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Global Trends in Computational Thinking Research in Physics Learning: A Systematic Literature Review

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Abstract

This research examines the global trends regarding applying computational thinking (CT) in physics learning through a Systematic Literature Review (SLR) approach. By analyzing 30 selected articles published in 2019-2024, this study aims to provide insight into the types of research, subjects, instruments, physics materials, and supporting media used. The results showed that most studies focused on developing CT-based learning products, such as interactive modules and simulations, which were predominantly applied to high school students with materials such as electricity, temperature, and heat. Frequently used media include Scratch, Arduino, and Visual Python, which are proven to improve students' critical thinking, collaboration, and algorithmic skills. However, CT implementation is faced with challenges such as limited technology facilities, teacher training needs, and the complexity of curriculum integration. This research recommends the exploration of problem-, project-, and game-based learning approaches to support the development of CT at different levels of education. The results are expected to be the basis for developing more innovative and effective learning strategies to face the challenges of the 21st century.

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INTRODUCTION

The development of science and technology in the 21st century is progressing so rapidly that it encourages innovation in Science, Technology, Engineering, and Mathematics (STEM) (Maharani et al., 2020; Yin, 2020). This condition requires students not only to master basic scientific concepts but also to have 21st-century skills to deal with the complexity of the modern world (Akmam et al., 2023; Wu & Su, 2021). Socio-scientific STEM positively impacts students' 21st-century skills, including digital literacy, creative thinking, and effective communication (Benek & Akçay, 2022). In addition, effective STEM education can strengthen 21st-century skills through relevant and contextual learning experiences (Çevik et al., 2024).

In physics learning, learners are expected to understand basic theories and concepts and apply 21st-century skills. Physics, as a fundamental branch of science, requires a deep understanding of the principles of nature and their application in everyday life. Research shows that students with critical and creative thinking skills can solve complex problems and better apply their knowledge in real-life situations (Akmam et al., 2019; Weller, 2022). Integrating 21st-century skills into physics learning is necessary for teachers to prepare students for future challenges.

One of the main skills relevant to physics learning in the digital age is Computational Thinking (CT). CT is defined as a thinking process that involves systematic problem analysis, problem-solving, and solution implementation, often using concepts from computer science (Gong et al., 2020; Maharani et al., 2023). Through CT, students can hone their problem-solving skills involving decomposition by breaking down large problems into smaller parts, pattern recognition, abstraction, and algorithms to create efficient solutions. This concept was first introduced by J. M. Wing in 2006, who emphasized the importance of computational thinking as a basic skill that every individual should have, not only in the context of computer science but also in various other disciplines (Latifah et al., 2022). Computational thinking includes understanding and using algorithms, models, and simulations relevant to learning physics (Seiter & Foreman, 2013; Yin, 2020).

The link between 21st-century skills and computational thinking is increasingly evident in education, especially the development of critical thinking, problem-solving, and creative thinking skills. The integration of computational thinking in STEM education has been proven to significantly improve academic achievement and computational thinking skills in students who use computer-based STEM applications (Berk & Gülcü, 2024). Using coding in physics experiments has proven effective in deepening students' conceptual understanding (Anderson et al., 2022). This approach reduces cognitive load so that students can focus more on the underlying physics concepts, making coding a tool for problem-solving and a means of conceptual learning.

The application of computational thinking in physics learning can be done in various ways, including using digital tools, simulations, and research-based projects (Khasyyatillah & Osman, 2019). Studies show that this approach improves students' understanding of physics concepts and critical and creative thinking skills (Amenyo et al., 2023; Fayanto, 2024; Yin, 2020). For example, visual programming in physics learning has improved students' problem-solving skills and strengthened their understanding of physics principles (Pérez, 2018). Thus, integrating computational thinking (CT) in physics learning is an important step in preparing students to face the challenges of the 21st century. CT allows learners to understand scientific concepts and develop the high-level thinking skills needed in the world of work.

Research on computational thinking in learning has shown significant potential for improving the quality of education and teaching. CT, which involves the ability to solve complex problems using computer science techniques and concepts, is recognized as one of the essential competencies in 21st-century education (Marifah, 2022). Research by Rahman (2022) shows that applying CT in the EDP-STEM model can improve students' critical thinking skills. Thus, the application of CT in learning improves conceptual understanding and facilitates students in developing skills relevant to the challenges of the modern era.

