International Journal of Advanced and Applied Sciences, 11(7) 2024, Pages: 149-159

Contents lists available at Science-Gate

International Journal of Advanced and Applied Sciences

Journal homepage: http://www.science-gate.com/IJAAS.html

Fostering critical thinking in science education: Exploring effective pedagogical models

Sigit Sujatmika *, Mohammad Masykuri, Baskoro Adi Prayitno, Sutarno Sutarno

Faculty of Teacher Training and Education, Universitas Sebelas Maret, Surakarta, Indonesia

ARTICLE INFO

Article history:
Received 16 September 2023
Received in revised form
14 January 2024
Accepted 8 July 2024

Keywords:
Critical thinking
Science education
Instructional models
COVID-19 pandemic
Research trends

ABSTRACT

In the digital age, accessing information has both advantages and disadvantages. It is crucial to analyze available data before making decisions. Critical thinking (CT) skills are vital in mitigating the negative impacts of misleading information. This was exemplified during the COVID-19 pandemic, which caused emotional distress in society and other harmful effects. Educators should aim to develop CT skills in students from a young age, incorporating them into various subjects, including science education. This research aims to investigate trends in CT research over the past decade, identify instructional models that facilitate CT, and evaluate the efficacy of these models in enhancing CT abilities. The search focused on research articles on CT in science education at the K-12 level. The PRISMA model was followed, and the Science Direct, Taylor and Francis, Springer, Wiley Online Library, and ERIC databases were utilized. The results suggest a significant increase in research related to CT over the past decade. Eighteen articles that met our established criteria were identified and included. These findings demonstrate that STEM, inquiry-based learning, problem-based learning, cooperative learning, and predict-observe-explain (POE) instructional models are suitable for fostering CT. These models exhibit characteristics that promote the development of CT skills in the learning process. However, when selecting the most appropriate instructional model, it is important to consider learning objectives, subject matter, student characteristics, and contextual elements within the learning environment.

1. Introduction

The advancement of the digital world has significantly influenced various aspects of human life. Technology has provided numerous benefits to humanity, such as speed and convenience in accessing information, facilitating work processes, and enhancing social interactions. We are in an era of profound transformation and reform (Barak, 2017). In education, information technology has provided tools that can optimize the learning process (Castro, 2019; Henriksen et al., 2018). It has become commonplace for education to be conducted online in blended or hybrid formats (Boling et al., 2012). Innovative internet-based instructional media can cultivate a heightened enthusiasm for learning among students (Arici et al., 2019; Sukendro et al., 2020). Harnessing diverse, freely available online resources can readily overcome spatial limitations. Additionally, students can use different artificial intelligence (AI) applications to assist them in their learning process (Zhang and Aslan, 2021).

However, the rapid advancement of information technology doesn't always positively affect people (Tarafdar et al., 2015). Information circulating freely online and on social media is sometimes accurate or reliable. Meticulously evaluating and sorting through information becomes essential when making decisions. This practice holds equal significance for students incorporating diverse technological tools within their classroom environments. The negative impact of misinformation occurred during the COVID-19 pandemic when false information led to psychological problems (Rose, 2020). Therefore, we must be skillful at choosing and trusting the information available before making crucial decisions. We require a profound ability to analyze existing information, commonly called critical thinking skills.

The skill of analyzing information constitutes a form of critical thinking (Piawa, 2010; Thompson,

* Corresponding Author.
Email Address: sujatmika@ustjogja.ac.id (S. Sujatmika)
https://doi.org/10.21833/ijaas.2024.07.016
Corresponding author's ORCID profile:
https://orcid.org/0000-0001-8832-2394

2019). According to Ennis (2018), critical thinking (CT) involves a profoundly analytical process of deciding and acting. The CT process involves interconnecting all the available information and analyzing it systematically, step by step (Sujatmika et al., 2022). Analytical thinking encompasses clarifying, comparing, drawing conclusions, and evaluating (Griffin et al., 2012; Gunduz and Hursen, 2015; Marin and Halpern, 2011). CT is characterized as self-regulation that yields interpretations, analyses, evaluations, inferences, and explanations based on evidential, conceptual, methodological, and contextual considerations that serve as the foundation for decision-making. Individuals who engage in CT do not exhibit recklessness in their actions, contributing to life success (Sujatmika et al., 2019). CT has been recognized as one of the essential skills for the 21st century (Trilling and Fadel, 2009). Education in schools should ideally foster the cultivation of CT skills in students from an early age (Niu et al., 2013).

Introducing CT training in the classroom, especially in science lessons, is a practical idea and viable. Recent studies have indicated a strong connection between science lessons and the development of CT and reasoning skills (Forawi, 2016; Yuan et al., 2014). Moreover, a validated evaluation tool for assessing CT in elementary school children's science education has been developed by Siew and Mapeala (2002). Educators actively integrate various activities into the science and education curriculum to foster student engagement in inquiry, problem-solving, and decision-making processes (Duran and Dökme, 2016).

Furthermore, CT is a metacognitive process that includes various sub-skills. Using these sub-skills correctly can increase the chances of reaching logical conclusions in an argument or finding solutions to a problem (Dwyer et al., 2017). According to experts, CT has become a pivotal 21st-century skill that needs to be nurtured in students through education (Van Laar et al., 2017). Teachers should facilitate the learning process by employing fitting methods and providing adequate support to enhance students' CT capabilities. The appropriate pedagogical model required to cultivate CT needs to be identified.

Over the last decades, numerous publications have been on utilizing instructional models and learning media that support the development of CT, yet a more profound investigation is warranted. The most effective among these models, methods, or media still necessitates further scrutiny. There is a need for research on CT targeted explicitly at middle school students, enabling the cultivation of CT skills from a young age through efficient methods. Limited research has been conducted in this area. Through this study, we aim to address this gap and provide answers using suitable approaches.

The correlation between the learning model and CT has been investigated by Anggraeni et al. (2023). The learning model primarily focuses on Problem-Based Learning (PBL) and confines its scope to the field of social sciences. The database employed spans five years (2018-2022). Our study distinguishes itself through variations in the database's scope, the research's time frame, and a different area of inquiry. The findings of our model may have broader applicability, extending beyond PBL and encompassing a more comprehensive time range over the past decade.

