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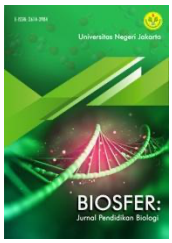

Exploring the relationship and integration of 21st-century skills in biology learning

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ABSTRACT

The relationship and integration of 4C competences, biological literacy, creative problem-solving, and science process skills in biology learning are rarely analyzed simultaneously. On the other hand, integrating the four skills is important in 21st-century biology learning. The research aim is to explore the relationship and integration of 21st-century skills in biology learning, including 4C competence, biological literacy, creative problem-solving, and science process skills. The research method was quantitative research with a non-experimental explanatory design using 44 participants through filling out questionnaires, which were then analyzed using Structural Equation Modeling with Partial Least Squares (SEM-PLS) at the 5% significance level. The results prove that 4C competences have a significant influence on biological literacy; 4C competences have a significant influence on creative problem-solving; 4C competences have a significant influence on science process skills; biological literacy has a significant influence on creative problem-solving; biological literacy has a significant influence on science process skills; and creative process skills have a significant influence on science process skills. The research concluded that 4C competences through biological literacy and creative problem-solving skills significantly affect science process skills. The study has direct practical implications for educators in developing innovative biology learning strategies that integrate 21st-century skills through strengthening 4C competencies. This integration is crucial not only for improving biology literacy, creative problem solving, and scientific process skills but also as an essential step in enhancing the quality of future biology teachers.

INTRODUCTION

21st-century skills are divided into three major groups: foundational literacies, competencies, and character qualities (Fitri et al., 2024). 21st-century skills have become essential along with the complexity of the challenges of the global world and the development of digital technology, which is increasingly fast (Kain et al., 2024; Rehman, 2025). Essential 21st-century skills are needed in all learning areas, especially in biology learning. One of the 21st-century skills needed in biology learning is biological literacy, science process skills, creative problem solving, and 4C competence. The 21st-century competence is the 4C, which includes critical thinking, communication, collaboration, and creative thinking (Dilekçi & Karatay, 2023; Osiesi & Blignaut, 2025). Besides the need for 4C competence, biological literacy is important in measuring a person's literacy level in the 21st century (Ferniawan et al., 2025). Biological literacy is a person's ability to understand scientific concepts, processes, and methodologies that enable students to actively participate and make decisions about science-based global issues (Rahmonova, 2025; Saraiva et al., 2025). Students also need Science Process Skills (SPS) in their application in line with biological literacy. SPS helps students develop critical and creative thinking skills and systematically find alternative solutions to problems (Wardani et al., 2025). In finding alternative solutions to the problems faced, students' SPS application must be accompanied by Creative Problem-solving Skills (CPS). CPS is an ability strategy in exploring various problems and formulating solutions that are used creatively (Paek et al., 2025; Suryanto et al., 2021).

4C competence, biological literacy, creative problem-solving, and science process skills are important in learning biology in the 21st century. Therefore, integrating these 21st-century skills into learning is urgently needed, alongside the rapid development of ICT (Agolla, 2022). However, this expectation is not optimal and inversely proportional to the factual conditions in the field. Many urgent and real problems are faced globally and nationally now, and must be addressed immediately. Many school and higher education graduates have not fully mastered 21st-century skills, so the demands of an increasingly competitive global job market and the speed of ICT development are unmet. However, integrating 21st-century skills has also encountered obstacles from some educational institutions and educators (Gonzalez-perez & Ramirez-montoya, 2022; Wawak et al., 2024).

Problems occur not only in acquiring 21st-century skills but also in learning biology in Indonesia. Although biology learning is widely given in various educational institutions, several factors cause low student interest in learning biology which results in low biological literacy, SPS, and CPS of students, such as the lack of innovative biology learning approaches, the lack of promotion of inspirational figures in the field of biology in learning, the lack of relevance of biology learning to everyday life by educators, learning methods focused on conventional approaches, and the lack of school laboratory facilities (Nugroho, 2025). This is supported by several studies using PISA and OECD data that indicate that the level of literacy and numeracy required for 21st-century skills in Indonesia remains relatively below standard (Ismawati et al., 2023; Putri et al., 2024; Sujadi et al., 2023; Susilowati et al., 2022). This makes students view learning biology as abstract and difficult to understand. The lack of 21st-century skills in biology learning directly impacts the ability to solve national and global problems, such as solving energy crises, climate change, food security, natural disaster mitigation, public health, and environmental sustainability. The reason is that without a strong understanding of the field of biology, the current generation is considered to be increasingly left behind and has difficulty in the current era's global competition, which will impact the country's weak national competitiveness. This challenge can ultimately hinder the integration of students' 21st-century skills development in biology learning.

