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Designing a Biology-Computational Thinking Framework Using Project-Based Learning Approach: The Fuzzy Delphi Method Study

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ABSTRACT

The integration of Biology with Computational Thinking (CT) skills holds significant potential to enhance educational practices. This study addresses the lack of frameworks that effectively combine these domains at the matriculation level by developing a comprehensive Biology-Computational Thinking framework grounded in Project-Based Learning (PjBL). The Fuzzy Delphi Method (FDM) was employed to systematically collect and analyse expert opinions to reach a consensus. Eleven Computer Science or Biology Education experts actively engaged in CT were selected through purposive sampling. Findings showed strong acceptance of the framework's elements within the PjBL context, supported by a threshold value 'd' not exceeding 0.2, expert consensus above 75%, and fuzzy scores over 0.5. The expert panel agreed on the arrangement of elements for the Biology-Computational Thinking framework (BioCT-PjBL framework). This consensus affirms the framework's effectiveness, comprehensiveness, and potential to enhance educators' instructional practices. The study contributes to bridging the gap in CT education within biological sciences by providing a structured and validated model for integrating CT skills into biology curricula. This is especially relevant as most existing frameworks focus on computer science and overlook interdisciplinary applications. The framework addresses current educational needs and supports future curriculum development by offering a clear, expert-validated guide. However, the study highlights the need for further validation in real educational settings. Future research should include longitudinal studies to assess long-term impact, pilot testing in diverse contexts to examine adaptability, and developing supplementary materials and educator training to support effective implementation and improve students' understanding of computational thinking.

Keywords: Biology education, computational thinking, Fuzzy Delphi method, project-based learning

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INTRODUCTION

In the ever-changing arena of global Science, Technology, Engineering and Mathematics (STEM) education, Computational Thinking (CT) has gained prominence, extending its influence from computer science to a range of academic disciplines, notably Biology (Jaafar & Ishak, 2023; Peel et al., 2023; Peters-Burton et al., 2022). This transdisciplinary expansion is in line with the Malaysian Education Blueprint 2013-2025, which advocates for the fusion of various subjects and teaching methodologies to elevate the quality of education. While the importance of CT in diverse fields like biology is increasingly recognised, there remains a substantial challenge in equipping educators to effectively impart these skills (Chookhampaeng et al., 2023; Kong et al., 2023; Luo et al., 2023). The present study endeavours to develop a specialised Biology-Computational Thinking framework to address this gap. This framework employs a Project-Based Learning (PjBL) approach, a pedagogical strategy known for its effectiveness in fostering real-world problem-solving skills.

In shaping this framework, the Fuzzy Delphi Method (FDM) serves as an instrumental tool. This method is beneficial for gathering insights from a panel of experts in the fields of biology, CT, and education (A. Chang & Ariffin, 2023; Naser et al., 2023). Through a structured consensus-building process, the FDM aids in making informed decisions, thereby enriching the educational strategies employed. The culmination of this rigorous approach is the Biology–Computational Thinking Project-Based Learning (BioCT-PjBL) framework. Designed to integrate CT into biology education seamlessly, this framework aims to create a dynamic learning environment that benefits educators and students.

Three specific research objectives steer the study. First, it aims to reach a consensus among experts regarding the core constructs and elements to be included in the BioCT-PjBL framework. Second, it seeks to establish a ‘d’ threshold value that indicates a level of expert agreement for the inclusion of these elements. Lastly, it aims to identify which elements are considered suitable for integration into the BioCT-PjBL framework. Together, these objectives contribute to the ongoing efforts to advance education in a manner consistent with national and international educational goals.

Computational Thinking (CT)

CT is a critical cognitive skill set in the 21st century that transcends academic and professional boundaries (Yadav et al., 2022). Pioneered by early visionaries like Seymour Papert and Jeannette Wing, CT was conceptualised as a mental framework. Specifically, it equips individuals with the ability to tackle complex challenges using precision and logic akin to computer scientists. In today’s rapidly evolving landscape, CT has become indispensable. This is particularly true in diverse subject areas such as biology. Within this context, CT serves as a powerful tool that enables educators and learners to dissect intricate biological processes, identify patterns in genetic data, and develop algorithms for data analysis, thereby facilitating a deeper understanding of this crucial field (Ersozlu et al., 2023; Schmidthaler et al., 2023).