This research aims to determine (1) research trends in CT over the last decade, (2) instructional models that support the development of CT in students, and (3) identify models that have proven effective in enhancing CT. The scope of this research is confined to the secondary school level (K-12) within the domain of science education. These instructional models encompass pedagogical methods, supportive media, and the integration of information technology. The research findings can be invaluable to secondary school science teachers, offering insights into how to support students' CT through their teaching methods. Using diverse teaching models facilitates teachers' adaptation to the presented science material, thus creating opportunities for developing students' CT skills through effective instructional strategies.

2. Methodology

2.1. Type of research

The methodology is a systematic literature review guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) guidelines (Page et al., 2021). The PRISMA model serves as a framework for gathering existing evidence objectively to address research questions or identify trends, knowledge gaps, or recommendations for further action. The PRISMA diagram visually depicts the present review process's identification, screening, and inclusion stages (Fig. 1).

2.2. Search strategies

A structured and comprehensive search strategy of this nature helps ensure that the literature obtained through databases is relevant to the research question. The steps used in the search strategy are as follows:

1. Extracting the main search terms from the research question.
2. Identifying relevant terms, synonyms, and alternate spellings for the main search terms used in published literature.
3. Constructing search strings from the main search terms for use in online digital libraries for abstract-based searches.
4. Selecting various reputable indexed online databases comprising scholarly journals. By employing this approach, we can minimize the risk of bias and ensure that the search and literature

selection processes are conducted objectively and systematically.

2.3. Synonyms and alternative terms

Based on the previously presented research question, we identified the variables that would be explored through the database. The process of identifying research variables guided the formulation of search strings, incorporating four primary terms: CT skills, science education, educational level, and instructional models. Derived from these four terms, synonyms and commonly used alternative terms employed by researchers were identified. This information is presented in Table 1.

2.4. The utilized databases

This SLR study employed several leading databases that are well-recognized in the academic realm to gather relevant literature. The databases we utilized encompass a range of disciplines and topics pertinent to the research question. The amalgamation of these databases ensures that the study achieves a comprehensive literature overview, enhancing the robustness of the review's findings and conclusions. The combined database selection is outlined in Table 2.

Table 1: Synonyms and alternative terms

CT synonyms	Subject	Level	Models
CT	Science education	Secondary school	Teaching model
CT skills	Nature of science	Middle school	Learning model
CT ability	Science lesson	K-12	

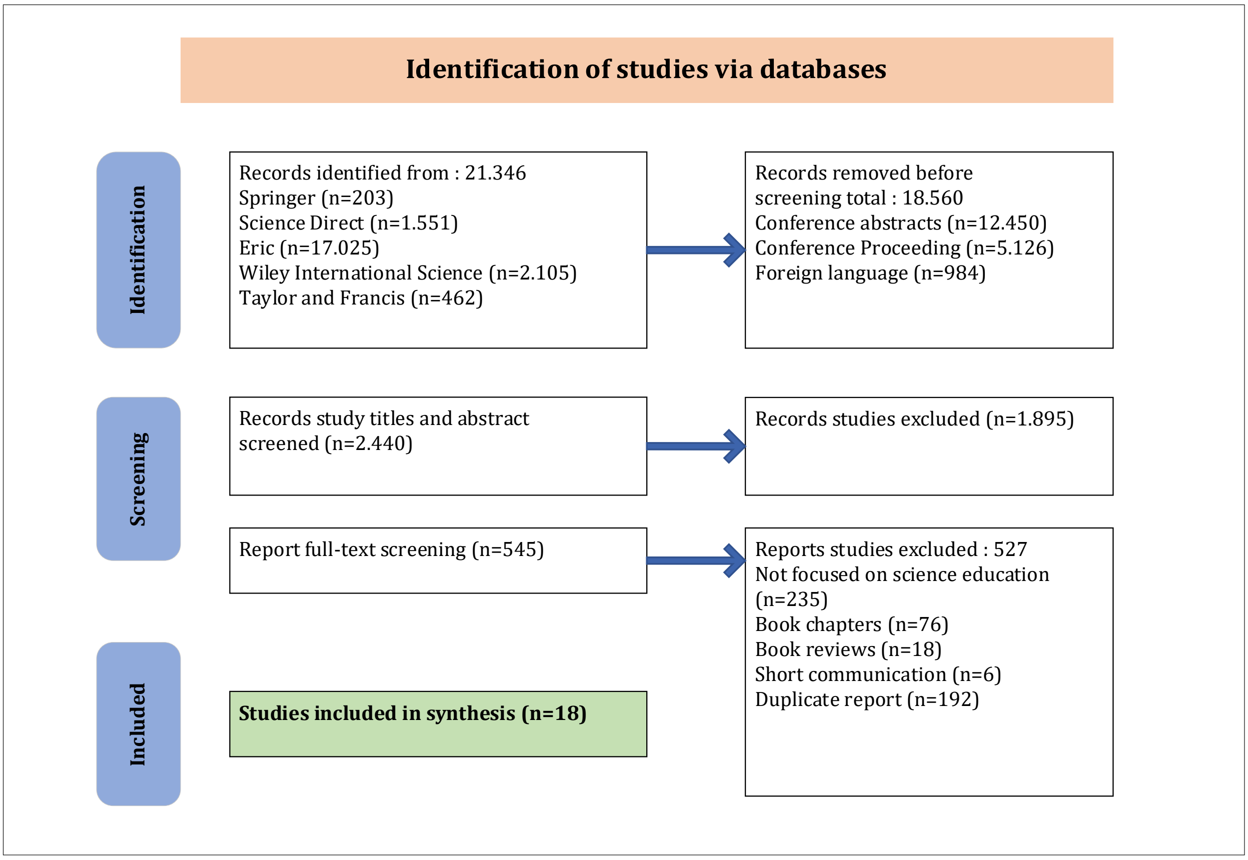

Fig. 1: PRISMA flow diagram (Page et al., 2021)

Table 2: Database and research string

Database/Search Engine	Web link	String
Science Direct	http://www.sciencedirect.com	"learning model" AND "science education" AND "critical thinking"
Taylor and Francis	https://www.tandfonline.com	
Springer	https://link.springer.com	
Wiley Online Library	https://onlinelibrary.wiley.com	
Education Resources Information Center (ERIC)	https://eric.ed.gov	

2.5. Inclusion and exclusion criteria

The inclusion and exclusion criteria in the SLR study are crucial steps that assist us in selecting literature that aligns with the research objectives. Furthermore, they ensure that the literature or articles included in the SLR analysis are highly relevant and high quality. In Table 3, there is a description of the utilization of the inclusion and exclusion criteria in the literature selection process.