The imperative to equip students with 21st-century skills is a cornerstone of modern biology education, aiming to prepare them for complex future challenges. Existing literature highlights the importance of discrete skills; for instance, research has established a positive correlation between 4C competencies and academic achievement (Amin et al., 2022; Supena et al., 2021). Other studies have independently explored the role of biological literacy in fostering science process skills (Maulina, 2020) or the impact of creative problem-solving on student engagement (Samson, 2015). However, these studies examine these crucial skills in isolation, providing a fragmented understanding of their interplay. A significant gap persists in the literature concerning a comprehensive, integrated model that examines the simultaneous relationships among 4C competencies, biological literacy, creative problem-solving, and science process skills within the learning of biology. The research addresses this gap by proposing a novel investigation into the statistical relationships and integrated nature of these four key 21st-century skills. The urgency of this study is underscored by recent educational reforms, namely the

Merdeka Curriculum in Indonesia, which demands a holistic approach to developing 21st-century skills. Understanding this complex interplay is critical for designing effective pedagogical strategies that can holistically cultivate a generation of scientifically literate and adaptable graduates. Therefore, this research explores the relationship and integration of 21st-century skills in biology learning, including 4C competence, biological literacy, creative problem-solving, and science process skills.

The formulation of the problem taken in the research is how to explore the relationship and integration of 21st-century skills in biology learning, including 4C competence, biological literacy, creative problem-solving, and science process skills. The formulation of the problem is further detailed into six research questions, as follows:

RQ1. Do 4C competencies have a significant influence on biological literacy?
RQ2. Do 4C competencies have a significant influence on creative problem-solving skills?
RQ3. Do 4C competencies significantly influence students' science process skills?
RQ4. Does biological literacy have a significant influence on creative problem-solving skills?
RQ5. Does biological literacy have a significant influence on science process skills?
RQ6. Do creative problem-solving skills significantly influence science process skills?

The research aims to explore the relationship and integration of 21st-century skills in biology learning, including 4C competence, biological literacy, creative problem-solving, and science process skills.

METHODS

Research Design

The research method is quantitative research with a non-experimental explanatory design that describes the statistical relationship between four variables, namely 4C Competence (4C), Biological Literacy (BL), Creative Problem-solving Skills (CPS), and Science Process Skills (SPS). The research variables consist of the independent variable (4C competence), the moderator variable (biological literacy and creative problem-solving), and the dependent variable (science process skills). The research design refers to Imjai et al. (2024), which is modified to present the relationship arrangement between each variable as Figure 1, which is the basis for proposing six research hypotheses, including:

H1. 4C competencies have a significant influence on biological literacy.
H2. 4C competencies have a significant influence on creative problem-solving skills.
H3. 4C competencies have a significant influence on science process skills.
H4. Biological literacy has a significant influence on creative problem-solving skills.
H5. Biological literacy has a significant influence on science process skills.
H6. Creative problem-solving skills have a significant influence on science process skills.