Although various studies have highlighted the potential of Computational Thinking in improving the quality of education and learning, studies that comprehensively analyze the application of CT in physics learning are still limited. Some important aspects have not been thoroughly explored, such as the type of research conducted, the research subjects, the instruments used, the physics material studied, and the supporting media in applying CT-based learning. In addition, although the application of CT in physics learning offers various benefits, many challenges need attention, such as limited infrastructure, the readiness of teachers to adopt CT-based learning methods, and obstacles in integrating Computational Thinking into the physics curriculum (Khasyyatillah & Osman, 2019).

This study aims to provide an overview of global developments in research on computational thinking in physics learning. This study analyzes various aspects, including the type of research used, research subjects, research subjects, instruments used, physics materials studied, and supporting media in CT-integrated physics learning. In addition, this study identifies opportunities and challenges in implementing CT-based learning. It is hoped that this study will have significant implications for future research, gaps that still need to be explored, and curriculum development that accommodates CT with the integration of technology in physics learning.

METHODS

The research method used is a Systematic Literature Review (SLR). Systematic Literature Review is a systematic research method for collecting, critically evaluating, integrating, and presenting findings from various studies related to a particular topic or research question. This approach provides a comprehensive overview by adopting a consistent and widely accepted methodology (Sari et al., 2023). SLR research is a planned and systematic process to answer specific research questions, with explicit steps in identifying, selecting, evaluating, and critically synthesizing research results, resulting in reliable and bias-free findings (Rother, 2007). The research phase consists of three stages: identification, screening, and analysis. These stages can be illustrated in Figure 1.

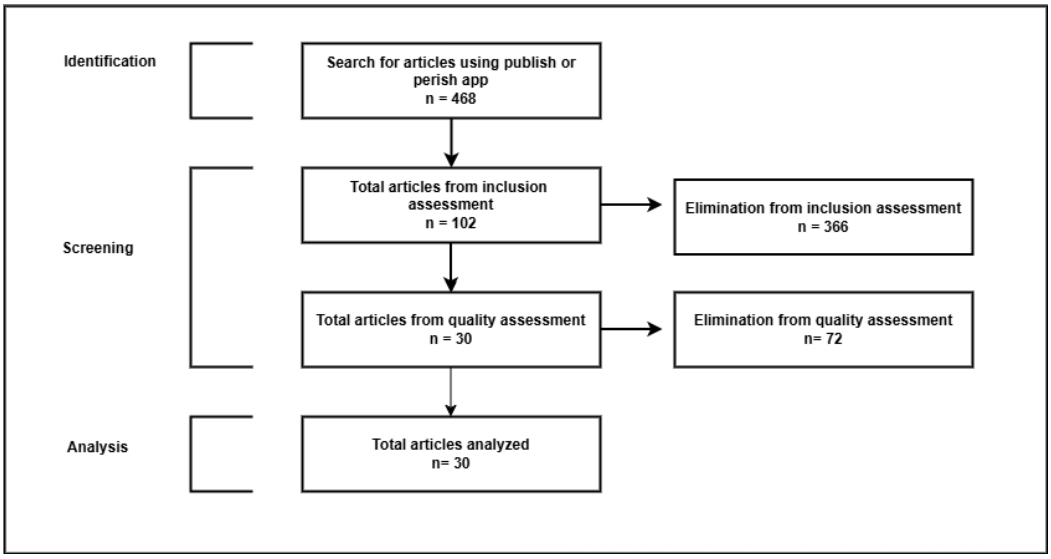

Figure 1 Stages of research

In the identification stage, the literature search used digital tools such as Publish or Perish (PoP), Google Scholar, and Scopus search focus. This selection aims to increase data coverage and validity. Scopus was chosen because it provides indexed and verified journals, while Google Scholar provides additional journals, including open access and from non-Scopus publishers. This research only includes journal articles, without proceedings or technical reports, to maintain the quality and relevance of the sources. The search process was carried out by entering the keyword “computational thinking," a key term in this research topic. The search results successfully identified as many as 468 articles, with details of Google Scholar results as many as 268 and Scopus as many as 200 articles relevant to these keywords.