Table 3: Inclusion and exclusion criteria

Include if all of these criteria are available	Exclude if any of these criteria are present
Published in English Follows an empirical research method Targets middle school and/or high school students and/or educators (K-12) Issued between 2012 and 2022	Research in the form of a thesis or dissertation Research lacks adequate research design, data analysis, and empirical data Conceptual or discursive paper Published in proceedings, book chapters, or editorial review Level in higher education

3. Result and discussion

3.1. Characteristics of the included studies

Discovering the most suitable articles to address the research objectives begins with identifying databases and thorough screening. The initial database search yielded 21,346 findings. However, the results were still general; not all were research articles. This category included non-English writings and conference proceedings. The exclusion criteria screening process narrowed the selection to 545 out of 2,440 papers. Meanwhile, the inclusion criteria yielded 18 most relevant articles (Fig. 1). The database search yielded 18 relevant articles based on the predetermined inclusion and exclusion criteria—the article selection process aimed to ensure that the chosen articles meet the required standards. Consist of quality and relevance to research questions. These 18 articles have passed this selection phase and are considered the most suitable resources. They will be used in the analysis and discussion. Based on the conducted literature search, the journals most frequently publish research results on improving CT skills have been identified and presented in Table 4. It should be emphasized that data only includes the primary journals crucial in publishing research articles on CT skills.

Table 4: Description of SLR result data

No.	Journal publications	SJR 2022	Q category	Number of publication
1	Science and Education	1.31	Q1 in education	1
2	Interactive Learning Environments	1.17	Q1 in computer science application	1
3	Thinking Skills and Creativity	1.15	Q1 in education	4
4	Environmental Education Research	1.12	Q1 in education	1
5	International Journal of Science Education	1	Q1 in education	2
6	The Journal of Educational Research	0.65	Q2 in education	1
7	International Journal of Instruction	0.61	Q2 in education	1
8	Educational Studies	0.61	Q2 in education	1
9	EURASIA Journal of Mathematics, Science and Technology Education	0.51	Q2 in applied mathematics	1
10	European Journal of Educational Research	0.34	Q3 in education	1
11	Participatory Educational Research	0.26	Q3 in education	1
12	International Online Journal of Education and Teaching	Eric	Eric	1
13	SN Social Sciences	Eric	Eric	1
14	Pedagogies: An International Journal	Eric	Eric	1

The conference proceedings search results were excluded to maintain a focus on journals that have a significant impact and reputation in disseminating research related to efforts in enhancing CT skills. The search results for journal articles were subsequently cross-referenced with their Scimago Journal Rank (SJR) rankings. Table 4 presents the rankings of selected journals based on their 2022 SJR values. This data ranking signifies their level of influence and prestige within scientific research. The SJR value is one indicator employed to gauge a journal's impact within the scholarly community. While not necessarily the sole criterion in journal selection, the information provided in Table 4 can furnish initial guidance for researchers intending to disseminate their CT skills-related research outcomes.

Based on the data presented in Table 4, it is clear that articles from the journals International Online Journal of Education and Teaching, SN Social Sciences, and Pedagogies: An International Journal have not been included in the Scopus database. Consequently, these journals do not have SJR values and Q category assignments, which are commonly used indicators for assessing a journal's influence and impact within the scholarly community. Nevertheless, it's worth noting that these journals are indexed in the Education Resources Information Center (ERIC). ERIC indexing underscores the recognition and documentation of these journals as relevant literature resources within the educational context. ERIC serves as a vital resource for researchers, educators, and practitioners to access quality information within the field of education. The journal articles hold significant value within the educational literature, even though they might not yet be indexed in Scopus. The academic community has acknowledged the articles published in these journals as contributing literature resources that enhance the understanding of efforts to improve CT skills.

3.2. Research trends on CT

The distribution of search results across 18 articles on CT skills from 2012 to 2022 is illustrated in Fig. 2. The search results indicate a significant increase in research trends focused on enhancing CT skills from 2004 to 2022. Researchers took data from the last ten years but included data since 2004 to make the increase more visible. The data retrieved demonstrates that there has been a clear and consistent growth in both interest and research related to CT skills during this period. Studies on enhancing CT skills have been increasingly identified and documented throughout this timeframe. This phenomenon is reflected in the number of articles, publications, and literature resources dedicated to teaching strategies, approaches for developing CT skills, and other endeavors to strengthen CT.

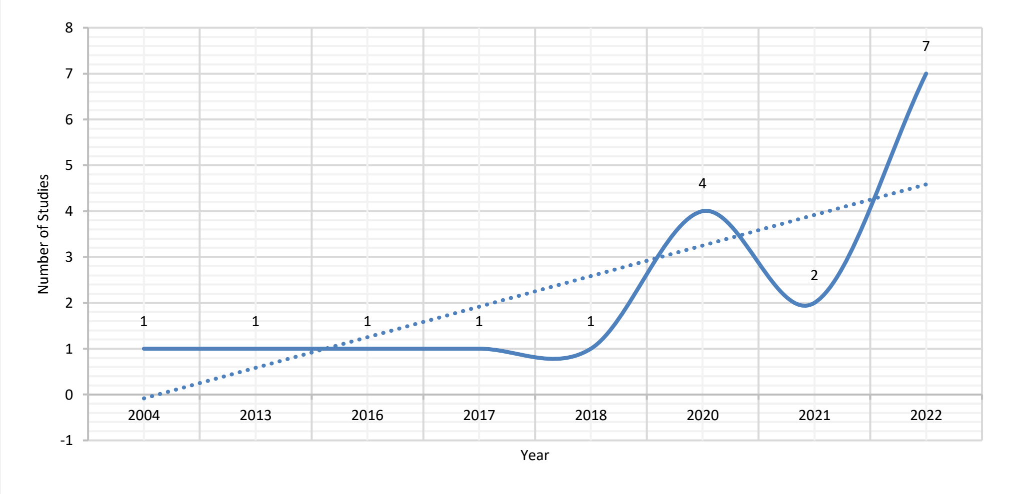

Fig. 2: Distribution of search results for articles about CT

The outcomes of this literature search provide crucial insights into how awareness of the significance of CT skills has escalated between 2004 and 2022. CT, within the context of education and learner development, demonstrates that numerous stakeholders, including academics, educators, and practitioners, are increasingly paying attention to and investing in cultivating CT skills to respond to the world's complexities. Notably, the rising research trend furnishes a robust foundation for developing learning models, instructional methods, learning media, teaching strategies, and educational curricula to enhance CT.