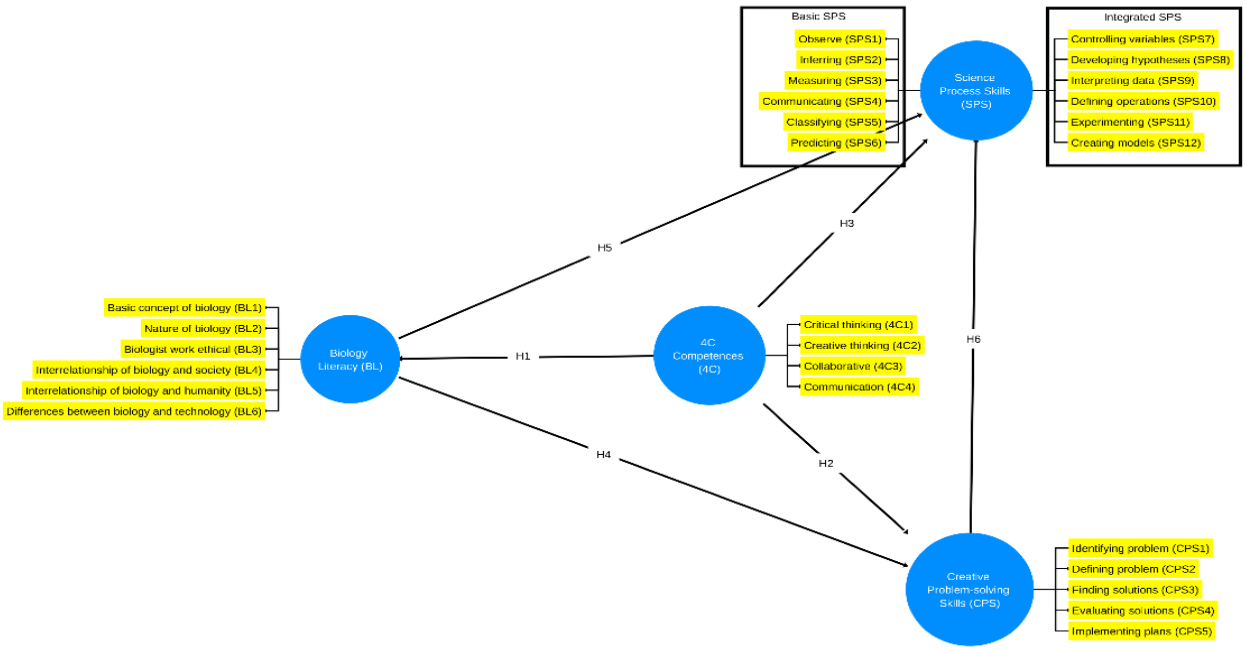

Figure 1. Research design model.

Research Participants

The research participants were 44 students majoring in biology education at Universitas PGRI Ronggolawe, as shown in Table 1. Research participants were selected and determined purposively based on their roles as active learners with a strong foundation in biology and direct experience in internalizing 21st-century skills, as well as prospective educators trained to transform these concepts and skills into future biology teaching practices.

Table 1
Research participants demographic

No	Class	Number of Participants
1	Biology Education students 2021	22
2	Biology Education students 2022	22
	Total	**44**

Instrument

The research instrument used was a questionnaire developed and adopted from various literature, consisting of four main components aligned with the number of research variables measured, including: 1) 4C competencies, consisting of four items (Osiesi & Blignaut, 2025); 2) creative problem solving, consisting of five items (Chen & Chang, 2024); 3) science process skills, consisting of 12 items (Melesse et al., 2025); and 4) biology literacy, consisting of six items (Turiman et al., 2012), which have been modified. Each item used in each component can be seen in Figure 1. The rating scale used in the research instrument is a five-point Likert scale, ranging from strongly agree (5) to strongly disagree (1) (Ponsiglione et al., 2022).

Data Collection Techniques

The data collection technique was completed by filling out research instruments distributed online via Google Form by researchers to research participants. Participants filled out the questionnaire by responding to each questionnaire item objectively and according to their knowledge and experience as biology education students. The data explicitly collected describes students' 21st-century skills because each item in the questionnaire is designed according to the indicators of each variable. In addition, students' responses on the Likert scale also provide a self-perception that reflects their confidence in their abilities.

Data Analysis Techniques

Data analysis in the study used Structural Equation Modeling with Partial Least Squares (SEM-PLS) technique via SmartPLS 3.2.7 software at a 5% significance level to estimate the hypotheses. This study follows two main calculations, namely: 1) measurement model (outer model), which aims to determine the level of validity and reliability of indicators of each construct; 2) structural model (inner model,) which meets reliability criteria based on Cronbach's alpha (ÿA), Composite Reliability (CR), and Dijkstra-Henseler rho (ÿA) values. Convergent validity of a model is based on the Cross-Loading and Average Variance Extracted (AVE) values. Furthermore, construct assessment to achieve discriminant validity is based on the Fornell-Larcker and Heterotrait-Monotrait Ratio (HTMT) criteria. The structural model (inner model) is determined based on the Collinearity Issue, evaluating Path Coefficient, performing R-Square (R^2) level, estimating effect size (f^2), and assessing predictive relevance (Q^2).