The next stage is screening; the screening process is carried out to ensure that the articles identified in the previous stage are relevant and qualified in accordance with the research objectives. Screening is done by applying predetermined inclusion and exclusion criteria. The inclusion criteria focused on physics research published in the last 5 years, namely in

2019-2024. Table 1, is a guideline for determining which articles are eligible for inclusion in the study.

Table 1 List of criteria for selecting relevant research articles

Inclusion Criteria	**Exclusion Criteria**
Computational thinking articles in physics education	Articles discussing computational thinking in other fields
Articles published from 2019-2024 (last 5 years)	Publication before 2019
Full article and open access	Incomplete and closed-access articles
Publications not in the form of seminars or conferences	Articles in the form of seminars or conferences

After the screening stage, 102 articles were obtained, which were carried out in the next stage. The next stage is screening by looking at the quality of national and international indexed quality, namely 30 articles consisting of SINTA 1 indexed articles as many as 1 article, SINTA 2 as many as 5 articles, SINTA 3 as many as 5 articles, SINTA 4 as many as 2 articles, Scopus Q1 indexed as many as 12 articles, Q2 as many as 3 articles, and Q4 as many as 2. Data analysis using the concept of data analysis from several sources (Ashraf et al., 2021; Li et al., 2020; Marín et al., 2018) was modified to suit the specific objectives of the research by synthesizing and replicating.

RESULTS AND DISCUSSION

Computational thinking is a problem-solving approach involving computational thinking to analyze, design, and evaluate algorithm-based solutions. Its implementation in physics education has been limited to the university level, especially in developing students' computational thinking skills in computational physics and programming. At the high school level, CT is more often applied as student worksheet trials or CT-based learning media, with students as the research subjects. This shows that the application of CT at the school level is still in the development stage, unlike in higher education, which focuses more on strengthening programming skills and logical thinking.

Based on a review conducted (Herwinarso, 2023), the computational thinking approach is the ability to think to solve problems effectively by following processes such as those that occur in computers. The main components of CT include abstraction, decomposition, algorithmic thinking, and pattern generalization. In addition, CT goes hand in hand with other important skills such as creativity, problem-solving, and critical thinking. Thinking like a computer is not just about how to operate programming on a computer. However, it involves thinking at various levels of abstraction that are needed in every aspect of life (Muliyati, 2022).

The application of computational thinking in the learning process trains students to think structurally, logically, and critically in problem-solving. The implementation of CT conveys (Dewi et al., 2021) that students are first introduced to the problem, then create an algorithm to simulate the function of a formula, and conclude the results.

Integrating computational thinking in physics learning is done in several mutually supportive ways. Physics provides a structured, mathematics-based context for applying CT, such as using numerical modeling, algorithmic problem-solving, and simulation. Conversely, CT assists physics learning by simplifying the analysis process and enabling broader exploration of physics phenomena. In line with research conducted (Gambrell, 2024) through programs such as Projects and Practices in Physics (P3), students work in small groups to solve physics problems computationally, which allows them to understand complex physics concepts through simulation and exploration of parameters that are difficult to achieve analytically. In addition, an introductory physics course integrating CT provides students with skills such as code reading and writing, data visualization, and numerical analysis using tools such as Python or spreadsheets. Physics, as a discipline that studies natural phenomena, has characteristics that demand the ability of deep analysis, abstraction, and complex problem-solving. With the CT approach, students can be trained to understand physics concepts in a more structured manner through data representation, simulation, and mathematical modeling.

Implementing physics learning to foster CT skills certainly requires active learning approaches, such as collaboration, structured discussions, and practical exercises, which are recommended to help students solve problems effectively. Emphasis is also placed on the importance of intensive practice for pattern recognition and algorithm application. In addition, learning that focuses on decomposition and pattern recognition can improve the understanding of physics concepts and assist students in developing systematic solutions (Amrizaldi et al., 2024).

Figure 2 shows the distribution of articles by year of publication, showing the number of publications from 2017 to 2023 that discuss computational thinking in physics learning.