3.3. Learning models that support CT

After conducting a comprehensive Systematic Literature Review (SLR), we identified several instructional models that support CT. These models include Quantum Teaching and Science Technology and Society (Kristiyanto et al., 2020), Group work (Fung et al., 2016), Think-Read-Group-Share-Reflect (Giri and Paily, 2020), Digital games (Chen and Wu, 2023), Science Technology Engineering Mathematics (Alpizar et al., 2022), Reciprocal Teaching Strategy (Mafarja and Zulnaidi, 2022), Electronic Interactive Teaching Materials (Sinaga et al., 2022), Cooperation-driven Socio-scientific Issues (Wang et al., 2017), Project-Based Learning (Oliveras et al., 2013), Student Task and Cognition Model (Lamb et al., 2019), PBL, Predict, Observe, Explain (Fitriani et al., 2020, STEM-based Activities (Mater et al., 2022), PBL with Metacognitive Prompts, High-Intensity PBL, Low-Intensity PBL (Marthaliakirana et al., 2022), STEM-Inquiry Model (Pahrudin et al., 2021), and Guided Discovery Learning-Argument Mapping (Ristanto et al., 2022).

These instructional models can be broadly categorized into five major groups: STEM (Science, Technology, Engineering, Mathematics), Inquiry-based models, PBL, Cooperative Learning, and the Predict, Observe, Explain (POE) model. The frequent mention of these five major instructional model groups in the literature highlights their perceived effectiveness in enhancing students' CT skills. Each model promotes CT and problem-solving with unique features and can be adapted to different learning contexts.

The STEM instructional model teaches students to connect interdisciplinary concepts and encourages the application of CT skills in solving real-world problems. The inquiry-based learning model prompts students to develop questions, gather information, analyze data, and draw conclusions through independent investigation. The PBL model engages students in resolving authentic or complex simulations. They must apply their knowledge and skills to tackle these challenges, fostering analytical and CT. The cooperative learning model emphasizes collaboration and interaction among students. They work in small groups to achieve common goals, share knowledge, and discuss solutions. Meanwhile, the Predict, Observe, Explain (POE) model involves students predicting what will occur in a phenomenon, observing an experiment or event, and then explaining the outcomes.

3.4. Comparison of the research findings

The comparison of findings from various studies identified in the literature review is presented in Table 5. Table 5 shows data that provides an overview of the similarities, differences, and emerging trends from the results of previous research. The comparison of findings aims to consolidate these outcomes into a single table to observe patterns or consistencies in what has been uncovered by different studies.

Table 5: Comparison of the research findings

Study	Participants	Research tools	Grade	Findings
Alpizar et al. (2022)	N = 817	Cornell CT test (CCTT)	Middle school	Reading proficiency is critical in developing CT skills in STEM instructional strategies CT development may rely on various components of language ability The interaction of gender and reading scores was not related to initial status
Chen and Wu (2023)	N = 32 Male = 12 Female = 20	CT test level II (CTT-II)	Senior high school	Role-playing games lead to a significant improvement in CT Role-playing games may increase learning motivation among student participants
Ernst and Monroe (2004)	N = 404	Cornell CT test California measure of mental motivation	Senior high school	Environment-based programs are improving students' CT skills Environment-based programs are helping them become more disposed toward using CT skills
Fitriani et al. (2020)	N = 98	Essay CT Test	Senior high school	PBL POE and PBLPOE had an effect on the student's CT skills PBL POE and PBLPOE had an effect on the scientific attitudes
Fung et al. (2016)	N = 140 Experiment class = 70 Control class = 70	California CT disposition inventory Test of CT skills for primary and secondary school students	Senior high school	Group work exerts positive effects on both CT dispositions and skills Teacher participation in collaborative discussions has an impact on students' CT
Giri and Paily (2020)	N = 25 Male = 13 Female = 12	Watson-Glaser CT	Senior high school	Think-Read Group-Share-Reflect strategy that is integration of Toulmin's argument pattern within TRGSR was effective in the development of CT
Kristiyanto et al. (2020)	N = 300	Questionnaire CT skills	Elementary schools	Quantum teaching models are better in terms of CT skills. Natural science learning outcomes of the students who have high CT skills are better than the science learning outcomes of the students who have medium CT skills
Lamb et al. (2019)	N = 120	Performance assessment	Elementary schools	Examination of the confidence intervals for each condition illustrates the ablation network Elementary students are not statistically different in the number of correct responses
Lin and Shih (2022)	N = 312	Open-ended creativity Closed-ended creativity CT	Junior high school Senior high school	Closed-ended creativity development could account for closed-ended creativity performances Closed-ended creativity relates closely to CT CT plays a crucial role in closed-ended creativity
Mafarja and Zulnaidi (2022)	N = 120 Male = 60 Female = 60 Experiment class = 60 Control class = 60	CT test	Secondary school	CT skills were positive and moderate using a reciprocal teaching strategy Positive relation between students' CT skills and academic self-concept
Manassero-Mas and Vázquez-Alonso (2022)	N = 781 Male = 406 Female = 375	CT skills test Nature of science test	Secondary school	Correlation coefficients revealed a pattern of the relationships between NOS and thinking skills Positive relationships between thinking skills and NOS beliefs about science definitions
Marthaliakirana et al. (2022)	N = 121	CT test Scientific argumentation test	Senior high school	Metacognitive can help students participate in the argumentation Students develop into skilled thinkers capable of applying their argumentation and CT skills to problem-solving situations
Mater et al. (2022)	N = 59 Experiment class = 30 Control class = 29	The California CT skills test Technology acceptance model (TAM)	Senior high school	Positive results in the development of CT skills An opportunity for students to employ their knowledge and concepts to solve their problems
Oliveras et al. (2013)	N = 61	Critical reading activities	Secondary school	Critical reading activities in the classroom improve the ability to read critically The critical reading activities analyzed helped to connect different concepts studied in science classes
Pahrudin et al. (2021)	N = 50 Experiment class = 25 Control class = 25	CT skills test	Senior high school	CT skill in the experimental class is higher than in the control class STEM-based inquiry model is effective in improving students' CT skills
Ristanto et al. (2022)	N = 66 Experiment class = 33 Control class = 33	CT skills test	Senior high school	Guided Discovery Learning-Argument Mapping (GDL-AM) was proven to be capable of influencing CT skills GDL-AM implementation assisted the teacher in achieving learning objectives
Sinaga et al. (2022)	N = 46 Male = 11 Female = 12 Experiment class = 23 Control class = 23	CT ability test	Junior high school	CT skills of the experimental group increased with high criteria The increase in CT skills of students who used EITMs both in the overall and per-aspect scores Positive difference in the CT skills between the experimental and control groups
Wang et al. (2017)	N = 49	California CT disposition inventory	Junior high school	Students were encouraged to work together cooperatively without any personal competition or blame within group members. Students were more engaged in sharing evaluating reflecting and achieving consensus on a variety of arguments

