.

Greenstein, L. (2012). *Assessing 21st century skills: A guide to evaluating mastery and authentic learning.* (H. Perigo (ed.)). Corwin A Sage Company.

Guo, P., Saab, N., Post, L. S., & Admiraal, W. (2020). A review of project-based learning in higher education : Student outcomes and measures. *International Journal of Educational Research*, *102*(May), 101586. https://doi.org/10.1016/j.ijer.2020.101586

Husamah, Adlini, M. N., Luzyawati, L., & Lestari, N. (2024). Trends and coverage of strengthening literacy in biology learning: Systematic literature review of the Scopus database in four decades. *Jurnal Biolokus: Jurnal Penelitian Pendidikan Biologi Dan Biologi*, *7*(1), 19–38. http://dx.doi.org/10.30821/biolokus.v7i1.3550

Husna, A., & Handayani, D. (2023). Correlation analysis of biotechnology theme project-based learning with students creative thinking skills at the junior high school A . Introduction. *BIO-INOVED : Jurnal Biologi-Inovasi Pendidikan*, *5*(3), 341–347.

Iftanti, D. A., Sari, M. W., & Probosari, R. M. (2025). The effect of the PjBL-STEAM model on students' creative thinking and scientific communication skills in biotechnology. *Innovations in Science Education and Practice*, *2*(1), 8–24.

Jiménez-Gaona, Y., & Vivanco-Galván, O. (2024). Biotechnology project-based learning encourages learning and mathematics application. *Frontiers in Education*, *9*(April), 1–9. https://doi.org/10.3389/feduc.2024.1364640

Joo, S. H., & Ko, E. G. (2025). [AI peers] are people learning from the same standpoint: Perception of AI characters in a Collaborative Science Investigation. *Proceedings of Artificial Intelligence in Education (AIED)*, 1–14. https://arxiv.org/pdf/2506.06165

Johnson, D. W., & Johnson, R. T. (2017). *The use of cooperative procedures in teacher education and professional development*. *Journal of Education for Teaching*, *43*(3), 284–295. https://doi.org/10.1080/02607476.2017.1328023

Khafah, F., Suprapto, P. K., & Nuryadin, E. (2023). The effect of project-based learning model on students ' critical and creative thinking skills in the ecosystem concept. *JPBI (Jurnal Pendidikan Biologi Indonesia)*, *9*(3), 244–255.

Kokotsaki, D., Menzies, V., & Wiggins, A. (2016). Project-based learning: A review of the literature. *Improving Schools*, *19*(3), 267–277.https://doi.org/10.1177/1365480216659733

Kurniawan, A., Jumadi, Kuswanto, H., & Syar, N. I. (2024). The 21st century education: A systematic literature review of transforming learning methods to foster critical thinking skills through augmented reality. *Jurnal Eduscience (JES)*, *11*(3), 601–622.

Larmer, J., Mergendoller, J. R., & Boss, S. (2015). *Setting the standard for project based learning: A proven approach to rigorous classroom instruction*. ASCD. https://www.ascd.org/books/setting-the-standard-for-project-based-learning?variant=114017

Lenzer, S., Pannullo, L., Nehring, A., & Stinken-Rösner, L. (2024). *Towards Scientific Literacy in Inclusive Science Education*. Springer Nature. https://arxiv.org/pdf/2411.03020

Listiani, I., Susilo, H., & Sueb. (2022). Relationship between scientific literacy and critical thinking of prospective teachers. *Al-Ishlah: Jurnal Pendidikan*, *14*(1), 721–730. https://doi.org/10.35445/alishlah.v14i1.1355

Lubis, A., Pantiwati, Y., & Rahardjanto, A. (2025). Students' scientific literacy in critical thinking skills in science learning: A bibliometric analysis from the scopus database. *Bioscientist: Jurnal Ilmiah Biologi*, *13*(2), 1100–1112.

Markula, A., & Aksela, M. (2022). The key characteristics of project-based learning: how teachers implement projects in K-12 science education. *Disciplinary and Interdisciplinary Science Education Research*, *4*(2), 1–17.