RESULTS AND DISCUSSION

Measurement model (outer model)

The measurement model must be evaluated to determine the validity and reliability of each construct and item tested. The first step is the validity test, which analyzes the item loading value above 0.708 (Hair & Alamer, 2022). Table 2 shows that all items have a value above 0.708, so they are declared valid to represent each construct tested, except for one item, namely 4C3 (<0.708), which requires the item to be deleted. The second step is the reliability test by analyzing the value of Cronbach's Alpha, Composite Reliability, and Dijkstra-Henseler rho (ÿA), all of which must be above 0.7 (Hair & Alamer, 2022). Table 2 shows that the values of Cronbach's Alpha, Composite Reliability, and rho Dijkstra-Henseler (ÿA) for the four constructs have exceeded the value of 0.7, indicating that the values of the three for all constructs are reliable. According to Hair & Alamer (2022), a good AVE value must be more

than 0.5. The AVE analysis results obtained for each construct have exceeded 0.5, namely 0.598-0.755 (Table 2). The next step is to calculate the discriminant validity for each construct based on the Fornell-Lacker criteria, where the value must be greater than the value of other variables below. Table 3 shows that the discriminant validity based on Fornell-Lacker criteria has met this prerequisite. Meanwhile, discriminant validity based on HTMT requires a value below 0.85 or 0.90 (Hair & Alamer, 2022). In this study, all of them have met these requirements except for two items, namely 0.915 and 0.930 (Table 4).

Table 2
Measurement model (outer model)

Construct	Item	Item Loading	Cronshbach' Alpha	ÿA	CR	AVE
4C Competence (4C)	4C1	0.814	0.837	0.844	0.902	0.755
	4C2	0.888				
	4C4	0.903				
Biological literacy (BL)	BL1	0.722	0.878	0.882	0.908	0.623
	BL2	0.827				
	BL3	0.830				
	BL4	0.772				
	BL5	0.725				
	BL6	0.851				
Creative Problem-solving Skills (CPS)	CP1	0.701	0.899	0.905	0.926	0.716
	CP2	0.898				
	CP3	0.884				
	CP4	0.855				
	CP5	0.879				
Science Process Skills (SPS)	SP1	0.819	0.939	0.940	0.947	0.598
	SP2	0.770				
	SP3	0.804				
	SP4	0.767				
	SP5	0.747				
	SP6	0.805				
	SP7	0.754				
	SP8	0.805				
	SP9	0.734				
	SP10	0.759				
	SP11	0.768				
	SP12	0.743				

Note(s): ÿA: Dijkstra-Henseler's Rho; CR = Composite Reliability; AVE = Average Variance Extracted.

Table 3
Discriminant validity based on the Fornell-Larcker criteria

	4C	BL	CPS	SPS
4C	**0.869**			
BL	0.562	**0.789**		
CPS	0.737	0.712	**0.846**	
SPS	0.754	0.836	0.859	**0.774**

Table 4
Discriminant validity based on the Heterotrait-Monotrait Ratio (HTMT) criteria

	4C	BL	CPS	SPS
4C				
BL	0.646			
CPS	0.842	0.802		
SPS	0.849	0.915	0.930	

Structural model (inner model)

The results of the previous evaluation show that all constructs and items tested are valid and reliable. Before hypothesis testing, first measure the quality of the model by testing the structural model based on R^2 (coefficient of determination), Q^2 (cross-validation redundancy), f^2 (effect size), and path coefficient (O) (Hair & Alamer, 2022). The coefficient of determination (R^2) assesses the model's

predictive accuracy. An R-squared value of about 0.670 is considered substantial, an R-squared value of about 0.333 is considered moderate, and an R-squared value of about 0.190 is considered weak (Hair & Alamer, 2022). The results showed that the biological literacy construct had moderate prediction accuracy, while the creative problem solving and science process skills constructs had substantial prediction accuracy (Table 5). Q-square measures the predictive relevance of a block of manifest variables. Q^2 values are categorized as small (0.000), moderate (0.250), or substantial (0.500), and the proposed threshold value is $Q^2>0$ (Hair & Alamer, 2022). Table 6 shows that the biological literacy construct has moderate prediction accuracy, while the creative problem solving and science process skills constructs have substantial prediction accuracy. The third metric to assess the prediction of the structural model is to calculate f^2 (effect size) for each construct. The f^2 criteria include 0.02 (considered small); 0.15 to 0.35 (medium); and values of 0.35 and above (large) (Hair & Alamer, 2022). Table 7 presents that the effect size of all relationships between constructs is large, except the effect of 4C and creative problem-solving skills on science process skills is in the medium category.