Based on Table 5, a comparison of findings from various studies reveals the typical characteristics of STEM (Science, Technology, Engineering, and Mathematics), Inquiry-based learning, PBL, cooperative learning, and Predict-Observe-Explain (POE) in facilitating students' CT skills. These common characteristics converge towards the ability to foster CT through authentic problem-solving, collaboration, evidence analysis, and reflection. The judicious selection of an appropriate instructional model in alignment with the learning context and objectives can significantly enhance students' CT skills.

The characteristics of STEM in efforts to enhance CT are as follows: (1) Integration of science, technology, engineering, and mathematics within learning objectives to reinforce the interconnections between concepts (Alpizar et al., 2022). (2) Emphasis on real projects or challenges relevant to the real world, prompting students to apply CT in problem-solving (Mater et al., 2022). (3) Encouragement of group collaboration to solve complex problems, enhancing communication and teamwork skills (Pahrudin et al., 2021). (4) Stimulating creative thinking in students to design innovative solutions for the challenges they encounter (Alpizar et al., 2022). Integrating technology in STEM education supports the attainment of students' CT skills. Today's rapidly advancing information technology can be incorporated into the learning process as a means of information acquisition and problem-solving. Modern technology offers several advantages in facilitating CT. These characteristics collectively contribute to cultivating CT skills in students through STEM education.

In the inquiry-based learning model, the supporting characteristics are as follows (Mafarja and Zulnaidi, 2022; Pahrudin et al., 2021; Ristanto et al., 2022): (1) Student Empowerment: This model enables students to assume control over their learning by formulating questions, planning and conducting experiments, and evaluating outcomes. (2) Stimulation of CT: Inquiry-based learning fosters CT by posing open-ended questions that trigger reflection, analysis, and further exploration. (3) Application of CT: The model encourages students to apply CT skills in data analysis, concluding, and problem-solving within the context of investigation. Inquiry-based learning empowers students to participate in their learning journey actively, prompting them to critically examine information, develop analytical capabilities, and apply their cognitive skills effectively. This approach aligns with contemporary educational paradigms prioritizing learner-centered and experiential learning methodologies.

The PBL model supports CT skills for the following reasons (Fitriani et al., 2020): (1) Students are presented with authentic, real-world problems or complex simulations, compelling them to apply their knowledge and skills in designing solutions. (2) PBL trains students to identify and seek relevant information, develop their understanding, and solve problems with minimal instructor guidance. (3) The model encourages group discussions to share ideas, perspectives, and solutions. In conclusion, PBL engages students in active problem-solving experiences, fostering their ability to apply theoretical knowledge to practical situations, think critically, and collaborate effectively. This approach resonates with contemporary educational trends emphasizing student autonomy and experiential learning.

The characteristics of the cooperative learning model in supporting CT are as follows (Fung et al., 2016; Giri and Paily, 2020): (1) Cooperative learning encourages students to share their understanding, exchange viewpoints, and pose questions that stimulate CT. (2) This model necessitates problem-solving by applying CT to analyze situations, identify potential solutions, and select the most appropriate steps to achieve goals. (3) Cooperative learning demands group synergy in contributing, adapting to individual roles, and resolving potential group challenges. Incorporating the cooperative learning model cultivates an environment where students actively engage with diverse perspectives, exercise analytical thought, and collaborate effectively. This approach aligns with modern educational ideals emphasizing collaborative skills and CT development.

Lastly, the characteristics of the POE learning model in enhancing CT are as follows (Fitriani et al., 2020): (1) POE encourages students to predict outcomes, observe phenomena, and formulate causal explanations based on the evidence they keep. (2) The model facilitates meticulous observation and profound analysis of observation outcomes, fostering a better understanding of concepts. (3) Students are prompted to explain observation results by linking them to initial predictions, encouraging reflection and reasoning. Incorporating the POE learning model prompts students to engage in predictive reasoning, honing their observational acumen, enhancing conceptual comprehension, and promoting reflective thinking.

4. Discussion

The STEM model is aptly suited for enhancing CT skills due to its characteristics and approaches that can stimulate the development of CT through the learning process (Alpizar et al., 2022; Mater et al., 2022; Pahrudin et al., 2021). STEM integrates various elements that support the cultivation of CT skills, such as analysis, evaluation, information synthesis, and problem-solving (Mater et al., 2022). Consequently, students learn about concepts and understand how to apply them in real-world contexts, thus eliciting profound and contextually relevant CT pertinent to what is being studied. The STEM model amalgamates science, technology, engineering, and mathematics, enabling students to perceive relationships among concepts across diverse disciplines (Pahrudin et al., 2021). The interconnection of material concepts in STEM learning aids students in achieving a deeper level of understanding and propels them to think critically about the relationships between these concepts.

The interconnectedness of concepts in STEM learning supports students in contextual problem-solving processes (Alpizar et al., 2022). Often, students are confronted with authentic problems that necessitate critical problem-solving. This stimulation prompts students to design solutions, identify relevant variables, and apply knowledge and skills to overcome challenges (Pahrudin et al., 2021). Indirectly, the STEM model fosters collaborative skills in designing, implementing, and evaluating projects. We conclude that STEM encourages students to comprehend the intricate connections between concepts, prepares them for contextual problem-solving, and cultivates collaboration. This framework not only imparts knowledge but also equips students to apply that knowledge effectively and critically in real-world scenarios.