Mujriati, A., Purwoko, A. A., Rudyat, L., & Savalas, T. (2025). A systematic review of scientific inquiry research: Trends in science literacy and critical thinking (2016 – 2025). *Current Educational Review*, *1*(3), 110–121. https://doi.org/10.56566/cer.v1i3.404

Organisation for Economic Co-operation and

Development. (2019). *OECD future of education and skills 2030: OECD learning compass 2030 a series of concept notes.* France. https://www.oecd.org/content/dam/oecd/en/about/projects/edu/education-2040/1-1-learning-compass/OECD_Learning_Compass_2030_Concept_Note_Series.pdf

Pahrudin, A., Misbah, Alisia, G., Saregar, A., Asyhari, A., Anugrah, A., & Susilowati, N. E. (2021). The effectiveness of science, technology, engineering, and mathematics-inquiry learning for 15-16 years old students based on k-13 Indonesian curriculum: the impact on the critical thinking skills. *European Journal of Educational Research*, *10*(2), 681–692. https://doi.org/10.12973/eu-jer.10.2.681

Panadero, E., Jonsson, A., & Strijbos, J.-W. (2016). Scaffolding self-regulated learning through self-assessment and peer assessment: Guidelines for classroom implementation. *Assessment for Learning: Meeting the Challenge of Implementation*, 1–15.

Papagiannis, P., & Pallaris, G. (2024). *Evaluating 21st century skills development through makerspace workshops in computer science education*. 1–5. https://arxiv.org/abs/2411.05012?

Partnership for 21st Century Learning. (2019). *Framework for 21st Century Learning. United Stated of America.* https://www.battelleforkids.org/insights/p21-resources/

Perignat, E., & Katz-Buonincontro, J. (2019). STEAM in practice and research: An integrative literature review. *Thinking Skills and Creativity, 31*, 31–43. https://doi.org/10.1016/j.tsc.2018.10.002

Piaget, J. (1972). *To understand is to invent: The future of education*. Grossman Publishers.

Priani, N. K., Hutagaol, J., Siregar, K. R., & Jumiah. (2025). Pengaruh Media Pembelajaran Interaktif Terintegrasi PBL terhadap Peningkatan Kemampuan Berpikir Kritis pada Materi Sistem Ekskresi. *BIODIK*, *11*(04), 1–8. https://doi.org/10.22437/biodik.v11i04.49831

Purba, L. S. L., Dasna, I. W., & Habiddin. (2022). Creativity in project based learning: A systematic literature study (2015-2021). *Jurnal Pendidikan MIPA*, *23*(4), 1504–1514.

Rahmadayanti, D., Zaini, M., & Kaspul. (2022). Keterampilan berpikir kritis dan hasil belajar kognitif: Pembelajaran sistem peredaran darah menggunakan LKPD-Elektronik. *Practice of the Science of Teaching Journal: Jurnal Praktisi Pendidikan*, *1*(2), 65–77.

Ranjbar, M., Mohammad, S., Amirian, R., & Vaghayei, F. (2025). A qualitative analysis of the effect of group oral presentation and peer assessment on EFL learners ' self-efficacy. *Current Psychology*, 1–14.

Rasooli, A., Turner, J., Varga-atkins, T., Pitt, E., Moindrot, W., Rasooli, A., Turner, J., Varga-atkins, T., & Pitt, E. (2024). Students' perceptions of fairness in groupwork assessment: validity evidence for peer assessment fairness instrumen. *Assessment & Evaluation in Higher Education*, *0*(0), 1–16. https://doi.org/10.1080/02602938.2024.2354510

Romero, M. (2026). Evaluating the evolution of critical thinking, creativity, communication and collaboration in higher education courses. *Creative Education*, *17*, 49–57. https://doi.org/10.4236/ce.2026.171004

Sahlberg, P. (2020). *Finnish lessons 3.0: What can the world learn from educational change in Finland?* Teachers College Press.

