QUBAHAN ACADEMIC JOURNAL
VOL. 5, NO. 2, May 2025
https://doi.org/10.48161/qaj.v5n2a1716

Effects of Hybrid STEM Learning on 21st-Century Skills and Character Development in Prospective Elementary Teachers: A Mixed-Methods Study from Indonesia

Setyo Eko Atmojo [1*], Beny Dwi Lukitoaji [1], Rina Dyah Rahmawati [1], Mitha Dwi Anggriani [2], and Agista Putri Anindya [1]

1 Department of Elementary School Teacher Education, Faculty of Teacher Training and Education, Universitas PGRI Yogyakarta, Yogyakarta 55182, Indonesia;

2 Department of Elementary School Teacher Education, Faculty of Teacher Training and Education, Universitas Riau, Pekanbaru, 28293, Indonesia.

* **Corresponding author:** setyoekoatmojo@yahoo.co.id.

ABSTRACT: Traditional teaching methods have become obsolete in modern society, especially in preparing prospective elementary school teachers to face the challenges of the 21st century. Therefore, a new educational approach is needed that is able to develop globally relevant knowledge, skills, and character values. This study aims to analyze the effect of science, technology, engineering, and mathematics (STEM)-based hybrid learning on the 21st-century skills and character values of prospective elementary school teachers. This study uses a mixed-methods method with an explanatory sequential design, where quantitative data is collected first and then continued with qualitative data to deepen the findings. The sample consisted of 156 students from four universities in Indonesia: Universitas PGRI Yogyakarta, STKIP Majenang, Universitas Islam Sultan Agung, and Universitas PGRI Semarang. The validity of the instrument was tested through expert judgment, while reliability was tested using Cronbach's alpha. The research instruments included an essay test to measure critical thinking skills and creativity, as well as a Likert scale questionnaire (1–5) to assess communication, collaboration, and character. Data were analyzed using Multivariate Analysis of Variance (MANOVA), with results showing significant F values for all indicators (Pillai's Trace = 7.709; Wilks' Lambda = 8.115; Hotelling's Trace = 8.344; Roy's Largest Root = 14.295; $p < 0.001$), indicating that the hybrid-STEM model has a significant effect on improving 4C skills (critical thinking, creativity, collaboration, and communication) and students' character values. Surveys and observations also showed a positive response to this model, which was proven to improve conceptual understanding, problem-solving skills, and active involvement in learning. This study recommends strengthening STEM-based learning in higher education as a strategy to produce prospective teachers who excel academically and in character. The limitations of the study lie in the scope of the institution and the number of samples, which are still limited, so it is recommended to conduct further studies with a broader context to strengthen the generalization of the findings.

Keywords: teacher education, Indonesian education, mixed methods, critical thinking, collaboration skills, creativity, communication, character.

I. INTRODUCTION

The 21st century is marked by rapid technological advances, which have fundamentally changed the way humans work, communicate, and learn [1, 2]. In the context of education, technology is not only a tool but also a strategic medium for forming adaptive and meaningful learning experiences. Various studies show that the integration of technology in learning can increase motivation, engagement, and open wider access to knowledge [3-7]. In addition, technology also contributes to the development of positive attitudes in students and teachers [8-10], as well as facilitating a more enjoyable learning process [11]. Along with the rapid development of this technology,

countries in the world are increasingly aware of the importance of digital transformation in their education systems. Many developed countries, such as those in Europe and the English-speaking region, have utilized digital technology as part of their education reforms [12, 13].

In this global framework, 21st century education emphasizes not only the mastery of academic knowledge, but also the development of transformative skills such as critical thinking, creativity, collaboration, communication, and problem solving [14-16]. Thus, these abilities are core in preparing prospective teachers who are ready to face complex challenges. The 4Cs framework (Critical thinking, Creativity, Communication, Collaboration) which has been widely adopted by international institutions such as the Partnership for 21st Century Learning, emphasizes the importance of these skills as a foundation for students' readiness in facing social, economic, and cultural challenges [17-20]. However, pre-research studies show that the mastery of these skills among prospective teacher students is still low, especially in the aspects of critical thinking (49.76) and written communication (39.08), while creativity (42.19) and collaboration (58.46) are only in the sufficient category [15]. Moreover, developing these skills in traditional classrooms has proven difficult, as it requires a multidisciplinary approach and access to better technology [21-23].

In line with these skills, character building is also an important pillar in contemporary education. Strong characters such as responsibility, honesty, and cooperation are very much needed in the context of teacher education, which inherently involves the role of agents of social transformation [24-26]. In an international context, [27] showed that prospective teachers' positive attitudes towards their profession contribute directly to teaching motivation and self-efficacy, which ultimately encourage the creation of a healthy classroom climate that supports learning. These findings underline the importance of character building as part of the professional competence of future teachers. However, research related to character building in teacher education is still minimal, both quantitatively and in the development of systematic and integrated models.

In response to these challenges, the integration of the STEM (science, technology, engineering, and mathematics) approach is becoming increasingly relevant in emphasizing content mastery, creativity, and critical thinking skills [28-30], but also encouraging problem-based learning and character building [31-36]. This approach encourages active student involvement through cross-disciplinary projects that foster conceptual understanding and social values. Several countries in Asia, Europe, and Australia have implemented STEM in their education policies [37], and Indonesia is also developing this model to strengthen the quality of its education system [38]. This reflects a commitment to adapting learning to global demands. The success of this approach is increasingly recognized because it is able to increase the relevance of science learning [39], making it more contextual and applicable. STEM encourages students to understand science not just as a theory, but as a tool to solve real problems.

As global demands for educational flexibility increase, hybrid learning models are gaining popularity and are considered an adaptive response to the transformation of the education system, especially after the COVID-19 pandemic [40]. This model combines the advantages of face-to-face and online learning [41, 42]. Through this combination, hybrid learning opens up wider opportunities for students to access various learning resources independently, develop digital skills, and strengthen independence in learning. On the other hand, the application of this model also encourages educators to be more adaptive to technology and learning innovation. However, as the implementation of this model becomes more widespread, it is important to continue to critically examine its effectiveness, including reviewing the long-term impacts and potential challenges that can affect the quality of learning [43].

Against this background, it is clear that there is a gap in the literature, namely the absence of a learning model that interactively combines hybrid and STEM approaches to strengthen the character and 21st-century skills of prospective teachers. Most local studies are descriptive and have not produced strong theoretical contributions. In the global context, similar studies have been developed, but have not been widely adopted and adapted to the local characteristics of Indonesia.

This study aims to address this gap by developing and testing a STEM-based hybrid learning model designed to support character building and mastery of 21st-century skills of prospective elementary school teachers. The main question raised in this study is, how does the STEM-based hybrid learning model affect the mastery of 21st-century skills and character building of prospective elementary school teachers? This question arises from the urgent need to integrate various learning approaches synergistically in the teacher education curriculum, especially in the context of educational digitalization.

This study contributes to expanding the literature on STEM-based and hybrid teacher education by emphasizing the integration of character values and transformative skills, which are still minimally explored in the Indonesian and global contexts. In addition, this study offers an innovative model framework that can be used as a reference

for curriculum developers, educators, and researchers in the field of future pedagogy. By including findings and good practices from various countries and adapting them to local characteristics, this study strengthens its contribution to the development of teacher education in the era of globalization and digitalization.

II. RELATED WORK

1. STEM

STEM (science, technology, engineering, and mathematics) education is now one of the learning approaches that can equip the younger generation with the skills needed to face the challenges of the 21st century [44, 35]. To ensure a deep understanding of the material, this learning process must be accompanied by skill development, as well as the formation of positive attitudes, character, and habits. The application of STEM in education encourages students to design, develop, and utilize technology while honing cognitive, affective abilities and applying the knowledge they have acquired [45, 46]. One of the characteristics of STEM learning is the emphasis on the design process, engineering, and solution development. The design process is a systematic approach to solving a problem with the aim of finding the best solution or method from various existing ideas [47, 48]. In STEM learning, students are faced with real problems that encourage them to conduct investigations [49]. At this stage, the learning process occurs more through discussion and exploration, thus helping students understand abstract concepts related to the problem being studied [50]. Some STEM learning models also implement a small group work system, where students are encouraged to propose solutions to a problem, collaborate, and build effective cooperation with fellow team members [51]. However, the success of STEM implementation in education also depends heavily on the beliefs and knowledge of the educators themselves. As stated by [52], educators' self-efficacy in digital technology, as well as their understanding of STEM activities, plays a significant role in shaping meaningful digital education experiences.