With 5000 basic bootstrapping iterations, information on the results of hypothesis testing in this study using a 5% significance level is shown in Table 8 and Figure 2. The formulated hypotheses were analyzed based on this procedure. The standard value of the path coefficient is between -1 (strong negative relationship) and +1 (strong positive relationship) (Hair & Alamer, 2022). A t-statistic value >1.96 indicates a strong positive relationship with the model (Feng & Sumettikoon, 2024). The results of hypothesis testing, as shown in Table 8, show that the path coefficient (O) has a positive value, and the t-statistic value obtained is above the value of 1.96, indicating that all relationships between constructs have a strong positive effect. This also proves that all hypotheses (H1, H2, H3, H4, H5, and H6) proposed can be accepted and supported.

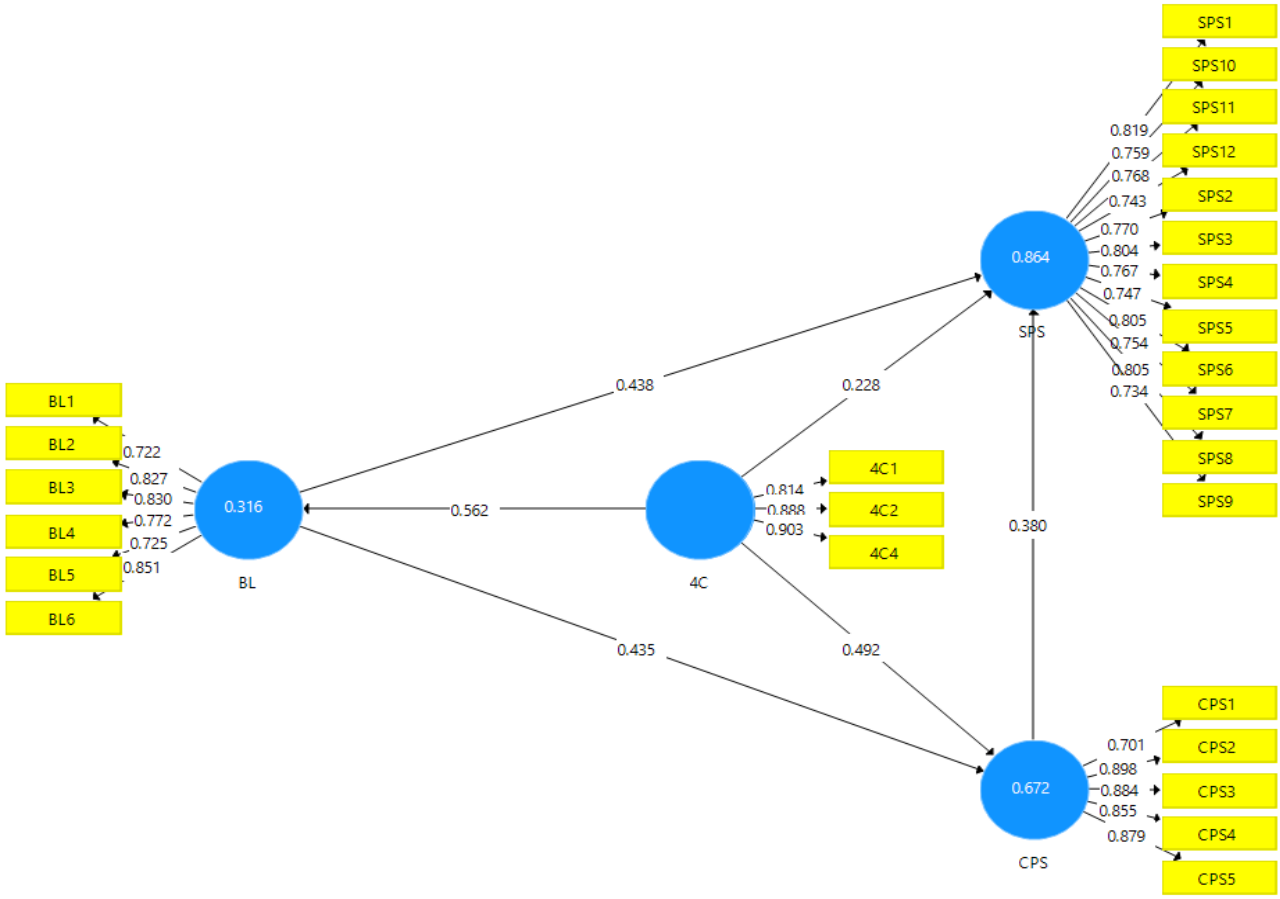

Figure 2. Measurement and structural model estimation

Table 5.
R-Square (R^2) values

	R^2
4C	
BL	0.316

	R^2
CPS	0.672
SPS	0.864

Table 6.
Predictive relevance (Q^2)

	SSO	SSE	Q^2 (1-SSE/SSO)
4C	126	126	
BL	252	210.189	0.166
CPS	210	113.381	0.460
SPS	504	254.990	0.494

Note(s): SSO = Sum Square Observation; SSE = Sum Square Error.

Table 7.
Effect size (f^2)

	4C	BL	CPS	SPS
4C		0.461	0.506	0.175
BL			0.396	0.692
CPS				0.348
SPS				

Table 8.
Path coefficients and hypothesis testing

Hypothesis	O	M	STDEV	(|O/STDEV)	*P* Values	Supported
H1: 4C→BL	0.562	0.568	0.101	5.536	0.000	Yes
H2: 4C→CPS	0.492	0.488	0.111	4.446	0.000	Yes
H3: 4C→SPS	0.228	0.220	0.089	2.552	0.011	Yes
H4: BL→CPS	0.435	0.441	0.117	3.726	0.000	Yes
H5: BL→SPS	0.438	0.432	0.111	3.947	0.000	Yes
H6: CPS→SPS	0.380	0.393	0.130	2.917	0.004	Yes

Note(s): n = 5000 subsample; O = Original Sample/path coefficient; M = Sample Mean; STDEV = Standard Deviation; |O/STDEV = T Statistics.

The results showed that the four skills, namely 4C competences, biological literacy, creative problem-solving skills, and science process skills, significantly influence each other. This is supported by the acceptance of testing all the hypotheses proposed, so that 4C competences are proven to have a significant effect on biological literacy; 4C competences are proven to have a significant effect on creative problem-solving; 4C competences are proven to have a significant effect on science process skills; biological literacy is proven to have a significant effect on creative problem-solving; biological literacy provides a significant effect on science process skills; and creative process skills are proven to have a significant effect on science process skills.