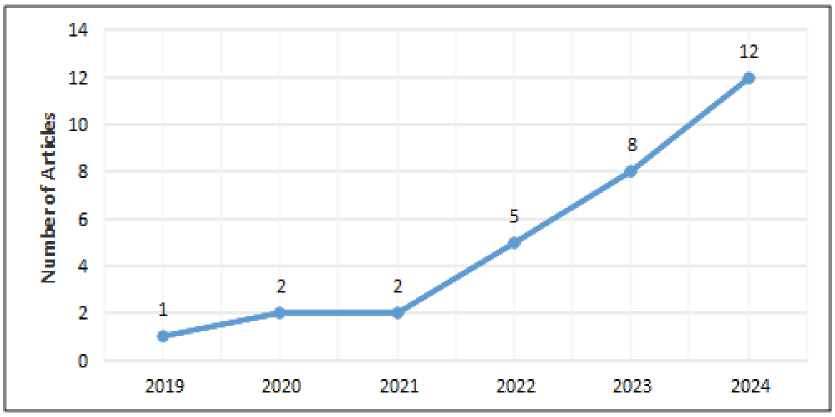

Figure 2 Distribution of articles from 2019-2024

Publication of computational thinking articles in physics learning has increased significantly yearly. Based on the analyzed data, the number of published articles increased from 1 article in 2019 to 12 articles in 2024. In 2019–2021, the number of articles published was still relatively low, ranging from 1 to 2 articles per year. However, starting in 2022, there was a significant increase with 5 articles published, followed by 8 articles in 2023, and reaching a peak with 12 articles in 2024.

Most research focuses on developing modern technology-based learning, such as programming, simulation, and CT-based media in physics education. This trend shows a growing interest in computational thinking in physics learning and its relevance in supporting technology-based learning innovation. One of the innovations that is developing is the development of e-modules for junior high school students on simple business and aircraft materials based on CT indicators called the computational thinking corner. This can help students take an active role in the learning process by working on projects with the help of e-modules. In addition, this approach trains students to learn independently with the support of technology, which is in line with the learning needs of the 21st century (Ulfa et al., 2023).

An analysis of the type of research used in the articles studied is presented in Figure 3.

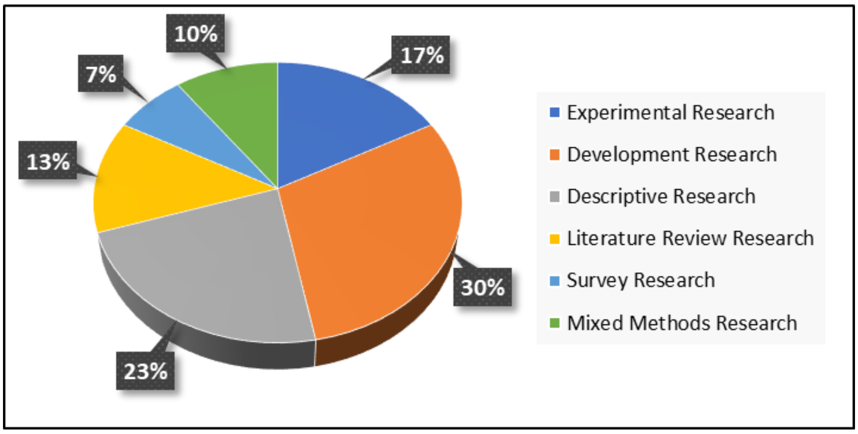

Figure 3 Analysis of research types in articles

Based on Figure 3, it can be seen that the most widely used development research dominates the proportion of the various types of research used. Nine articles use this type of research. This dominance is due to the increasing need for computational thinking-based teaching materials and assessments to support modern learning. Development research is used with a structured process that includes several stages: design, development, validation, and evaluation before implementation. According to Sugiyono (2010), development research aims to produce and test the effectiveness of a product that can be widely applied. CT-based teaching materials are created as an integrated Google collaboration e-module that students can access easily and for free (Ulfa et al., 2023).