2. HYBRID LEARNING

The world continues to experience dynamic changes and transformations. However, the most striking difference between past and present changes lies in their speed and scope. Innovations in information technology, globalization, digitalization, and advances in communication technology have pushed organizations to drastically overhaul their management processes. Broadband internet access, smart mobile devices, artificial intelligence, virtual reality, and various technology-based applications have now penetrated almost all aspects of modern life [53]. In the context of education, hybrid learning (HL) has become one form of adaptation to these changes. Several studies define HL as a student-centered learning process, with instructional designs that integrate face-to-face learning, digital (internet and mobile devices), printed materials, recorded materials, and traditional methods pedagogically and practically [54-57]. HL can also be understood as a combination of face-to-face learning methods in class and materials delivered online [58]. The hybrid learning environment opens up opportunities for educational teams to find alternative methods to enhance the traditional teaching and learning environment [59]. This strategy can facilitate students learning science concepts that are not fully understood during traditional or face-to-face classes [60, 61] emphasized that learning should not only focus on the transfer of technical knowledge related to mobile technology but also on increasing students' awareness of the educational value that arises from the integration of technology in formal contexts. Blended learning allows students to learn independently, develop, and achieve higher educational mastery [62, 57]. Research shows that hybrid learning improves students' abilities because it supports information seeking and problem solving and creates a flexible learning environment [63]. Hybrid learning has the additional advantage that, in addition to the face-to-face approach, HL also uses information, communication, and technology (ICT), both mobile and non-mobile technologies [59]. Therefore, this hybrid learning needs to be continuously developed and implemented by teachers and lecturers.

3. 4C SKILLS

The impact of the emergence of a global consensus on the importance of including 21st century skills in the education curriculum has brought about major changes in the world of education [64]. Increasing critical thinking, problem solving, creativity, communication, and collaboration (4C) skills among students is expected to enable each student to communicate and collaborate in solving problems critically and creatively with people around the world [65]. According to [66] critical thinking includes mental processes and strategies used to solve problems, make decisions, and understand and learn new concepts. Creativity involves the ability to produce ideas or works that

are original, innovative, and relevant to the existing context and needs. Collaboration is a coordinated process of cooperation, where individuals actively contribute, take initiative, share insights, take responsibility, and build shared understanding in a team. Meanwhile, communication includes the ability to express ideas effectively in various forms, adjust communication styles to diverse goals and audiences, and utilize various media and technologies to convey messages clearly. By integrating 4C skills in education, students can be better prepared to face global challenges and contribute actively to an ever-evolving society. Implementing 4C skills in daily teaching practice is highly recommended due to its long-term benefits [67, 68]. Therefore, these skills should be an integral part of the curriculum and daily teaching.

4. CHARACTER

Character refers to a set of basic moral values that shape a person's personality, including concern for others, honesty in acting, fairness in treating others, responsibility for decisions taken, and respect for oneself and the environment [24]. Furthermore, [25] added that character strength plays an important role in helping individuals face various life challenges. Individuals with strong characters tend to be more resilient in the face of difficulties, better able to withstand the negative impacts of external pressures, and have the ability to rise and see challenges as opportunities for growth. Character education covers various fundamental aspects in the formation of students' personalities. These values include religiosity, honesty, tolerance, discipline, hard work, creativity, independence, democracy, curiosity, national spirit, love of the homeland, and appreciation for achievement. In addition, character education also instills a communicative attitude, love of peace, a love of reading, care for the environment and society, and responsibility [69]. By integrating these values into the learning process, it is hoped that students will not only excel academically but also have a strong personality, good ethics, and care for others and the environment.

5. STEM-INTEGRATED HYBRID LEARNING

STEM-Integrated Hybrid Learning is an approach that combines online and offline methods in learning Science, Technology, Engineering, and Mathematics. This model allows students to understand theoretical concepts through digital learning and apply them in live experiments, projects, or case studies. Thus, this approach enhances critical thinking, problem-solving, creativity, and collaboration skills that are essential in the professional world. In addition to academic aspects, this learning also contributes to the formation of students' character. Through collaboration in STEM-based projects, they are trained to be responsible, disciplined, innovative, and adaptive to technological developments and global challenges. Thus, this approach not only builds technical competence, but also forms individuals who are independent, professional, and ready to contribute to the world of work and society.

6. LEARNING THEORY

The development of a STEM-based hybrid learning model in this study is based on constructivism theory, which emphasizes the active role of students in building knowledge through interaction and direct experience. Piaget stated that cognitive development occurs in stages, and knowledge is formed through actions on the environment [70, 71]. This understanding is important for prospective teachers to be able to design learning that is appropriate to the developmental stage of students [72]. STEM learning, which is based on experiments and problem solving, is very much in line with Piaget's approach because it provides space for active exploration. On the other hand, Vygotsky through social constructivism theory emphasizes the importance of social and cultural interactions in learning, especially through the concept of the Zone of Proximal Development (ZPD) and scaffolding [73, 74]. The STEM-based hybrid model allows the integration of online and offline learning that supports collaboration, social interaction, and the development of 21st century skills. In addition, this model also trains prospective teachers to be adaptive and reflective in facing the challenges of future education.

III. MATERIAL AND METHOD

This study used a mixed methods method with an explanatory sequential design. This design was chosen because it allows researchers to first collect and analyze quantitative data to identify significant relationships, which are then deepened through qualitative data. This approach provides a more comprehensive understanding of the effectiveness of STEM-based hybrid learning in developing 21st century skills and character values of prospective elementary school teachers. Quantitative data were collected at an early stage through tests and questionnaires, while qualitative data were obtained through interviews and observations to elaborate and confirm quantitative

results. To conduct this research, several procedures were carried out and summarized as follow.

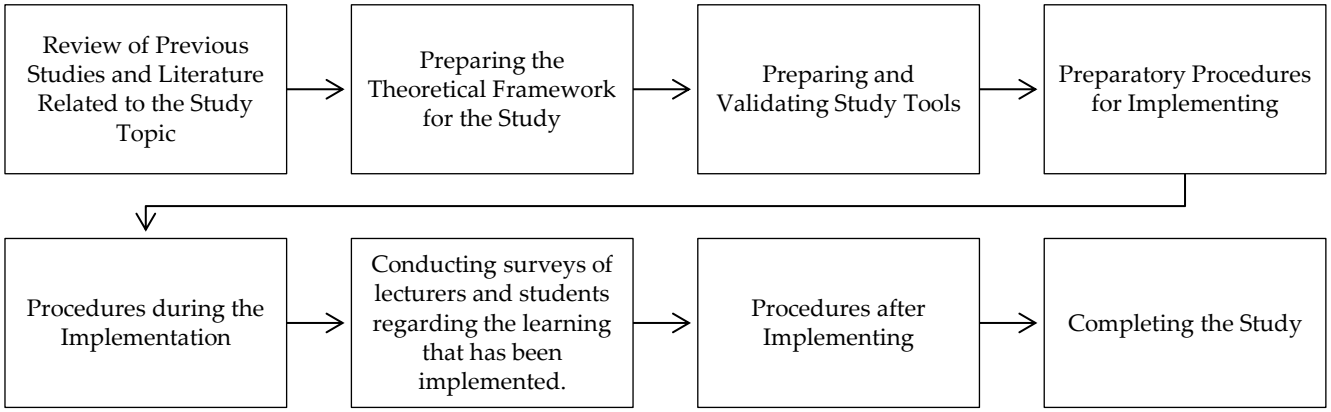

FIGURE 1. Study procedures.

1. STUDY SAMPLE

This study used a purposive random sampling technique in determining the sample. This technique was chosen because it allows researchers to select universities based on criteria that are in accordance with the objectives of the study while providing a fair random opportunity in selecting classes as units of analysis. The selection of universities was carried out purposively based on four main criteria: (1) having an Elementary School Teacher Education Study Program (PGSD); (2) having implemented or developed hybrid learning; (3) representing a variety of institutions in terms of status (private) and geographic area; and (4) having adequate facilities and infrastructure to support digital learning. The four universities that met these criteria were Universitas PGRI Yogyakarta (UPY), STKIP Majenang, Universitas Islam Sultan Agung (Unissula), and Universitas PGRI Semarang (UPGRIS). After the institutions were determined, sample selection was carried out using a simple random sampling technique in active classes in semester 4. Class selection was carried out randomly with the help of a digital random device to ensure that each class had an equal chance of being selected. Through this process, 156 students from the four universities were determined to be research samples.