The skill set of CT is comprehensive and encompasses key competencies like decomposition, pattern recognition, algorithmic thinking, and abstraction. Additionally, it includes skills such as algorithmic design, debugging, and computational creativity. In terms of activities, CT can be broadly categorised into 'unplugged' activities (Aytekin & Topçu, 2023; Chen et al., 2023), which do not require digital devices and 'plugged-in' activities (Aytekin & Topçu, 2023) that leverage technology and software for reinforcement. Lastly, assessment in this domain is multifaceted.

It involves a range of tools such as survey instruments (Espinal et al., 2021; Sondakh et al., 2020), pre-and post-tests (Jocius et al., 2022; Weng et al., 2022), portfolios (Fields et al., 2021; Lui et al., 2020), interviews (Luo et al., 2020), rubrics (Alegre et al., 2020), artefacts (Gotwals et al., 2020; Metcalf et al., 2021) projects (Fagerlund et al., 2021), classroom observations (Shahin et al., 2022) and reflective activity reports (Chevalier et al., 2022). In essence, CT stands as a multifaceted and indispensable skill set, deeply integrated into modern educational and professional landscapes, and its comprehensive assessment methods and diverse applications, particularly in biology, underscore its pivotal role in shaping future problem-solvers and innovators.

Project-Based Learning in Biology Perspectives.

Project-Based Learning (PjBL) in Biology is an effective instructional methodology that fosters deep, contextual learning and the development of essential skills for college and career readiness. Nijat (2022) highlights that PjBL engages students in applying knowledge and skills through hands-on experiences in biology classes, promoting deeper learning and practical application. Susanti et al. (2020) further support this by demonstrating the high validity of PjBL modules, with an average validation score of 97.34% from material experts, media, and language validators. The modules are praised for their quality, language, and the structured stages of the PjBL process, making the learning experience more accessible and manageable for students. Moreover, Fadzil and Mahmud (2020) emphasise that PjBL modules have significant implications for integrating project-based learning systematically at the matriculation level, particularly in teaching complex biology topics such as Cellular Respiration. This systematic integration helps students grasp intricate concepts through practical projects, enhancing their understanding and retention. Burks (2022) also introduces the BioArt model, which combines project-based learning and experiential learning to make biology more approachable and relevant. This model has been shown to reduce intimidation, improve academic success, and foster a positive learning environment in biology education. Together, these studies underscore the effectiveness of

PjBL in transforming biology education by making it more interactive, engaging, and impactful. Overall, Project-Based Learning (PjBL) in Biology represents a transformative instructional approach that effectively engages students and deepens their understanding of complex biological concepts. By emphasising hands-on, experiential learning, PjBL makes the educational process more accessible and comprehensive, helping students better grasp and retain intricate topics. The systematic integration of PjBL at various educational levels highlights its potential to improve academic outcomes and foster a positive learning environment. Overall, PjBL in Biology aligns with modern educational goals, preparing students with the necessary skills and knowledge for future academic and career success.

Project-Based Learning as the Pedagogical Approach Used in the Bio-CT Framework

From an educational standpoint, PjBL emerges as a highly effective pedagogical strategy for the instruction of CT (C. Y. Chang et al., 2023; Wang et al., 2023). This method provides educators with a well-structured yet adaptable framework that facilitates the incorporation of real-world challenges, thus enhancing the depth and breadth of their teaching methodologies. Furthermore, PjBL contributes to the continuous professional development of educators by offering opportunities for iterative refinement of teaching techniques based on student performance and project assessments (Markula & Aksela, 2022; Tsybulsky & Muchnik-Rozanov, 2023).

Additionally, PjBL aligns well with contemporary educational frameworks, such as the Malaysia Education Blueprint 2013–2025, by promoting a more learner-centric classroom environment. On the student side, the advantages are equally noteworthy. PjBL creates collaborative learning, disciplinary subject learning, iterative learning, and authentic learning settings where CT skills can be meaningfully applied and evaluated (Almulla, 2020; Markula & Aksela, 2022). It bolsters critical thinking, problem-solving capabilities, and cross-disciplinary learning, which are key elements of CT (Samri et al., 2021). Ultimately, PjBL stands as an ideal methodology for effective CT education, enriching both the pedagogical approaches of educators and students' learning experiences in a mutually beneficial manner.