Sapitri, A., Tambunan, M. I. H., Lubis, R. E. ., & Arisetya, D. (2024). Pembelajaran Kultur Jaringan Tanaman Obat Berbasis Project Base Learning (PjBL) Terintegrasi Lesson Study: Plant Tissue Culture Learning Based on Project Based Learning (PjBL) Integrated Lesson Study. *BIODIK*, 10 (4), 682–690. https://doi.org/10.22437/biodik.v10i4.38756

Sari, D. R., Saputro, S., Maret, U. S., & Maret, U. S. (2024). A systematic review on integrating SSI into science education: Its impact on 21st century skills (2014-2024). *Educational Studies and Research Journal*, *2*(1), 1–14.

Savery, J. R. (2015). Overview of problem-based learning: Definitions and distinctions. *Essential Readings in Problem-Based Learning: Exploring and Extending the Legacy of Howard S. Barrows*, 5–15.

Semilarski, H., & Laius, A. (2021). Exploring biological literacy: A systematic literature review of biological literacy. *European Journal of Educational Research*, *11*(1), 69–81.

Shimizu, I., Matsuyama, Y., Duvivier, R., & Vleuten, C. Van Der. (2022). Perceived positive social interdependence in online versus face-to-face team-based learning styles of collaborative learning: A randomized, controlled, mixed-methods study. *BMC Medical Education*, *22*(567), 1–10. https://doi.org/10.1186/s12909-022-03633-y

Siregar, S. (2017). *Metode penelitian kuantitatif: Dilengkapi dengan perbandingan perhitungan manual & SPSS*. Kencana.

Suleiman, A. D. (2025). Factors impacting faculty adoption of project-based learning in computing education: A survey. *ArXiv.*, 1–9. https://arxiv.org/pdf/2507.18039

Tarr, S. W., & Alicea-Muñoz, E. (2024). Reflecting to learn in a physics multimedia communication course. *American Association of Physics Teachers*, 432–437.

Tarigan, L. Z. (2025). Effective Leadership Model in Higher Education Management in the 21st Century. *Journal of Innovation and Scientific Collaboration*, *1*(1), 1-6.

Thomas, J. W. (2000). *A review of research on project-based learning*. Autodesk Foundation.

Trilling, B., & Fadel, C. (2009). *21st century skills: Learning for life in our times*. Jossey-Bass.

UNESCO. (2021). *Reimagining our futures together: A new social contract for education*. UNESCO.

Utari, D., Lengkana, D., & Hasnunidah, N. (2024). The need for biotechnology PjBL-STEM based learning programs associated with local contexts to enhance creative problem solving and entrepreneurial skills: teacher and student Perspectives. *Jurnal Penelitian Pendidikan IPA*, *10*(11), 9078–9086. https://doi.org/10.29303/jppipa.v10i11.9092

van Laar, E., van Deursen, A. J. A. M., van Dijk, J. A. G. M., & de Haan, J. (2020). Determinants of 21st-century skills and 21st-century digital skills for workers: A systematic literature review. *SAGE Open*, *10*(1), 1–14. https://doi.org/10.1177/2158244019900176

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. Harvard University Press. https://home.fau.edu/musgrove/web/vygotsky1978.pdf?

Yan, Z., Lao, H., Panadero, E., Fernández-Castilla, B., Yang, L., & Yang, M. (2022). Effects of self-assessment and peer-assessment interventions on academic performance: A meta-analysis. *Educational Research Review*, *37*, 100484.

Yani, I. P., Ahzari, S., & Novitra, F. (2026). Technology integration in the project based learning model: bibliometric analysis 2015-2024. *Pillar of Physics Education*, *17*(2), 143–149. https://arxiv.org/pdf/2601.09149

Yudhistian, & Cintamulya, I. (2026). Exploring the relationship and integration of 21st-century skills in biology learning. *Biosfer: Jurnal Pendidikan Biologi*, *19*(1), 59–70.

Zhang, L., & Ma, Y. (2023). A study of the impact of project-based learning on student learning effects : a meta-analysis study. *Frontiers in Psychology*, *14*(July), 1–14. https://doi.org/10.3389/fpsyg.2023.1202728