The study found that 4C competence proved to have a strong influence on biological literacy, creative problem-solving skills, and science process skills. 4C competences, including critical thinking, creative, collaborative, and communication, are important basic and supporting skills that substantially impact several skills in learning biology, such as biological literacy, creative problem-solving skills, and science process skills. 4C competencies include the ability of a person with a critical and creative mindset through collaboration, communication, and good teamwork. This is very much needed when the biology learning process occurs, because many practicum and problem-solving discussion activities between teams require mastery of the 4C competences. The study also found that with a critical and creative mindset, individuals can master biological literacy well through explaining biological concepts, understanding the phenomena that occur, understanding the fundamental differences between the application of biology and technology, and the relationship of biology to the community environment and human welfare. The characteristics of biological literacy as part of scientific literacy have a very close relationship with critical thinking skills as part of the 4C competences, which emphasize the application of biological knowledge to solve problems critically and creatively, reason logically, make personal and ethical decisions related to biological issues, and evaluate information (Kusuma, 2023; Primasari et al., 2020; Ridzal & Haswan, 2023). The research findings also show that critical and creative thinking as part of the 4C competences also have a strong and direct impact on the acquisition of creative

problem-solving skills, where identifying, explaining, finding, evaluating, and implementing solutions also requires this mindset. Critical thinking skills in 4C competencies are the main skills that play a significant role in problem-solving abilities (Kocak et al., 2021). This aligns with the findings of Almulla (2023) and Orakci (2023) that critical and creative thinking directly affect problem-solving ability.