This research has obtained ethical approval from the university where the research was conducted. All participants gave informed consent after being explained the purpose and procedures of the study. The identities of the participants were kept confidential through anonymous coding and secure data storage. All research procedures were designed to comply with international ethical standards in educational research

2. STUDY INSTRUMENTS

To measure the effectiveness of STEM-based hybrid learning implementation in improving 21st century skills and character development of prospective elementary teachers, this study used various data collection instruments consisting of tests and questionnaires. The instruments were designed to measure various relevant skills, including 21st century skills consisting of 4Cs (critical thinking, creativity, communication, and collaboration), as well as character development. In addition, a survey was also conducted to collect student and lecturer responses regarding the implementation of this model. The instruments used in this study include:

2.1 Test

The essay test is used to measure the critical thinking skills and creativity of prospective teacher students. This instrument consists of 10 open-ended questions developed based on indicators in the P21 Framework for 21st Century Learning, especially in the domains of Critical Thinking and Problem Solving and Creativity and Innovation. Each question is designed to stimulate participants in analyzing real learning situations, identifying problems, and developing innovative solutions.

The development of the instrument was carried out in several stages. First, a question grid was prepared that referred to high-level cognitive indicators based on the revised Bloom's taxonomy. Second, the questions were developed and validated in terms of content by two experts, namely a science lecturer and a primary education

lecturer. Input from the experts was used to refine the wording and difficulty level of the questions. Furthermore, a limited trial was conducted on 36 students to see the understanding and distribution of responses. The results of the validity test showed that all 10 questions met the criteria for content eligibility. The reliability test using the Cronbach's alpha coefficient produced a value of 0.86, which indicates a high level of internal consistency. So that all items were maintained in the final version of the instrument.

2.2 Questionnaire

The questionnaire in this study was designed to measure three aspects of 21st-century skills, namely communication, collaboration, and character. This instrument was developed based on indicators formulated by Mete (2021), with adjustments to the research context. The questionnaire consists of 30 statements divided into three main subscales, namely communication, collaboration, and character, each with 10 items. The questionnaire uses a five-point Likert scale (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree) to measure students' level of agreement with each statement.

The content validity of the instrument was reviewed by two expert lecturers. After revision based on expert advice, the questionnaire was tested on 36 students. The results of the empirical validity test showed that the item-total correlation coefficient was between 0.47 and 0.72. The reliability test using the Cronbach's alpha coefficient showed high results for each subscale: communication (0.81), collaboration (0.76), and character (0.87). These values indicate that the instrument has high internal consistency and can be used to reliably measure 21st-century skills in pre-service elementary school teachers.

3. QUANTITATIVE APPROACH

Quantitative data analysis in this study used a pre-experimental design approach with a one-group posttest-only model. The experimental group consisted of prospective elementary school teachers who received treatment in the form of implementing the STEM-based Integrated Hybrid Learning model. In this context, the independent variable is the learning model, while the dependent variable includes five aspects of 21st-century skills, namely critical thinking, creativity, communication, collaboration, and character. Each aspect is measured using an instrument that has gone through a content validation process by experts, as well as empirical testing to ensure its validity and reliability.

Data were analyzed using descriptive statistics and Multivariate Analysis of Variance (MANOVA). MANOVA was chosen because it allows testing the effect of independent variables on several dependent variables simultaneously. However, before testing the main hypothesis with MANOVA, a series of statistical assumption tests were first carried out to ensure the feasibility of the analysis.

First, the multivariate normality assumption was tested using the Kolmogorov-Smirnov test because the number of samples in this study exceeded 50 people. The test results showed that all dependent variables had a significance value of more than 0.05, which indicated that the data was normally distributed. Second, a homogeneity test of variance was conducted using Levene's Test through Box's M Test. The test results showed that all dependent variables had a significance value above 0.05, which means that the variance between groups was homogeneous. The entire statistical analysis process was carried out using SPSS software version 26.0. With all the basic assumptions required, the analysis was continued with MANOVA to thoroughly test the effect of the STEM-based hybrid learning model on the development of 21st-century skills of prospective elementary school teacher students.

However, it must be acknowledged that there are limitations in the methodology that can affect the interpretation of the results of this study. One of them is the potential for bias in self-reporting, which relies on respondents to report their own skills, as well as the lack of longitudinal data to capture the long-term impact of the implementation of this learning model. Thus, the short-term nature of this study may not fully reflect the long-term effects of the STEM-based hybrid learning model on prospective elementary school teacher students.

4. QUALITATIVE APPROACH

The qualitative approach in this study was carried out through direct observation of the implementation of the Integrated Hybrid Learning STEM model, semi-structured interviews, and analysis of survey results and observations of lecturers and students. Observations were carried out during the learning process to assess the effectiveness of the model, the level of student participation, interactions in the hybrid environment, and challenges that emerged during its implementation. Interviews were conducted with lecturers and a number of students to dig deeper into the experiences and perceptions they experienced during STEM-based learning. Additional data were also obtained from the results of surveys given to students and lecturers. The analysis process included stages of

open coding of raw data, grouping codes into meaningful categories, and identifying key themes that reflected participants' responses to learning. Each stage was carried out repeatedly to ensure consistency. Qualitative analysis provides in-depth insights into students' responses to STEM-based learning, the extent to which the model contributes to improving their skills, and aspects that need to be optimized to make the learning experience more effective. By combining quantitative and qualitative approaches, this study provides a comprehensive picture of the impact of Integrated Hybrid Learning STEM in preparing prospective elementary school teachers to face the challenges of education in the modern era.

IV. RESULTS AND DISCUSSION

In the modern era of education, innovative learning approaches are key in improving the quality of human resources that are ready to face global challenges. One method that has received widespread attention is STEM Integrated Hybrid Learning, which combines elements of Science, Technology, Engineering and Math with online and offline learning models. This approach not only improves academic understanding, but also plays a role in strengthening 21st century skills, such as critical thinking, creativity, communication, and collaboration (4C), as well as student character building.

In line with this, research conducted at STKIP Majenang, UPY (PGRI Yogyakarta University), UPGRIS (PGRI Semarang University), and UNISULA (Sultan Agung Islamic University) aims to analyze the effectiveness of STEM Integrated Hybrid Learning in improving 4C skills and student character. The following is the mean data of 4C skills and student character from the four universities.

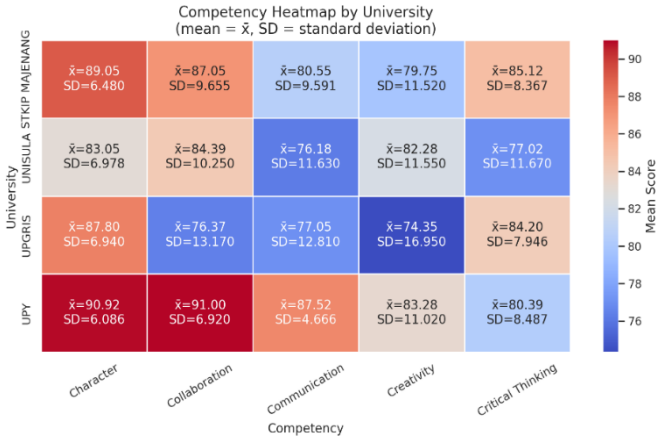

FIGURE 2. Mean 4C and character.

Figure 2 shows data on the average value and standard deviation of various competencies in four universities. In character competency, Universitas PGRI Yogyakarta (UPY) obtained the highest average of 90.92 with a standard deviation of 6.086. Followed by STKIP Majenang with an average of 89.05 and a standard deviation of 6.480, then UPGRIS with an average of 87.80 and a standard deviation of 6.940, and UNISULA with an average of 83.05 and a standard deviation of 6.978. In critical thinking competency, STKIP Majenang recorded the highest average of 85.12 and a standard deviation of 8.367. Next is UPGRIS with an average of 84.20 and a standard deviation of 7.946, UPY with an average of 80.39 and a standard deviation of 8.487, and UNISULA with an average of 77.02 and a standard deviation of 11.67.

For creativity competency, UPY again recorded the highest score with an average of 83.28 and a standard deviation of 11.02, followed by UNISULA with an average of 82.28 and a standard deviation of 11.55, STKIP Majenang with an average of 79.75 and a standard deviation of 11.52, and UPGRIS with an average of 74.35 and a standard deviation of 16.95. In the collaboration aspect, UPY excels with an average of 91.00 and a standard deviation of 6.920, followed by STKIP Majenang with an average of 87.05 and a standard deviation of 9.655, UNISULA with an average of 84.39 and a standard deviation of 10.25, and UPGRIS with an average of 76.37 and a standard deviation of 13.17.