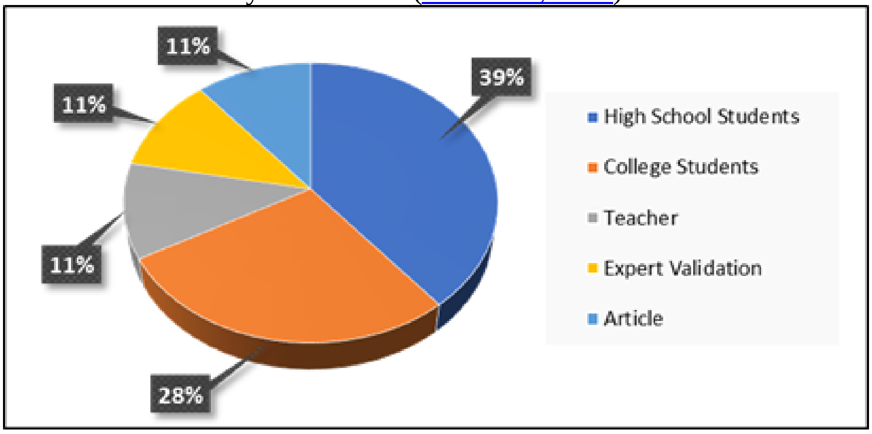

Figure 4 Analysis of research subjects in articles

The analysis results show that 30 articles based on five groups, namely 39% or around 12, focus on high school students who show primary attention to learning at this level for implementation in the scope of intervention or product trials. The variation in the number of samples depends on the type of research used. The research was conducted in two classes, namely the experimental and control classes, and the sample used ranged from 50 to 60 students (Bufasi, 2022). The main focus of research on high school students shows that CT integration is relevant to levels with algorithmic and logical-based cognitive abilities. At other levels, such as elementary school, the application of CT in learning is more effective if the learning approach used is simpler and exploration-based, such as introducing physical and visual activities. Meanwhile, at the college level, it can be integrated with advanced courses in computational physics and programming.

There are 8 articles discussing students as research subjects, especially those teaching computational physics and programming courses, aiming to train students to be more creative and think logically (Fayanto, 2024; Muliyati, 2022). Subject teachers and experts act as media validators for products developed, such as (Rahmawati et al., 2024) research assessing the validity and practicality of the module using a Likert scale questionnaire. Then, teachers also served as research participants attending professional development workshops. (Tofel-Grehl, 2022; Yin, 2022). Finally, this study's research subject is articles because the type of research used is a literature study that focuses on analyzing existing literature. The instruments used in the articles studied can be seen in Figure 5.

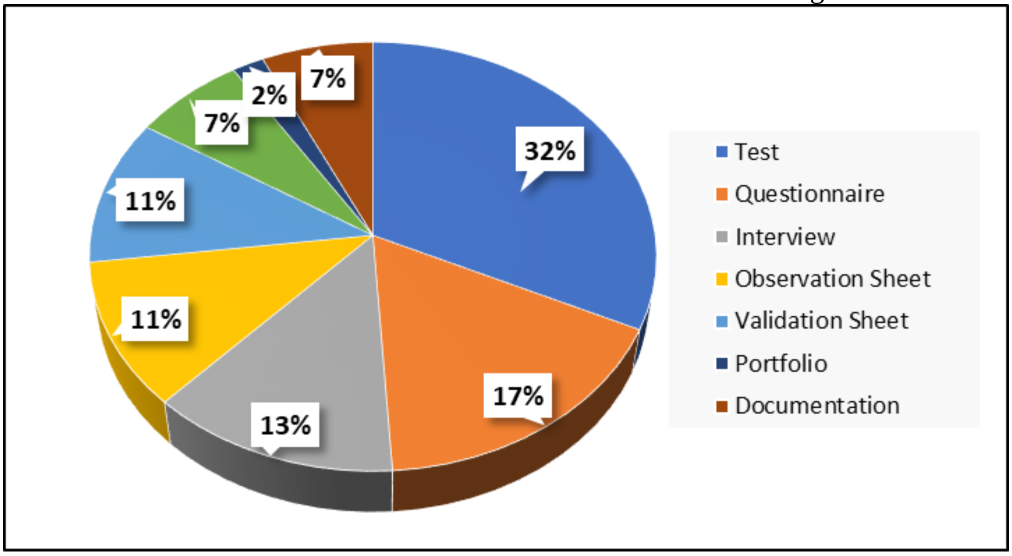

Figure 5 Analysis of research instruments in articles

Figure 5 shows the instruments widely used by researchers. Various instruments obtain accurate and robust data according to each research objective. The test is the most widely used, accounting for 32% of the total, with regular multiple-choice and graded formats. Tests are used to assess students' ability to solve problems using computational thinking skills. Then there is a multilevel test aimed at further diagnosing students' abilities, meaning to obtain a more comprehensive understanding of the problem-solving strategies applied by students, the extent to which they understand concepts conceptually or rely on memory, and how the level of confidence contributes to the decision-making process in computational thinking-based problem-solving. The multi-stage test model used is a two-stage test model (answer - reason), three-stage (answer - reason - confidence level), four-stage (answer - confidence level answer - reason - confidence level reason), up to five-stage (answer - confidence level answer - reason - confidence level reason - the relationship between answer and reason) (Zakwandi, 2024).