Research on the influence of STEM on CT in elementary school students by Hacioğlu and Gülhan (2021) shows a beneficial impact. STEM, in particular, has the capacity to enhance CT sub-scales, namely "truth-seeking and open-mindedness." These results provide valuable insights into the potential applicability of STEM in primary schools and its support for developing students' CT abilities.

The inquiry-based learning model can enhance CT through active exploration, evidence analysis, causal reasoning, and independent reflection. Students not only memorize information but also construct robust understanding and develop the ability to approach complex problems and questions in a structured and analytical manner. The inquiry learning model fosters an active, explorative, and student-centered learning process (Pahrudin et al., 2021; Ristanto et al., 2022). Implementing inquiry-based learning trains students to take an active role in their education. Students must be capable of formulating questions, planning and executing experiments or investigations, and drawing conclusions based on their findings.

The inquiry-based learning model can enhance CT through active exploration, evidence analysis, causal reasoning, and independent reflection (Pahrudin et al., 2021). This model goes beyond mere memorization of information, fostering the development of a robust understanding and the ability to tackle complex problems and questions in a structured and analytical manner (Ristanto et al., 2022). The inquiry learning model promotes an active, explorative, and student-centered learning process. Implementing inquiry-based learning empowers students to play an active role in their education, formulating questions, planning and conducting experiments or investigations, and drawing conclusions based on their findings.

The cognitive process that unfolds in students through inquiry involves evaluating the reliability and relevance of collected evidence, prompting CT about the validity and interpretation of data (Pahrudin et al., 2021; Ristanto et al., 2022). Additionally, students must identify cause-and-effect relationships and explore the impact of various variables on the studied phenomena (Rodrigues, 2014). Thus, it can be asserted that the cognitive process occurring in students can promote causal reasoning, cause-and-effect relationships, and comprehension of the intricacies of real-world relationships.

An exploratory process facilitates learning in the inquiry-based learning model, whereas the PBL model centers around real-world problem-solving. PBL is conducive to fostering CT skills (Fitriani et al., 2020) due to its emphasis on genuine problem resolution, necessitating analytical thinking, evidence evaluation, and information synthesis. Educators implementing PBL can effectively stimulate students to cultivate CT skills through active problem-solving, evidence analysis, causal reasoning, and reflective evaluation (Marthaliakirana et al., 2022). The domain of issues addressed in PBL is contextual. PBL readies students to confront intricate challenges and situations with profound comprehension and analysis. Furthermore, PBL fosters the development of CT skills in students by presenting contextual problems that are more accessible and relatable than traditional concepts and theory-based learning methods.

The cognitive processes that unfold within students when grappling with intricate real-world problems (Barrows, 1996), akin to those encountered in the actual realm (Marthaliakirana et al., 2022), come into play. PBL empowers students to perceive the nexus between theory and practice, fostering a more profound comprehension of concept interconnections (Bollen et al., 2016). Implementing the PBL model in the classroom propels students to identify problems, analyze pertinent information, and devise practical solutions. All these aspects are intertwined with CT.

The recent SLR research conducted by Anggraeni et al. (2023) indicates that PBL can enhance CT even when considering other variables. PBL can be combined with mind mapping to improve its effectiveness in promoting CT. Mind mapping assists students in enhancing their CT abilities. It can improve various aspects, including planning, communication, creativity, problem-solving, concentration, structuring and articulating ideas, memory retention, efficient learning, and comprehensively explaining concepts. This research outcome reinforces our analysis regarding PBL, which has proven effective in supporting CT.

In addition to the PBL model, cooperative learning and the POE model support CT skills. In the cooperative learning model, students actively interact and discuss with peers within their groups (Giri and Paily, 2020). The discussion process can trigger CT as students must reflect on various perspectives, exchange information, and formulate robust arguments to support their viewpoints (Mafarja and Zulnaidi, 2022). Each group member assumes a pivotal role in achieving collective objectives. Students must collaborate and ensure their contributions are relevant and beneficial, thus stimulating CT about contributing effectively (Fung et al., 2016). In the POE learning model, students are prompted to make predictions, observe phenomena, and formulate explanations based on observed evidence (Fitriani et al., 2020; Hong et al., 2021). Implementing the POE model enables students to develop CT skills through prediction, observation, and explanation supported by concrete evidence (Kearney et al., 2001; Palmer, 1995). Furthermore, students understand scientific concepts more deeply (Hong et al., 2021; Palmer, 1995). They internalize these concepts more tangibly by directly observing phenomena and formulating explanations. After undergoing the POE process, students contemplate how their predictions influence the observations and descriptions they generate. All of these activities encourage self-evaluation of their thinking and enhance CT.

5. Conclusion

The research on CT has experienced an increasing trend over the past decade. Based on the findings of the SLR, it can be concluded that STEM, Inquiry, PBL, cooperative, and POE instructional models are suitable and consistent for enhancing students' CT skills. These five models possess attributes that stimulate the development of CT within the context of learning. However, selecting the most appropriate instructional model has to consider learning objectives, subject matter, student characteristics, and the learning context. The practical implications of employing STEM, Inquiry, PBL, cooperative, and POE in education, as indicated by the SLR results, include (1) fostering student-centered learning, (2) promoting collaboration and communication, (3) enhancing analytical thinking and causal reasoning, (4) integrating cross-disciplinary concepts, (5) developing metacognitive skills, (6) applying concepts in real-world contexts, and (7) encouraging investigation and observation. With these implications, educators can design learning experiences that align with students' needs and learning objectives. These models can serve as frameworks for cultivating CT skills, which are essential for students in an era characterized by high information flow and complexity. For future research, we recommend conducting a comprehensive meta-analysis to compare the effectiveness of STEM, Inquiry, PBL, cooperative, and POE models in enhancing CT skills. An advanced meta-analytic approach can provide deeper insights into the most effective model for improving CT skills. Such results can guide educators and practitioners in selecting the most appropriate instructional model to achieve desired learning outcomes.