While in communication competence, UPY obtained the highest average of 87.52 and a standard deviation of 4.666. Then STKIP Majenang with an average of 80.55 and a standard deviation of 9.591, UPGRIS with an average of 77.05 and a standard deviation of 12.81, and UNISULA with an average of 76.18 and a standard deviation of 11.63. Overall, each university has varying scores for each variable, with the highest score for collaboration competency at UPY, while the lowest score is for creativity competency at UPGRIS.

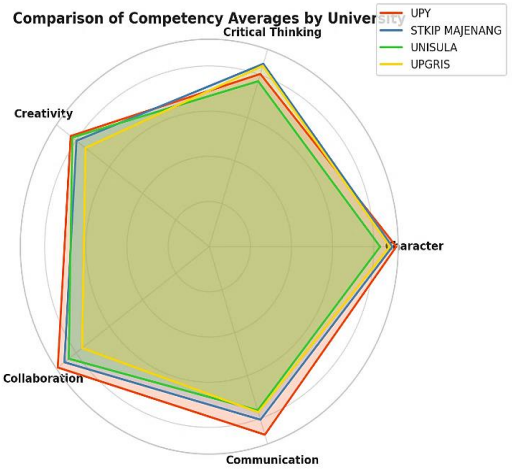

FIGURE 3. Comparison 4C and character by university.

Furthermore, in Figure 3, information can be obtained that each university shows good results in character variables and 4C skills, which include critical thinking, creativity, collaboration, and communication. The difference in scores between universities is not very significant, which indicates that overall student achievement in this aspect is high and evenly distributed. This shows that the application of Integrated Hybrid Learning Science Technology Engineering and Mathematics (STEM) is able to improve 4C skills and build student character effectively. In Figure 2, it can be seen that the colored lines on the graph are almost close together, which indicates that the average results are good and there is no significant difference between one university and another.

Before starting the hypothesis testing, the data on 4C skills (critical thinking, creativity, collaboration, and communication) and student character were tested to fulfill the prerequisites, namely normality test and homogeneity test. After the data was collected completely, the next step was to analyze the data. The first step is to conduct a data normality test to determine whether the distribution of the analyzed data is normal, so that it can be used in parametric statistical analysis. The normality test was carried out using the Kolmogorov-Smirnov method, by paying attention to the Asymp.Sig value. The criterion for acceptance of normality is if the significance value of the test results is greater than $\alpha = 0.05$, then the distribution is considered normal. Conversely, if the value is smaller than $\alpha = 0.05$, then the distribution is considered abnormal. A summary of the data normality test results can be seen in Table 1 below.

Table 1. Normality test.

Variables	Class	Kolmogorov-Smirnov[a]		
		Statistic	df	Sig.
Character	UPY	.140	38	.057
	STKIP MAJENANG	.132	40	.076
	UNISULA	.134	38	.083
	UPGRIS	.108	40	.200*
Critical thinking	UPY	.119	38	.193
	STKIP MAJENANG	.134	40	.066
	UNISULA	.116	38	.200*

	UPGRIS	.134	40	.069
Creativity	UPY	.098	38	.200*
	STKIP MAJENANG	.099	40	.200*
	UNISULA	.100	38	.200*
	UPGRIS	.115	40	.195
Collaboration	UPY	.127	38	.128
	STKIP MAJENANG	.098	40	.200*
	UNISULA	.137	38	.068
	UPGRIS	.111	40	.200*
Communication	UPY	.093	38	.200*
	STKIP MAJENANG	.098	40	.200*
	UNISULA	.138	38	.066
	UPGRIS	.097	40	.200*

In Table 1, the normality test results show that the significance value (Sig.) for each university in the character variable and 4C skills, which includes critical thinking, creativity, collaboration, and communication, is above the significance level of α = 0.05. On the character variable, the significance values for UPY (0.057), STKIP Majenang (0.076), UNISULA (0.083), and UPGRIS (0.200) indicate that the data is normally distributed. The same thing happened to the critical thinking variable, where the significance values of UPY (0.193), STKIP Majenang (0.066), UNISULA (0.200), and UPGRIS (0.069) also showed normal distribution. For creativity, all universities have a significance value above 0.05, namely UPY (0.200), STKIP Majenang (0.200), UNISULA (0.200), and UPGRIS (0.195), so the data is significantly normally distributed. In collaboration, the significance values of UPY (0.128), STKIP Majenang (0.200), UNISULA (0.068), and UPGRIS (0.200) also show data normality. Similarly, in communication, where UPY (0.200), STKIP Majenang (0.200), UNISULA (0.066), and UPGRIS (0.200) have a normal distribution. Thus, it can be concluded that the data in this study meet the assumption of normality and can be further analyzed using parametric statistical methods. This finding is important because normal distribution is a prerequisite in the use of parametric statistical analysis. With this assumption fulfilled, further analysis, such as hypothesis testing, can be carried out validly using a parametric approach.

After the normality test results are obtained, the next step is to test the research hypothesis. This test was conducted using the F test, with decisions taken based on Pillai's Trace, Wilks' Lambda, Hotelling's Trace, and Roy's Largest Root analysis. The test criteria used is the significance level of F = 5%. If the calculated F significance value

is less than 0.05, the null hypothesis is rejected and the alternative hypothesis (Ha) is accepted. The test calculation results are presented in Table 2 below:

Table 2. Multivariate test.

Multivariate tests[a]							
Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Class	Pillai's Trace	.613	7.709	15.000	450.000	.000	.204
	Wilks' Lambda	.487	8.115	15.000	408.964	.000	.213
	Hotelling's Trace	.853	8.344	15.000	440.000	.000	.221
	Roy's Largest Root	.477	14.295[c]	5.000	150.000	.000	.323

Based on Table 2, the results show that the calculated F values for Pillai's Trace (F = 7.709), Wilks' Lambda (F= 8.115), Hotelling's Trace (F = 8.344), and Roy's Largest Root (F = 14.295) all have a significance value of 0.000, which is smaller than 0.05. Thus, the null hypothesis (H_0) was rejected, and the alternative hypothesis (H_a) was accepted. The results of this study indicate that the application of the Integrated Hybrid Learning Science Technology Engineering and Mathematics (STEM) model has a significant influence on the improvement of 4C skills which include Critical Thinking, Creativity, Collaboration, and Communication, as well as the formation of student

character. Furthermore, these findings were strengthened by further analysis through the between-subjects effects test presented in Table 3.

Table 3. Tests of between-subjects effects.

Tests of Between-Subjects Effects							
Source	**Dependent Variable**	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**	**Partial Eta Squared**
Class	Character	1288.190	3	429.397	9.758	.000	.161
	Critical Thinking	1613.397	3	537.799	6.339	.000	.111
	Creativity	1886.076	3	628.692	3.702	.013	.068
	Collaboration	4504.082	3	1501.361	14.204	.000	.219
	Communication	3053.035	3	1017.678	9.792	.000	.162

The results of the Between-Subjects Effects test in table 3 show that the class variable has a significant effect on all dependent variables, namely character, critical thinking, creativity, collaboration, and communication, with a significance value of $p < 0.05$ for each. This finding is reinforced by the analysis of the effect size through the Partial Eta Squared (η^2) value, which reflects the practical contribution of the learning model to each competency.

For character competency, the η^2 value of 0.161 indicates a moderate to large effect, indicating that the learning model contributes significantly to the formation of students' character. For critical thinking competency, η^2 is obtained at 0.111, reflecting a moderate effect, while creativity shows a relatively smaller effect ($\eta^2 = 0.068$) but still has a consistent effect. Collaboration competency recorded the highest η^2 value, namely 0.219, which indicates a large effect and confirms the strength of the learning model in building cooperation skills between students. Meanwhile, communication competence also showed a significant influence with an η^2 value of 0.162.

Overall, these findings confirm that the integrated STEM-based learning model applied in a hybrid manner provides a significant contribution, both statistically and practically, to the development of 4C skills and the formation of students' character. The effectiveness of this model is reflected not only in cognitive abilities but also in the social and affective aspects of learning. Therefore, this model is worth considering for wider application in the context of basic education, especially in efforts to improve the quality of 21st-century learning as a whole.

1. QUALITATIVE ANALYSIS

In Stage 1, with the aim of building students' initial understanding of the concept of Integrated Hybrid Learning STEM-based learning, lecturers introduce the concept of Science, Technology, Engineering, and Mathematics (STEM) through a combination of online and offline methods. Students are given introductory materials in the form of interactive videos and digital simulations that can be accessed through online learning platforms. In face-to-face sessions, lecturers demonstrate how the STEM approach can be applied in solving real problems using case studies from various fields.