The instrument used is a questionnaire consisting of several questions in the form of a Likert scale. As mentioned (Martins & Baptista, 2024), one of the functions of the questionnaire as a measurement tool for CT and programming skills is a validated questionnaire, "Computational Thinking Test," before and after the intervention with the help of Google Form. In addition, the questionnaire was also used to measure the confidence level in CT (Syafril, 2022). Interviews, observation sheets, and performance assessment sheets are combined to provide qualitative data that enrich the context of the research results and validate the results through data triangulation so that the results obtained are more reliable and consistent (Gambrell, 2024; Kumala et al., 2024; Rahmawati et al., 2024). Finally, documentation and portfolio instruments are used as analytical materials in the research to provide additional supporting data for the findings, such as recordings, videos, notes, and portfolios, which are used to collect and evaluate a collection of individual work that shows the development of certain abilities or skills over time.

The physics materials used in the articles studied can be seen in Figure 6. Figure 6 shows that 11 articles do not mention physics material because researchers use survey research and literature review. A total of 20 articles mention specific physics materials, such as electrical material, because it requires skills and software to understand the material. In addition, according to Yin (2020), electrical materials are closely related to computational thinking, especially in problem-solving approaches, modeling, and technology applications. In this context, CT plays a major role by providing a systematic way of thinking to solve complex problems through decomposition, compiling algorithms, and making abstractions, such as using circuit diagrams to understand interactions between electrical components. In addition, it is revealed by Hadad (2020) that learning electrical materials with computational thinking starts from completing simple electrical tasks that do not use computers and then proceeds to more complex and open-ended projects. In this process, students use tools such as Makey Makey and Arduino, which combine physics learning through hardware with computational learning through software. This approach is designed to help students understand how CT can be applied to solve real problems while honing critical thinking, creativity, and collaboration skills. Thus, students learn technical concepts and important skills relevant to real-world challenges. The material of temperature and heat, students still have difficulty mastering concepts and solving problems, as well as a lack of skill in operating mathematical equations and difficulty analyzing physical quantities, so it is important to apply CT skills in physics learning (Amrizaldi et al., 2024). The understanding of static fluid material is still relatively low, especially in the material part of Pascal's law, so it is necessary to apply Conceptual change model learning with a computational thinking approach (Anfusiyah et al., 2024).