Acknowledgment

We would like to express our profound gratitude to the Indonesian Ministry of Education and LPPM Universitas Sebelas Maret for their generous financial support and the gracious provision of essential research facilities. Their unwavering support has played a pivotal role in enabling the successful execution of our research initiatives and the subsequent publication of our research articles.

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

Alpizar D, Vo T, French BF, and Hand B (2022). Growth of critical thinking skills in middle school immersive science learning environments. Thinking Skills and Creativity, 46: 101192. https://doi.org/10.1016/j.tsc.2022.101192

Anggraeni DM, Prahani B, Suprapto N, Shofiyah N, and Jatmiko B (2023). Systematic review of problem based learning research in fostering critical thinking skills. Thinking Skills and Creativity, 49: 101334. https://doi.org/10.1016/j.tsc.2023.101334

Arici F, Yildirim P, Caliklar Ş, and Yilmaz RM (2019). Research trends in the use of augmented reality in science education: Content and bibliometric mapping analysis. Computers and Education, 142: 103647. https://doi.org/10.1016/j.compedu.2019.103647

Barak M (2017). Science teacher education in the twenty-first century: A pedagogical framework for technology-integrated social constructivism. Research in Science Education, 47: 283-303. https://doi.org/10.1007/s11165-015-9501-y

Barrows HS (1996). Problem-based learning in medicine and beyond: A brief overview. New Directions for Teaching and Learning, 1996: 3-12. https://doi.org/10.1002/tl.37219966804

Boling EC, Hough M, Krinsky H, Saleem H, and Stevens M (2012). Cutting the distance in distance education: Perspectives on what promotes positive, online learning experiences. The Internet and Higher Education, 15(2): 118-126. https://doi.org/10.1016/j.iheduc.2011.11.006

Bollen L, Van Kampen P, Baily C, and De Cock M (2016). Qualitative investigation into students' use of divergence and curl in electromagnetism. Physical Review Physics Education Research, 12(2): 020134. https://doi.org/10.1103/PhysRevPhysEducRes.12.020134

Castro R (2019). Blended learning in higher education: Trends and capabilities. Education and Information Technologies, 24(4): 2523-2546. https://doi.org/10.1007/s10639-019-09886-3

Chen HL and Wu CT (2023). A digital role-playing game for learning: Effects on critical thinking and motivation. Interactive Learning Environments, 31(5): 3018-3030. https://doi.org/10.1080/10494820.2021.1916765

Duran M and Dökme I (2016). The effect of the inquiry-based learning approach on student's critical-thinking skills. Eurasia Journal of Mathematics Science and Technology Education, 12(12): 2887-2908. https://doi.org/10.12973/eurasia.2016.02311a

Dwyer CP, Hogan MJ, Harney OM, and Kavanagh C (2017). Facilitating a student-educator conceptual model of dispositions towards critical thinking through interactive management. Educational Technology Research and Development, 65: 47-73. https://doi.org/10.1007/s11423-016-9460-7

Ennis RH (2018). Critical thinking across the curriculum: A vision. Topoi, 37: 165-184. https://doi.org/10.1007/s11245-016-9401-4

Ernst J and Monroe M (2004). The effects of environment-based education on students' critical thinking skills and disposition toward critical thinking. Environmental Education Research, 10(4): 507-522. https://doi.org/10.1080/1350462042000291038

Fitriani A, Zubaidah S, Susilo H, and Al Muhdhar MHI (2020). PBLPOE: A learning model to enhance students' critical thinking skills and scientific attitudes. International Journal of Instruction, 13(2): 89-106. https://doi.org/10.29333/iji.2020.1327a

Forawi SA (2016). Standard-based science education and critical thinking. Thinking Skills and Creativity, 20: 52-62. https://doi.org/10.1016/j.tsc.2016.02.005

Fung DCL, To H, and Leung K (2016). The influence of collaborative group work on students' development of critical thinking: The teacher's role in facilitating group discussions. Pedagogies: An International Journal, 11(2): 146-166. https://doi.org/10.1080/1554480X.2016.1159965

Giri V and Paily MU (2020). Effect of scientific argumentation on the development of critical thinking. Science and Education, 29(3): 673-690. https://doi.org/10.1007/s11191-020-00120-y

Griffin P, McGaw B, and Care E (2012). Assessment and teaching of 21st century skills. Springer, Dordrecht, Netherlands. https://doi.org/10.1007/978-94-007-2324-5

Gunduz N and Hursen C (2015). Constructivism in teaching and learning; Content analysis evaluation. Procedia-Social and Behavioral Sciences, 191: 526-533. https://doi.org/10.1016/j.sbspro.2015.04.640

Hacioğlu Y and Gülhan F (2021). The effects of STEM education on the students' critical thinking skills and STEM perceptions. Journal of Education in Science Environment and Health, 7(2): 139-155. https://doi.org/10.21891/jeseh.771331

Henriksen D, Henderson M, Creely E, Ceretkova S, Černochová M, Sendova E, and Tienken CH (2018). Creativity and technology in education: An international perspective. Technology, Knowledge and Learning, 23: 409-424. https://doi.org/10.1007/s10758-018-9380-1

Hong JC, Hsiao HS, Chen PH, Lu CC, Tai KH, and Tsai CR (2021). Critical attitude and ability associated with students' self-confidence and attitude toward "predict-observe-explain" online science inquiry learning. Computers and Education, 166: 104172. https://doi.org/10.1016/j.compedu.2021.104172

Kearney M, Treagust DF, Yeo S, and Zadnik MG (2001). Student and teacher perceptions of the use of multimedia supported predict–observe–explain tasks to probe understanding. Research in Science Education, 31: 589-615. https://doi.org/10.1023/A:1013106209449

Kristiyanto W, Gunarhadi, and Indriayu M (2020). The effect of the science technology society and the quantum teaching models on learning outcomes of students in the natural science course in relation with their critical thinking skills. International Online Journal of Education and Teaching, 7(1): 177-191.