In Stage 2, students begin to apply STEM concepts in solving project-based problems. Students are divided into groups to develop innovative solutions using a hybrid approach, where they combine hands-on experiments with data analysis conducted through modeling software. In this stage, students use digital tools to design and test their solutions, as well as discuss through online forums to share results and get feedback from lecturers and peers.

In Stage 3, students test and evaluate their work. Lecturers provide project-based challenges where students must analyze problems, design solutions, and communicate the results through online and offline presentations. Students are given the freedom to utilize various digital technologies to facilitate remote collaboration. At this stage, interactivity between students, technology and instructors is very high, creating a dynamic and exploration-based learning environment.

In Stage 4, students reflect on their learning outcomes by conducting group discussions and peer evaluations. This process helps them deepen their understanding of STEM concepts and improve their 4C skills (Critical Thinking, Creativity, Collaboration and Communication). The final results of their projects are compiled in the form of research reports and presented using digital media, allowing students to hone their scientific communication skills.

Throughout these four stages, students showed a high level of participation in learning activities, both through hands-on experiments and online discussions. The Integrated Hybrid Learning STEM model is proven to improve students' analytical skills in solving problems, increase creativity in designing solutions, and form more independent and collaborative characters. With this approach, students not only understand STEM concepts

theoretically but are also able to apply them in a real context, preparing them for the challenges in the future professional and industrial world.

2. LECTURER PERSPECTIVES ON THE IMPLEMENTATION OF THE INTEGRATED HYBRID LEARNING STEM MODEL

Qualitative analysis in this study was conducted using Braun and Clarke's (2006) [75], thematic approach, covering a systematic process starting from data familiarization, coding, theme identification, and narrative construction. Data were obtained from lecturer observation instruments, evaluative survey results (Table 4), and short interviews after the learning process. In general, qualitative data showed high consistency between lecturer perceptions, classroom practices, and the effectiveness of the implementation of the Integrated Hybrid Learning STEM model in improving the quality of learning.

3. INNOVATIVE AND ADAPTIVE LEARNING PLANNING

Based on the survey results (Table 4), all lecturers gave a score of 4 out of a scale of 5 for the indicator in the Learning Plan category. This reflects that the learning design is considered easy to implement, integrates innovative methodologies, is effective, and is able to stimulate curiosity and exploration of new knowledge. Classroom observations support this finding, where lecturers run learning with a systematic flow and still provide flexible space for student exploration. One lecturer said, "The lesson plan is quite clear, structured, and very applicable. I can run it straight away without much modification, and the students adapt quickly." (Lecturer 1)

This shows that planning in this model is not only technically realistic, but is also able to adapt to the needs of 21st century learning which demands innovation and active involvement of students.

4. TECHNOLOGY INTEGRATION AND THE ROLE OF LECTURERS AS FACILITATORS

In the Lecturer in the Classroom aspect, all lecturers gave a score of 4, indicating that the use of digital technology in the learning process runs smoothly and supports learning activities. Lecturers are also considered to use an effective approach in guiding problem-solving and developing STEM skills.

The results of the observation showed that lecturers did not dominate the class but rather functioned as active facilitators who encouraged student interaction and provided continuous constructive feedback. This is illustrated by the following quote: "I don't just deliver the material but give more scenarios and provocative questions and then let them explore the answers. I see that as much more effective." (Lecturer 2)

This model creates a two-way learning dynamic that is oriented towards the formation of competencies through direct experience and critical reflection.

5. STUDENT ACTIVATION AND MEANINGFUL COLLABORATION

The Students in Class category in the lecturer survey also showed positive results with a score of 4 for both indicators. Students were considered active and proactive in exploring STEM concepts, and showed a better understanding of the material through collaborative learning. Class observations confirmed these findings, where interactions between students occurred intensely in small groups and class discussions. One lecturer said, "Students are very active. During group discussions, they share references, create visualizations of ideas, and are able to re-explain in their own words. This rarely happens in conventional models." (Lecturer 3)

This condition shows that hybrid-based learning with a STEM approach has succeeded in creating a participatory learning atmosphere and building student agency, namely the active role of students in directing and reflecting on their learning process.

6. STRENGTHENING 4C COMPETENCIES AND CHARACTER FORMATION

From a combination of observations, surveys, and interviews, a consistent pattern emerged that this model also contributed to improving 21st-century competencies (4C): critical thinking, creativity, collaboration, and communication. Students are involved in real projects, solving open-ended problems, and presenting their thinking collaboratively. A lecturer said, "Many students show courage in expressing opinions, conveying ideas logically, and even becoming leaders in teams. This is an extraordinary form of character development." (Lecturer 4)

Thus, learning not only strengthens cognitive abilities but also the social and affective dimensions of students, such as responsibility, self-confidence, and empathy.

Qualitative findings based on lecturer observation surveys, interviews, and field documentation indicate that the implementation of the Integrated Hybrid Learning STEM model has successfully created an innovative,

collaborative, and effective learning environment. Systematic planning, smooth technology integration, and increased student participation and skills indicate that this model is not only theoretically feasible but also practically robust. These data strengthen the quantitative results and provide a rich contextual basis for concluding that this model has a significant impact on the quality of learning in higher education.

Table 4. Lecturer observation survey results.

Evaluation Criteria	Assessment Levels				
	1	2	3	4	5
Learning Plan					
The lesson plan is easy to implement					4
Lesson plans incorporate innovative teaching methodologies					4
Lesson plans provide high effectiveness					4
Lesson plans stimulate student curiosity and exploration of new knowledge					4
Lecturer in the Classroom					
Lecturers seamlessly integrate the use of digital technology into the learning process					4
Lecturers use effective approaches to guide students in problem solving.					4
Lecturers provide excellent guidance for students in developing STEM skills					4
Students in Class					
Students are active and proactive in exploring and applying STEM concepts.					4
Students understand the material better and engage in collaborative learning					4

Rating Scale: 1 - Strongly Disagree; 2 - Disagree; 3 - Neutral; 4 - Agree; 5 - Strongly Agree

7. STUDENT PERSPECTIVES ON THE IMPLEMENTATION OF THE INTEGRATED HYBRID LEARNING STEM MODEL

The results of a student survey from four universities—Universitas PGRI Yogyakarta (UPY), STKIP Majenang, Universitas Islam Sultan Agung (UNISULA), and Universitas PGRI Semarang (UPGRIS) depict a positive acceptance of the implementation of the Integrated Hybrid Learning STEM model. The survey involved 156 students with an even distribution from each institution. As shown in Table 5, the majority of students (93.42%) stated that learning with this approach improved their ability to apply theory to practice, especially in the context of STEM-based problem solving. This data is supported by findings from open interviews, where one student stated: "Usually if it's just theory, I find it difficult to imagine the application. But with this model, especially when we are given a case study and have to have a group discussion, it feels more real and easier to understand." (Student, UPGRIS). In addition, 132 students (84.61%) stated that the integration of digital technology in learning helped them understand concepts more quickly and deeply. This shows that the use of technology not only accelerates the learning process but also enriches the way students explore the material.

Observation results of classes implementing this model also showed high student involvement, both in online and face-to-face discussions. Students appeared to be actively using digital platforms to collaborate, seek additional sources of information, and develop solutions to problems given. One of the observer lecturers said: "Students appear to be accustomed to LMS and other digital media. They do not just passively receive material but actively discuss and seek information themselves." (Observer Lecturer, UNISULA).

A total of 146 students (93.58%) also expressed their appreciation for the learning approach that combines the hybrid model and the STEM approach. They consider this method more interesting than conventional methods because it allows for a variety of learning experiences and strengthens teamwork. In an interview, one student from STKIP Majenang stated: "Regular lectures are sometimes boring, but with this method there are videos, online discussions, practices, and group work. Thus, it is more exciting and not monotonous."

Interestingly, 120 students (78.95%) hope that this learning model can continue to be applied in subsequent lectures. This hope reflects the perception of sustainability towards the learning approach that they consider adaptive to the challenges of the times. However, there are also some students who feel that the integration of technology and hybrid methods can still be optimized. Some students suggested improving the quality of digital materials and the stability of network access to facilitate the learning experience, especially when synchronous activities are taking place. Overall, these findings indicate that the Integrated Hybrid Learning STEM model is not

only well received by students but is also considered capable of providing a meaningful, contextual, and relevant learning experience to the needs of the 21st century.

Table 5. Student observation survey results.