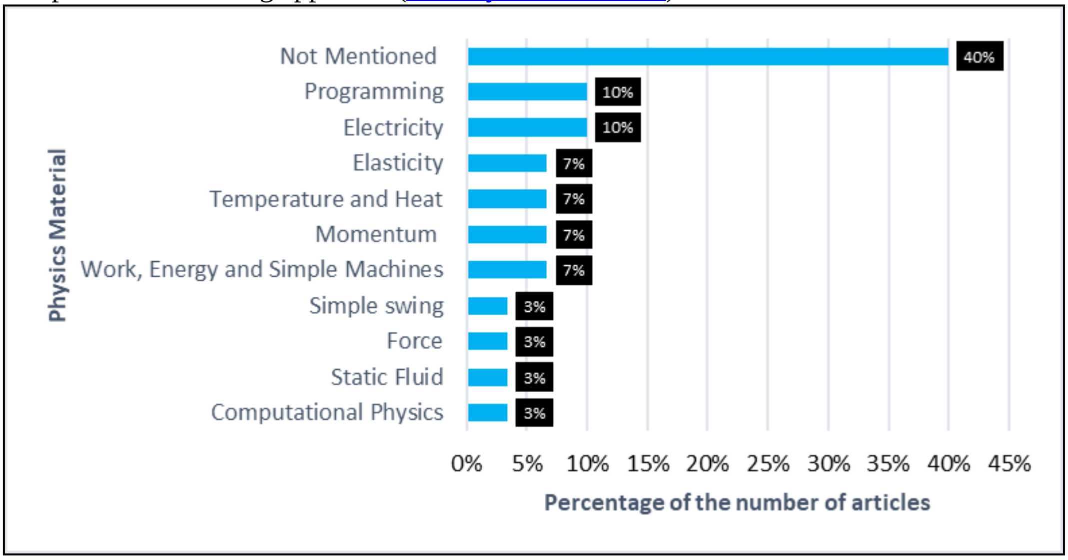

Figure 6 Analysis of physics materials in articles

Figure 7 shows how, in the application of physics learning, CT can be integrated through various media that support the thinking process in accordance with the article studied.

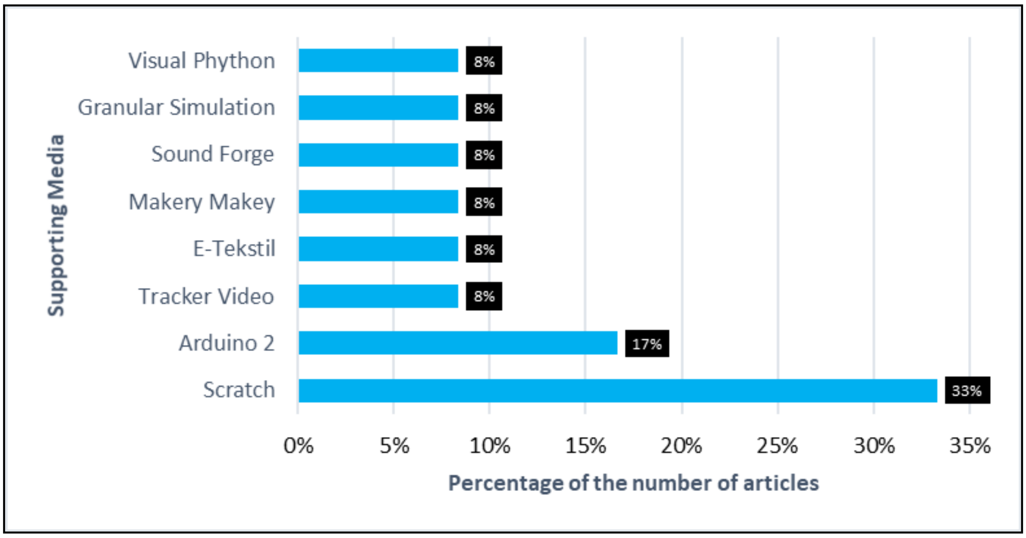

Figure 7 Analysis of CT supporting media

Figure 7 shows the media that support computational thinking in physics learning. Eight media were obtained, with the dominance of Scratch, which shows a higher frequency of use than other media. Scratch media is used in research (Martins & Baptista, 2024; Saputra et al., 2023; Wulandari et al., 2024; Yeni, 2024). Scratch is a puzzle-like programming blog with an interactive and attractive appearance suitable for abstract physics material and more concrete concepts. Science content in Scratch-based science education games is easier to understand with the science, technology, engineering, and math (STEM) approach (Wulandari et al., 2024). Some studies, such as (Saputra et al., 2023), showed that Scratch improved students' Computational Thinking skills. This is due to the media design that supports the development of creativity in designing animations and simulations, the ability to think systematically, collaboration, and the application of algorithms. Thus, Scratch allows students to apply logical thinking patterns to transform simple concepts into more complex ones in physics learning.

In physics materials, learn basic circuits, such as series and parallel circuits, then proceed to use E-textiles, Makey, and finally Arduino (Yin, 2022), and these three media are often used together. This unit aims to train students in computational thinking-based problem-solving skills. Students will learn from completing simple tasks that do not involve computers to creating more complex and creative projects using Makey and Arduino. These projects combine an understanding of physics (in hardware) with computational learning (in software), showing students the huge potential of CT in real life.