Furthermore, the research findings show that implementing the learning process that requires science process skills also requires the integration of 4C competences, ranging from critical thinking, creativity, collaboration, and communication. Almost every stage of the science process requires the integration of the 4C competencies. Science process skills have strong similarities and relationships to critical thinking skills as part of the 4C competences, especially in terms of indicators of measurement, interpretation, inference, and predictive ability (Firmansyah & Suhandi, 2021). Science processes and critical thinking skills are related to the cognitive scope of students. According to the relevant learning approach, educators can improve and integrate both skills into the learning process and assessment (Kartowagiran & Rohaeti, 2021). This shows that integrating science process skills and 4C competences, especially critical thinking skills, needs each other and are inseparable. Science process skills are needed by students in learning biology when carrying out practicum activities, observations, research, and experiments, most of which are carried out both individually and in teams to solve problems by finding solutions and novelty in them. This aligns with Wulandari et al. (2021), who stated that integrating 4C competencies towards science process skills can be done through practicum or experimental activities.

The following important research finding also underlines that biological literacy significantly influences creative problem-solving and science process skills. This is in line with the results of research by Semilarski & Laius (2021) and Sari et al. (2024) that biological literacy as part of scientific literacy which is an interdisciplinary concept that is responsible for providing a positive correlation to creative problem-solving in students' future lives through the scientific method and science process skills. Similarly, creative problem-solving skills significantly affect science process skills. Mercan & Köseoğlu (2022) mentioned that in its application, science process skills require creative problem-solving to make observations, hypothesize, test, collect information, interpret data, and share results. Biological literacy, creative problem-solving skills, and science process skills are among the important skills that individuals must master in learning biology, because in their application, the three skills depend on each other and cannot work alone. For example, in biological research activities, by making an observation, to begin observations, a person needs to master biological literacy, which is used to formulate research assumptions and hypotheses and provide insight into the observations to be made. Once in the research stage, the individual will need various science process skills from the observation stage to writing the observation report. After the research ends, the results cannot be directly written in the report but must be analyzed to answer the proposed problems and problem formulations. Therefore, creative problem-solving is needed in this case. This example proves that biological literacy, creative problem-solving skills, and creative problem-solving are very much bound and connected by providing a great significance of influence in learning biology. In addition to conducting experiments guided by the teacher, in learning biology, students are required to have the opportunity to design their experiments by designing relevant experimental methods, measurable data, data analysis techniques, and how to present their experimental results systematically (Nasir & Andrew, 2022). This makes the integration of 4C competencies, biological literacy, creative problem-solving, and science process skills critical in learning biology.

The integration of 4C competences, biological literacy, creative problem-solving, and science process skills in learning biology, along with the development of the 21st century, is a challenge in education that has an important impact on individual lives. Biology learning emphasizes understanding, application, analysis of conceptual and procedural knowledge, as well as its application to solve problems through biological concepts and important issues in biological learning broadly and deeply to produce graduates who are science literate and master 21st century skills (Dewi & Arifin, 2024; Suwono et al., 2023). Many benefits are provided through the four skills in 21st-century biology learning to deal with problems in daily human life. Integrating 4C competences into biology learning can improve students' academic performance, develop cognitive mindset and 21st-century soft skills, and help students apply knowledge in daily life. (Dewi & Arifin, 2024; Rehiara et al., 2024). This is because the four skills have a significant impact and significance on each other and need each other so they cannot run alone. 4C competences cannot run optimally without creative problem-solving skills that complement each other, and vice versa. Science process skills also cannot be mastered well if individuals

do not master biological literacy well and vice versa. Biological literacy is part of scientific literacy, and critical and creative thinking skills are part of 4C competencies, which play an important role in solving everyday problems and making decisions with basic scientific-based concepts (Perdana et al., 2023). Therefore, simultaneously integrating 4C competences, biological literacy, creative problem-solving, and science process skills is vital in 21st-century biology learning.

CONCLUSION

The research concluded that 4C competences through biological literacy and creative problem-solving skills significantly affect science process skills. Biological literacy increases creative problem-solving and science process skills, while creative problem-solving skills also affect science process skills. The findings show that the 4C competencies are core skills and a strong foundation that significantly affect the acquisition of biological literacy, creative problem-solving skills, and science process skills. The implications of the research findings serve as material for curriculum evaluation in biology education study programs. In addition, the study has direct practical implications for educators in developing innovative biology learning strategies that integrate 21st-century skills through strengthening 4C competencies. This integration is crucial not only for improving biology literacy, creative problem-solving, and scientific process skills but also as an essential step in enhancing the quality of future biology teachers.

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