Evaluation Criteria	UPY	STKIP Majenang	UNISULA	UPGRIS	Total Students
I really appreciate learning methods that combine hybrid and STEM approaches.	36	38	35	37	146
Integration of digital technology in learning helps me understand concepts faster and deeper	32	36	30	34	132
I can apply the theories learned to solve STEM problems more effectively.	34	39	33	36	142
I hope hybrid and STEM-based learning can continue to be applied in lectures.	30	35	27	28	120

Rating Scale: 1 - Strongly Disagree; 2 - Disagree; 3 - Neutral; 4 - Agree; 5 - Strongly Agree

From the results of this survey, it can be concluded that Integrated Hybrid Learning STEM is well received by students in all four universities. They feel the benefits of this learning model, especially in terms of concept understanding, application of theory in problem solving, and interactivity of learning. However, there are some students who still feel that the integration of technology and hybrid methods can be further optimized to make the learning experience more effective and comprehensive.

- Student Perceptions of Learning Experiences through Word Cloud

At the end of the questionnaire, respondents were asked to describe their experience in implementing STEM-based hybrid learning in only three words. Students who attended both face-to-face and online classes expressed their perceptions, which are visualized in Figure 4. Figure 4 displays the set of words used by students to describe their experience. The larger and bold words indicate the most frequently occurring words, while the smaller and light words indicate the less frequently used words. From about 152 students, the words "good," "enjoyable," "exciting," "productive," "fun," "happy" and so on were used the most, reflecting that STEM-based hybrid learning provided a positive and enjoyable experience for them. Thus, this word cloud not only displays general perceptions but also reflects students' affective engagement towards the learning process.

The results of the study indicate that the implementation of the Integrated Hybrid Learning model based on Science, Technology, Engineering, and Mathematics (STEM) has a significant impact not only on improving 4C skills, namely critical thinking, creativity, collaboration, and communication, but also on the formation of students' character as a whole. Positive responses from lecturers and students indicate that this method is not only effective in cognitive aspects but also has important implications for affective and character aspects such as adaptive, innovative, and collaborative attitudes that are very much needed in the modern era.

This finding is in line with the view [76] that emphasizes that STEM-based learning makes a significant contribution to strengthening 21st-century skills. Research [77] also shows that the integration of STEM in learning not only improves academic mastery but also strengthens students' collaboration and creativity competencies. This approach emphasizes project-based learning and direct applications so that students can understand concepts contextually and be able to apply them in real life.

Various previous studies have emphasized the importance of integrating STEM education into the global curriculum as an effort to bridge the gap between theory and practice [78-80]. This study strengthens these findings but also offers a synthetic approach between hybrid learning and STEM education principles that has not been widely explored in previous literature. STEM education is considered strategic in facing the challenges of the industrial revolution 4.0 and rapid technological developments. This is reinforced by studies [81] and views [82, 83], which state that STEM learning not only equips students with conceptual understanding but also forms adaptive and resilient characters in facing global dynamics.

FIGURE 4. The word cloud to describe STEM-based hybrid learning.

In its implementation, the hybrid integrated STEM learning model that synergistically combines online and offline learning has been proven to improve conceptual understanding, critical and creative thinking skills, and collaborative abilities of students. In addition, character values such as discipline, responsibility, and positive attitudes in academic activities have also been shown to increase significantly [84]. The main advantage of this method lies in its flexibility in providing a dynamic conceptual exploration space where students can analyze, visualize, and apply theory to real practice through technology-based simulations.

However, it must be acknowledged that the results obtained in this study are still short-term and are greatly influenced by the specific context in which the study was conducted, so they cannot be generalized to all educational environments. The main expected findings, such as improving students' critical thinking skills, creativity, collaboration, and communication, indicate that the STEM-based Integrated Hybrid Learning model has strong potential in encouraging the strengthening of 21st-century skills. However, there are also findings that are not fully anticipated, namely the emergence of challenges in adapting technology, especially for students who are not yet familiar with digital devices or STEM learning support applications. This indicates that the success of the model implementation is not only determined by the instructional design but also by the readiness of technology and digital literacy of individual students.

To overcome these obstacles, initial training sessions, technology usage guides, and independent practice time have been provided to build student confidence in using digital devices. Another challenge is time management in the hybrid learning process, which requires careful synchronization between online and offline activities. Although activity design optimization has been carried out to minimize disorientation of the learning flow, this fact still shows the importance of mature and flexible instructional planning, as well as the readiness of supporting infrastructure. Thus, the success of this approach cannot be separated from the role of adaptive educators, adequate technology, and strong institutional support.

The results of this study provide important implications for the development of pre-service teacher education curriculum, especially in preparing future educators who are not only academically competent but also responsive to technological developments and the demands of the times. Policy makers, school administrators, and curriculum developers need to pay attention to the great potential of this model in encouraging more meaningful and contextual learning innovations. In addition, this approach can also be a strategic alternative in building a collaborative and inclusive technology-based learning ecosystem. For further research, it is recommended to explore the application of this model at various levels of education and other fields of study and review its long-term impact on 21st century skills and character formation. Cross-disciplinary studies that combine STEM with the humanities or arts can also be a direction for further development to create holistic and transformative learning.

V. CONCLUSION

Based on the results of this study, it can be concluded that the hybrid learning model integrated with STEM (Science, Technology, Engineering, and Mathematics) has a significant influence on improving 21st century skills and character formation of prospective elementary school teachers. The results of the multivariate analysis showed

a significance value of 0.000 <0.05, which indicated a significant difference in students' skills and character after implementing this learning model. Surveys and observations of lecturers and students from four universities also showed that STEM-Integrated Hybrid Learning was well received and provided benefits in improving conceptual understanding, application of theory in problem solving, and interactivity in learning.

These findings reinforce the importance of integrating the STEM approach in learning in higher education, especially in teacher education programs, to prepare educators who are adaptive to the challenges of the times and are able to utilize technology effectively in learning. The practical implication is that teacher education study programs need to consider a STEM-based hybrid model as part of the core curriculum, with the support of technology training, strengthening digital literacy, and flexible but structured learning design. However, this study has several limitations that need to be acknowledged. The methodology used relies on self-reporting from participants, which has the potential to contain subjective bias. In addition, the absence of longitudinal data limits the understanding of the long-term impact of this learning model. Therefore, these results need to be interpreted carefully in the temporal and spatial context of the study. As a follow-up, further research is needed with a longitudinal approach to evaluate the sustainability of the impact of this model in the long term. In addition, cross-disciplinary exploration that integrates STEM with other fields such as the humanities and arts, as well as the adaptation of this model at various levels of education, can enrich the understanding of the effectiveness and flexibility of this approach in a broader context. Thus, the STEM-based Integrated Hybrid Learning model not only answers the pedagogical challenges of the 21st century, but also paves the way for the creation of a learning ecosystem that is more inclusive, transformative, and relevant to the needs of the future of education.

Funding Statement

Directorate of Research and Community Service (DRPM) Kemendikbudristek Indoenesia which has funded this research and all parties involved in the research process. With contract Number: 2155.1/LL5-INT/PG.02.00/2022.

Authors Contributions

All authors contributed equally to the development, design, and execution of this study.

Conflict Of Interest

The authors have no potential conflicts of interest.

Acknowledgment

The authors would like to express their sincere gratitude to the Directorate of Research and Community Service (DRPM), Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia, for the financial support provided through contract number: 2155.1/LL5-INT/PG.02.00/2022, which has enabled the successful implementation of this research and its publication in a reputable international journal. The authors also extend their deep appreciation to all parties who have been involved, either directly or indirectly, in the research process, for their contributions, collaboration, and dedication from the planning stage to the preparation of this scientific article. It is our sincere hope that the results of this research will contribute meaningfully to the advancement of scientific knowledge and the improvement of academic quality in Indonesia.

REFERENCES

1. Aiba, I. (**2024**). Information technology, market congestion, and economic geography. *Annals of Regional Science, 73*(3), 1269–1295.
2. Bera, S., & Rahut, D. (**2024**). Technology development pathways: Enigmas of appropriate technology choice. *Discover Sustainability*, *5*(45), 1–10.
3. Farjon, D., Smits, A., & Voogt, J. (**2019**). Technology integration of pre-service teachers explained by attitudes and beliefs, competency, access, and experience. *Computers & Education, 130*, 81–93.
4. Backfsch, I., Lachner, A., Stürmer, K., & Scheiter, K. (**2021**). Variability of teachers' technology integration in the classroom: A matter of utility. *Computers & Education, 166*, 104159.
5. Sun, Y., & Yan, Z. (**2025**). Factors influencing teachers' technology adoption in technology-rich classrooms: Model development and test. *Educational Technology Research and Development*.
6. Gbormittah, D., Korsah, D. P., Osiakwan, J. K., & Adom, G. (**2024**). Perceived attitude of preservice teachers towards the integration of technology in teaching and learning college geometry: cases of two selected colleges of education in Ghana. *Discover Education*, *3*(1), 1–13.