Visual Python (vPython) is a Python module that allows users to easily create interactive 3D simulations. This module is often used in education and research to visualize various physics, mathematics, and other science concepts. One of the main advantages of vPython is its ability to create simple 3D visualizations with few lines of code. Through vPython, students can create 3D environments using tools such as Visual Python (vPython) to apply physics principles through mathematical expressions and parameterizing variables. By utilizing the ability to change the values of variables, students can visualize how the behavior of a system changes under various specific circumstances (Bufasi, 2022).

Video tracker media (Handayani et al., 2023) can be used to analyze concepts in physics, such as velocity, position, and energy by uploading experimental videos. In addition, this software allows mathematical modeling to compare experimental results with theoretical predictions. Tracker Video is often used in classrooms to provide a more interactive learning experience, allowing students to see first-hand how physics principles are applied in real-world situations. The supporting media is also Sound Forge, software designed to record, edit, restore, and process high-quality audio files that can be used for sound spectrum, frequency, intensity, and decibel experiments (Handayani et al., 2023). Finally, granular simulation is used to observe microscopic scales in physics materials such as pressure and waves, which are often used in computational physics courses because granular programming encourages the development of structured thinking skills, problem-solving, and systematic processing of information (Muliyati, 2022).

Computational thinking is one of the important skills in STEM learning, both as a learning objective and a tool to facilitate mastery of STEM concepts. In physics learning, the application of CT is able to improve the quality of learning, as evidenced by (Bufasi, 2022). The results of computational thinking interventions carried out for 6 weeks found that classes that applied CT showed increased material understanding compared to classes that only used traditional approaches. Another finding is that CT helps understand problems by involving deep understanding and logical reasoning and improving visualization skills. Research (Tofel-Grehl, 2022) also states that using e by integrating physics with computing provides convenience in conducting scientific investigations in physics.

The challenge of applying computational thinking in physics learning presented by Muliyati (2022) is that teachers must design CT-based learning activities and know how to teach, assess, and use technology-based media to support CT skills in learning. The role of the teacher is not only to deliver material by lecturing and using text methods but also to provide active roles to students, such as simulations, projects, and programming, by emphasizing full involvement in exploration, experimentation, and problem-solving (Yin, 2022). The characteristics of physics material, which is dominated by symbols, are also a challenge for students to understand the coding simultaneously, so most students rely on comments in the code to understand or explain the steps taken (Tofel-Grehl, 2022). Implementing Computational Thinking in schools also requires support from facilities in the form of adequate media to meet the needs of diverse students and media that are feasible to be applied effectively in the learning process (Yeni, 2024). For physics learning to apply computational thinking, teachers must design activities that integrate physics concepts with computational thinking processes. This can be done using technology-based tools like computer simulations, simple programming, or digital data analysis. For example, students can be asked to create a parabolic motion simulation using software such as Python or GeoGebra. In addition, learning should be student-centered, allowing them to explore and solve problems independently. Teachers also need to ensure the availability of adequate technological resources and provide appropriate guidance for students to connect physics concepts with CT applications effectively. This approach helps students understand physics and trains them to think logically and systematically.

CONCLUSION

Based on data analysis and discussion, applying computational thinking to physics learning is crucial in developing technology-based pedagogical innovation. The results of this study show that the integration of CT in physics learning has undergone significant development, especially through the use of various learning media such as Scratch, Arduino, and Visual Python, which are widely applied to electricity, temperature, and heat. Research trends in this field indicate that a CT-based approach can enrich teaching methods by enabling more interactive and systematic exploration of concepts. However, the implementation of CT still faces challenges, including limitations in technological infrastructure, the need for training for educators, and difficulties in integrating CT into the curriculum. Then, insights into various aspects of CT in physics help develop more innovative learning strategies and open up opportunities for educators and researchers to continue optimizing technology-based teaching methods. With the right approach, the integration of CT in physics learning can be the key to creating a more interesting and relevant learning experience that is in line with the educational challenges of the digital era. The limitation of this study lies in the lack of in-depth exploration of the variables measured in the implementation of Computational Thinking (CT) in physics learning in the form of its impact on important variables such as concept understanding, critical thinking skills, and problem-solving using more diverse scientific journal database sources such as Web of Science, IEEE Xplore, DOAJ, and others.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS STATEMENT

ID designed the research background and developed and implemented the methodology with guidance from SK and P. The data review and analysis process was conducted collaboratively. All authors contributed to the research planning, drafting, revising, and refining the final results.

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