Lamb R, Firestone J, Schmitter-Edgecombe M, and Hand B (2019). A computational model of student cognitive processes while solving a critical thinking problem in science. The Journal of Educational Research, 112(2): 243-254. https://doi.org/10.1080/00220671.2018.1514357

Lin WL and Shih YL (2022). Developmental trends of different creative potentials in relation to adolescents' critical thinking abilities. Thinking Skills and Creativity, 43: 100979. https://doi.org/10.1016/j.tsc.2021.100979

Mafarja N and Zulnaidi H (2022). Relationship between critical thinking and academic self-concept: An experimental study of reciprocal teaching strategy. Thinking Skills and Creativity, 45: 101113. https://doi.org/10.1016/j.tsc.2022.101113

Manassero-Mas MA and Vázquez-Alonso Á (2022). An empirical analysis of the relationship between nature of science and critical thinking through science definitions and thinking skills. SN Social Sciences, 2: 270. https://doi.org/10.1007/s43545-022-00546-x

Marin LM and Halpern DF (2011). Pedagogy for developing critical thinking in adolescents: Explicit instruction produces greatest gains. Thinking Skills and Creativity, 6(1): 1-13. https://doi.org/10.1016/j.tsc.2010.08.002

Marthaliakirana AD, Suwono H, Saefi M, and Gofur A (2022). Problem-based learning with metacognitive prompts for enhancing argumentation and critical thinking of secondary school students. Eurasia Journal of Mathematics, Science and Technology Education, 18(9): em2148. https://doi.org/10.29333/ejmste/12304

Mater NR, Haj Hussein MJ, Salha SH, Draidi FR, Shaqour AZ, Qatanani N, and Affouneh S (2022). The effect of the integration of STEM on critical thinking and technology acceptance model. Educational Studies, 48(5): 642-658. https://doi.org/10.1080/03055698.2020.1793736

Niu L, Behar-Horenstein LS, and Garvan CW (2013). Do instructional interventions influence college students' critical thinking skills? A meta-analysis. Educational Research Review, 9: 114-128. https://doi.org/10.1016/j.edurev.2012.12.002

Oliveras B, Márquez C, and Sanmartí N (2013). The use of newspaper articles as a tool to develop critical thinking in science classes. International Journal of Science Education, 35(6): 885-905. https://doi.org/10.1080/09500693.2011.586736

Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, and Moher D (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. International Journal of Surgery, 88: 105906. https://doi.org/10.1016/j.ijsu.2021.105906 **PMid:33789826**

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

Palmer D (1995). The POE in the primary school: An evaluation. Research in Science Education, 25: 323-332. https://doi.org/10.1007/BF02357405

Piawa CY (2010). Building a test to assess creative and critical thinking simultaneously. Procedia-Social and Behavioral Sciences, 2(2): 551-559. https://doi.org/10.1016/j.sbspro.2010.03.062

Ristanto R, Sabrina A, and Komala R (2022). Critical thinking skills of environmental changes: A biological instruction using guided discovery learning-argument mapping (GDL-AM). Participatory Educational Research, 9(1): 173-191. https://doi.org/10.17275/per.22.10.9.1

Rodrigues SJ (2014). Environmental education: A propose of high school. Procedia-Social and Behavioral Sciences, 116: 231-234. https://doi.org/10.1016/j.sbspro.2014.01.199

Rose J (2020). The mortal coil of COVID-19, fake news, and negative epistemic postdigital inculcation. Postdigital Science and Education, 2(3): 812-829. https://doi.org/10.1007/s42438-020-00192-7 **PMCid:PMC7527670**

Siew NM and Mapeala R (2017). The effects of thinking maps-aided problem-based learning on motivation towards science learning among fifth graders. Journal of Baltic Science Education, 16(3): 379-394. https://doi.org/10.33225/jbse/17.16.379

Sinaga P, Setiawan W, and Liana M (2022). The impact of electronic interactive teaching materials (EITMs) in e-learning on junior high school students' critical thinking skills. Thinking Skills and Creativity, 46: 101066. https://doi.org/10.1016/j.tsc.2022.101066

Sujatmika S, Irfan M, Ernawati T, Wijayanti A, Widodo S, Nurdiyanto H, and Rahim R (2019). Designing e-worksheet based on problem-based learning to improve critical thinking. In the 1st International Conference on Science and Technology for an Internet of Things, Yogyakarta, Indonesia. https://doi.org/10.4108/eai.19-10-2018.2281282

Sujatmika S, Widyawati A, Ernawati T, and Hastuti PW (2022). Gambier's product (Uncaria gambir Roxb.) as learning material to enhance critical thinking. AIP Conference Proceedings, 2600(1): 050003. https://doi.org/10.1063/5.0112224

Sukendro S, Habibi A, Khaeruddin K, Indrayana B, Syahruddin S, Makadada FA, and Hakim H (2020). Using an extended technology acceptance model to understand students' use of e-learning during COVID-19: Indonesian sport science education context. Heliyon, 6: e05410. https://doi.org/10.1016/j.heliyon.2020.e05410 **PMid:33195843 PMCid:PMC7644906**

Tarafdar M, Pullins EB, and Ragu-Nathan TS (2015). Technostress: Negative effect on performance and possible mitigations. Information Systems Journal, 25(2): 103-132. https://doi.org/10.1111/isj.12042

Thompson CC (2019). Advancing critical thinking through learning issues in problem-based learning. Medical Science Educator, 29: 149-156. https://doi.org/10.1007/s40670-018-00649-2 **PMid:34457462 PMCid:PMC8368909**

Trilling B and Fadel C (2009). 21st century skills: Learning for life in our times. John Wiley and Sons, Hoboken, USA.

Van Laar E, Van Deursen AJ, Van Dijk JA, and De Haan J (2017). The relation between 21st-century skills and digital skills: A systematic literature review. Computers in Human Behavior, 72: 577-588. https://doi.org/10.1016/j.chb.2017.03.010

Wang HH, Chen HT, Lin HS, Huang YN, and Hong ZR (2017). Longitudinal study of a cooperation-driven, socio-scientific issue intervention on promoting students' critical thinking and self-regulation in learning science. International Journal of Science Education, 39(15): 2002-2026. https://doi.org/10.1080/09500693.2017.1357087

Yuan SP, Liao HC, Wang YH, and Chou MJ (2014). Development of a scale to measure the critical thinking disposition of medical care professionals. Social Behavior and Personality: An International Journal, 42(2): 303-311. https://doi.org/10.2224/sbp.2014.42.2.303

Zhang K and Aslan AB (2021). AI technologies for education: Recent research and future directions. Computers and Education: Artificial Intelligence, 2: 100025. https://doi.org/10.1016/j.caeai.2021.100025