7. Schindler, L. A., Burkholder, G. J., Morad, O. A., & Marsh, C. (**2017**). Computer-based technology and student engagement: A critical review of the literature. *International Journal of Educational Technology in Higher Education, 14*(25), 1–28.
8. Kaptan, E., & Cakir, R. (**2024**). The effect of digital storytelling on digital literacy, 21st century skills and achievement. *Education and Information Technologies*.
9. Abou Karroum, S., & Elshaiekh, N. E. (**2024**). Exploring the Role of Artificial Intelligence on Educational Dynamics: Evaluating its Impact on Pedagogical Practices and Student Learning Outcomes. *Qubahan Academic Journal*, *4*(4), 318-329.
10. Nacaroğlu, O., & Göktaş, O. (**2024**). The Effect of Technology Supported Guided Inquiry Environmental Education on Preservice Science Teachers' Attitudes Towards Sustainable Environment, Environmental Education Self-Efficacy and Digital Literacy. *Journal of Science Education and Technology*, *34*(2), 298–313.
11. Cujba, A., & Pifarré, M. (**2024**). Enhancing students' attitudes towards statistics through innovative technology-enhanced, collaborative, and data-driven project-based learning. *Humanities and Social Sciences Communications*, *11*(1), 1–14.
12. Godsk, M., & Møller, K. L. (**2024**). Engaging students in higher education with educational technology (No. 0123456789). Springer US.
13. Payne, L. (**2019**). Student engagement: Three models for its investigation. *Journal of Further and Higher Education, 43*(5), 641–657.
14. Saleem, S., Dhuey, E., White, L., & Perlman, M. (**2024**). Understanding 21st century skills needed in response to Industry 4.0: Exploring scholarly insights using bibliometric analysis. *Telematics and Informatics Reports, 13*, 100124.
15. Muyambo-Goto, O., Naidoo, D., & Kennedy, K. J. (**2023**). Students' conceptions of 21st century education in Zimbabwe. *Interchange, 54*(1), 49–80.
16. Gravett, S. (**2019**). Preparing children for Industry 4.0. *Mail and Guardian*.
17. Joynes, C., Rossignoli, S., & Amonoo-Kuofi, E. F. (**2019**). *21st century skills: Evidence of issues in definition, demand and delivery for development contexts* (K4D Helpdesk Report). Institute of Development Studies.
18. Rizvi, F., & Lingard, B. (**2010**). *Globalizing education policy*. Routledge.
19. Zhong, Y., Guo, K., Fryer, L. K., Chu, S. K. W., & Deng, H. (**2024**). More than just fun: Investigating students' perceptions towards the potential of leveraging esports for promoting the acquisition of 21st century skills. In *Education and Information Technologies* (Vol. 30, Issue 1). Springer US.
20. Kipp, K., Kapros, E., & O'Keeffe, I. (2018). A universally accessible self-assessment gamified framework and software application to capture 21st century skills. *Designing for the user experience in learning systems*, 41-64.
21. Ioannou, A., Miliou, O., Adamou, M., Kitsis, A., Timotheou, S., & Mavri, A. (**2024**). Understanding practicing and assessment of 21st-century skills for learners in makerspaces and FabLabs. *Education and Information Technologies*.
22. Rayna, T., & Striukova, L. (**2021**). Fostering skills for the 21st century: The role of Fab labs and makerspaces. *Technological Forecasting and Social Change, 164*, 120391.
23. Kain, C., Koschmieder, C., Matischek-Jauk, M., & Bergner, S. (**2024**). Mapping the landscape: A scoping review of 21st century skills literature in secondary education. *Teaching and Teacher Education, 151*, 1–27.
24. Birhan, W., Shiferaw, G., Amsalu, A., Tamiru, M., & Tiruye, H. (**2021**). Exploring the context of teaching character education to children in preprimary and primary schools. *Social Sciences & Humanities Open, 4*(1), 100171.
25. Casali, N., Filippi, S., & Feraco, T. (**2024**). Does inequality shape human character? Cross-cultural associations between character strengths and the Gini index in 68 countries. *Journal of Happiness Studies, 25*(4), 1–17.
26. Sakti, S. A., Endraswara, S., & Rohman, A. (**2024**). Revitalizing local wisdom within character education through ethnopedagogy approach: A case study on a preschool in Yogyakarta. *Heliyon, 10*(10), e31370.
27. Karakose, T., et al. (**2023**). Assessment of the relationships between prospective mathematics teachers' classroom management anxiety, academic self-efficacy beliefs, academic amotivation and attitudes toward the teaching profession using structural equation modelling. *Mathematics, 11*(2), 1–23.
28. Abdurrahman, A. (**2019**). Developing STEM learning makerspace for fostering student's 21st century skills in the fourth industrial revolution era. *Journal of Physics: Conference Series, 1155*(1), 1–6.
29. Blackley, S., Sheffield, R., & Kou, R. (**2018**). Using a makerspace approach to engage Indonesian primary students with STEM. *Educational Research, 28*(1), 18–42.
30. Stehle, S. M., & Peters-Burton, E. E. (**2019**). Developing student 21st century skills in selected exemplary inclusive STEM high schools. *International Journal of STEM Education, 6*(1).
31. Lavi, R., Tal, M., & Dori, Y. J. (**2021**). Perceptions of STEM alumni and students on developing 21st century skills through methods of teaching and learning. *Studies in Educational Evaluation, 70*, 101002.
32. Adams, E. L. (**2021**). The effect of a middle grades STEM initiative on students' cognitive and non-cognitive outcomes. *Studies in Educational Evaluation, 68*.
33. Pamungkas, M. D., Waluya, S. B., Mariani, S., Isnarto, I., Rahmawati, F., Kholid, M. N., & Laksmiwati, P. A. (**2024**). Enhancing Complex Problem-Solving Skills through STEM-Based Spatial Geometry E-Modules. *Qubahan Academic Journal*, *4*(3), 541-556.

34. Stoet, G., & Geary, D. C. (**2018**). The gender-equality paradox in science, technology, engineering, and mathematics education. *Psychological Science, 29*(4), 581–593.
35. Chalmers, C., Carter, M. L., Cooper, T., & Nason, R. (**2017**). Implementing 'big ideas' to advance the teaching and learning of science, technology, engineering, and mathematics (STEM). *International Journal of Science and Mathematics Education, 15*(1), 25–43.
36. Bybee, R. W. (**2010**). Advancing STEM education: A 2020 vision. *Technology and Engineering Teacher, 70*, 30–35.
37. Marginson, S., Tytler, R., Freeman, B., & Roberts, K. (**2013**). *STEM: Country comparisons: International comparisons of science, technology, engineering, and mathematics (STEM) education. Final report*. Australian Council of Learned Academies.
38. Sumarni, W., Sudarmin, S., Sumarti, S. S., & Kadarwati, S. (**2022**). Indigenous knowledge of Indonesian traditional medicines in science teaching and learning using a science–technology–engineering–mathematics (STEM) approach. *Science Education, 17*(2). Springer Netherlands.
39. Çepni, S., & Ormancı, Ü. (**2018**). *The world of the future*. Pegem Academy.
40. Hamid, R. (**2024**). Exploring the effectiveness of hybrid learning models in higher education post-pandemic. *International Journal of Post Axial, 2*(3), 177–191.
41. Baker, L. A., & Spencely, C. (**2023**). Is hybrid teaching delivering equivalent learning for students in higher education? *Journal of Further and Higher Education, 47*(5), 674–686.
42. Garrison, D. R., & Vaughan, N. D. (**2008**). *Blended learning in higher education: Framework, principles, and guidelines*. Jossey-Bass.
43. Picciano, A. G. (**2009**). Blending with purpose: The multimodal model. *Journal of Asynchronous Learning Networks, 13*(1), 7–18.
44. Siregar, N. C., Rosli, R., Maat, S. M., & Capraro, M. M. (**2019**). The effect of Science, Technology, Engineering and Mathematics (STEM) program on students' achievement in mathematics: A meta-analysis. *International Electronic Journal of Mathematics Education, 15*(1).
45. Artobatama, I. (**2018**). Pembelajaran STEM berbasis outbound permainan tradisional. *Indonesian Journal of Primary Education, 2*(2), 40–47.
46. Afifah, A., Khoiri, M., & Qomaria, N. (**2018**). Mathematics preservice teachers' views on mathematical literacy. *International Journal of Trends in Mathematics Education Research, 1*(3), 92–94.
47. Capraro, R. M., Capraro, M. M., & Morgan, J. R. (**2013**). *STEM project-based learning: An integrated science, technology, engineering, and mathematics (STEM) approach* (2nd ed.). Sense Publishers.
48. Akgunduz, D., & Mesutoglu, C. (**2021**). Science, technology, engineering, and mathematics education for Industry 4.0 in technical and vocational high schools: Investigation of teacher professional development. *Science Education International, 32*(2).
49. Denton, M., Borrego, M., & Boklage, A. (**2020**). Community cultural wealth in science, technology, engineering, and mathematics education: A systematic review. *Journal of Engineering Education, 109*(3), 556–580.
50. Fernández-Cézar, R., Garrido, D., & Solano-Pinto, N. (**2020**). Do Science, Technology, Engineering and Mathematics (STEM) experimentation outreach programs affect attitudes towards mathematics and science? A quasi-experiment in primary education. *Mathematics, 8*(9), 1490.
51. Maker, C. J. (**2020**). Identifying exceptional talent in science, technology, engineering, and mathematics: Increasing diversity and assessing creative problem-solving. *Journal of Advanced Academics, 31*(3), 161–210.
52. Papadakis, S., Vaiopoulou, J., Sifaki, E., Stamovlasis, D., Kalogiannakis, M., & Vassilakis, K. (**2021**). Factors that hinder in-service teachers from incorporating educational robotics into their daily or future teaching practice. *Proceedings of the International Conference on Computer Supported Education (CSEDU), 2*, 55–63.
53. Karakose, T., Kocabas, I., Yirci, R., Papadakis, S., Ozdemir, T. Y., & Demirkol, M. (**2022**). The development and evolution of digital leadership: A bibliometric mapping approach-based study. *Sustainability, 14*(23), 16171.
54. Star, J. R., Chen, J. A., Taylor, M. W., Durkin, K., Dede, C., & Chao, T. (**2014**). Studying technology-based strategies for enhancing motivation in mathematics. *International Journal of STEM Education, 1*(1), 7.
55. Sujanem, R., Poedjiastuti, S., & Jatmiko, B. (**2018**). The effectiveness of problem-based hybrid learning model in physics teaching to enhance critical thinking of the students of SMAN. *Journal of Physics: Conference Series, 1040*(1), 012040.
56. Tall, D. (**1991**). Advanced mathematical thinking and the computer. In D. Tall (Ed.), *Advanced mathematical thinking* (pp. 231–248). Kluwer.
57. Aristika, A., Darhim, Juandi, D., & Kusnandi. (**2021**). The effectiveness of hybrid learning in improving teacher-student relationship in terms of learning motivation. *Emerging Science Journal, 5*(4), 443–456.
58. Dubinsky, E., & Tall, D. (1991). Advanced mathematical thinking and the computer. In *Advanced mathematical thinking* (pp. 231-248). Dordrecht: Springer Netherlands.
59. Alwadood, Z., Halim, S. A., Bakar, S. A., & Noor, N. M. (**2023**). Assessing student perceptions on hybrid learning. *International Journal of Evaluation and Research in Education, 12*(3), 1582–1590.
60. Rorimpandey, W. H. F., & Midun, H. (**2021**). Effect of hybrid learning strategy and self-efficacy on learning outcomes. *Journal of Hunan University, 48*(8), 181–189.

61. Kalogiannakis, M., & Papadakis, S. (**2020**). The use of developmentally mobile applications for preparing pre-service teachers to promote STEM activities in preschool classrooms. In S. Papadakis & M. Kalogiannakis (Eds.), *Mobile learning applications in early childhood education* (pp. 1–20). IGI Global.
62. Tsai, A. (**2011**). A hybrid e-learning model incorporating some of the principal learning theories. *Social Behavior and Personality: An International Journal, 39*(2), 145–152.
63. Vaughan, N., & Garrison, D. R. (**2005**). Creating cognitive presence in a blended faculty development community. *Internet and Higher Education, 8*(1), 1–12.
64. Wijayanto, P. W., Lumbantoruan, J. H., Judijanto, L., Mardikawati, B., & Huda, N. (**2024**). Mathematics teachers in teaching 4C skills: School-university perspective. *Journal of Educational Research and Evaluation, 8*(1), 195–206.
65. Tang, T., Vezzani, V., & Eriksson, V. (**2020**). Developing critical thinking, collective creativity skills and problem-solving through playful design jams. *Thinking Skills and Creativity, 37*, 100696.
66. Korfiatis, K., Grace, M., & Hammann, M. (2024). *Shaping the Future of Biological Education Research: Selected Papers from the ERIDOB 2022 Conference* (p. 353). Springer Nature.
67. Nousheen, A., Yousuf Zai, S. A., Waseem, M., & Khan, S. A. (**2020**). Education for sustainable development (ESD): Effects of sustainability education on pre-service teachers' attitude towards sustainable development (SD). *Journal of Cleaner Production, 250*, 119537.
68. Taufiqurrahman, M. (**2023**). Pembelajaran abad-21 berbasis kompetensi 4C di perguruan tinggi. *Progressa: Jurnal Pendidikan Islam dan Keagamaan, 7*(1), 77–89.
69. Susilo, M. J., Dewantoro, M. H., & Yuningsih, Y. (**2022**). Character education trend in Indonesia. *Journal of Education and Learning, 16*(2), 180–188.
70. Slavin, R. E. (**2000**). *Educational psychology: Theory and practice*. Pearson Education.
71. Lee, Y. (**2016**). Bridging constructivist theories and design practice for children to grow as active technology users. *Archives of Design Research, 29*(4), 53–63.
72. Efgivia, M. G., Rinanda, R. A., Hidayat, A., Maulana, I., & Budiarjo, A. (2021, October). Analysis of constructivism learning theory. In *1st UMGESHIC International Seminar on Health, Social Science and Humanities (UMGESHIC-ISHSSH 2020)* (pp. 208-212). Atlantis Press.
73. Do, H. N., Do, B. N., & Nguyen, M. H. (**2023**). How do constructivism learning environments generate better motivation and learning strategies? The design science approach. *Heliyon, 9*, e22862.
74. Jemberie, L. W. (**2021**). Teachers' perception and implementation of constructivist learning approaches: Focus on Ethiopian Institute of Textile and Fashion Technology, Bahir Dar. *Cogent Education, 8*(1), 1907955.
75. Braun, V., & Clarke, V. (**2006**). Using thematic analysis in psychology. *Qualitative research in psychology, 3*(2), 77-101.
76. Rogovaya, O., Larchenkova, L., & Gavronskaya, Y. (**2019**). Critical thinking in STEM (Science, Technology, Engineering, and Mathematics). *Utopía y Praxis Latinoamericana, 24*(6), 32–41.
77. Mu'minah, I. H., & Suryaningsih, Y. (**2020**). Implementation of STEAM (Science, Technology, Arts and Mathematics) in 21st-century learning. *Jurnal Biologi Edukasi, 5*(1), 65–73.
78. Zhang, J., Wang, Y., Leong, C., Mao, Y., & Yuan, Z. (**2024**). Bridging stories and science: An fNIRS-based hyperscanning investigation into child learning in STEM. *NeuroImage, 285*, 120486.
79. Li, Y., Wang, K., Xiao, Y., & Froyd, J. E. (**2020**). Research and trends in STEM education: A systematic review of journal publications. *International Journal of STEM Education, 7*(1), 1–16.
80. Wang, L. H., Chen, G., Hwang, J., & Guan, Y. (**2022**). Effects of digital game-based STEM education on students' learning achievement: A meta-analysis. *International Journal of STEM Education, 9*(1), 1–13.
81. Anning, A. S. (**2025**). Professional learning facilitators' contribution to sustainable STEM teacher learning in regional contexts. *International Journal of Educational Research Open, 8*, 100406.
82. Kelley, T. R., & Knowles, J. (**2016**). A conceptual framework for integrated STEM education. *International Journal of STEM Education, 3*, 1–11.
83. Kennedy, T. J., & Odell, M. R. L. (**2014**). Engaging students in STEM education. *Science Education International, 25*(3), 246–258.
84. Suardi, S. (**2020**). Implementation of STEM-based learning to enhance critical thinking, creativity, and collaboration skills of Grade VIIA students at SMP Negeri 4 Sibulue. *Jurnal Sains dan Pendidikan Fisika, 16*(2), 135–144.