Biology – Computational Thinking Project-Based Learning (BioCT-PjBL) Framework

Wing (2006) argues that CT is essential for everyone, not just computer scientists, and should be taught in schools as a basic skill alongside reading, writing, and arithmetic. From 2006 through 2019, despite Wing's seminal articles popularising the idea of integrating CT across the curriculum, the focus predominantly remained on computer science (Atmatzidou & Demetriadis, 2016; Kalelioglu et al., 2016; Selby & Woollard, 2013; Sentance & Csizmadia, 2015). Commencing in 2020, however, the concept of CT as a transdisciplinary and interdisciplinary skill started to gain momentum, especially within STEM education (Hsieh et al., 2022; Palts & Pedaste, 2020). Frameworks and models have emerged, but they primarily focus on defining CT and its dimensions (Annamalai et al., 2022), required understanding of code analysis and block-based visual programming languages (Tikva & Tambouris, 2021), and isolating CT from disciplines like biology or lacking empirical validation in educator training contexts (Killen et al., 2023). In Malaysia, the focus has been on introducing CT in programming and coding at the preschool level (Jack et al., 2019), the primary school level (Mensan et al., 2020) and the secondary school level (Chongo et al., 2020).

Frameworks on how to introduce CT from fundamental concepts are scarce at the matriculation level, making it difficult for matriculation educators and students to recognise the importance of CT. Such shortcomings can lead matriculation educators to perceive CT as overly complex and leave them without developmentally appropriate guidelines for integration. As a result, educators face the added burden of creating new, age-appropriate activities. In the increasing demand for educators to incorporate CT into science classrooms, the lack of a tailored framework for matriculation-level Biology is a glaring gap. This deficiency has critical implications for educator training programs and effective classroom practices. Current frameworks are often inadequate, mostly focusing on computer science curricula (Yadav et al., 2016), isolating CT from disciplines like Biology, or lacking empirical validation in educator training contexts (Killen et al., 2023).

The BioCT-PjBL framework emerges as a comprehensive educational resource to address these challenges. It offers a structured PjBL approach that simplifies the complexities often associated with interdisciplinary teaching. This framework provides a well-defined roadmap that seamlessly integrates CT skills with PjBL steps, complete with assessment criteria, thereby cultivating an interactive, student-centred learning environment. By enabling a shift from traditional lecture-based methods to real-world problem-solving that blends Biology and CT, the framework enhances student engagement and the assessment of critical skills.

Moreover, its alignment with the Malaysia Education Blueprint 2013–2025 ensures that educators are in sync with national goals, contributing to their professional development and elevating educational standards. As a dynamic tool, the BioCT-PjBL framework can be updated to reflect the latest research and technological advancements, ensuring educators remain at the cutting edge of pedagogical innovation.

Research Questions

This study aims to develop a framework using Project-Based Learning (PjBL) to integrate Biology with Computational Thinking skills for educators based on expert consensus. This study seeks to address the following questions:

1. What are the core constructs that experts agree should be included in the BioCT-PjBL framework?
2. What are the core elements that experts agree should be included in the BioCT-PjBL framework?
3. What is the 'd' threshold value that indicates a sufficient level of expert agreement for the inclusion of specific elements in the BioCT-PjBL framework?
4. Which elements are deemed suitable by experts for integration into the BioCT-PjBL framework?

METHODS

Fuzzy Delphi Method (FDM)

Introduced originally by Murray et al. (1985) and later refined by Kaufmann and Gupta (1988), this study utilises the FDM. The FDM enhances the conventional Delphi approach by integrating the Fuzzy Set Theory (Jamil & Noh, 2020; Saedah et al., 2020). Researchers such as Al-Rikabi and Montazer (2023) and Naser et al. (2023) have also adopted the improved FDM to meet their research objectives, streamline expert assessments, cut costs, and facilitate the individual articulation of expert opinions. Delphi's approach relies on group dynamics rather than statistical power to bring experts together in an agreement (Okoli & Pawlowski, 2004). FDM aligns perfectly with the study's objective of obtaining expert consensus on essential components for the BioCT-PjBL Framework. To obtain the constructs and elements using the Fuzzy Delphi Method (FDM), a comprehensive literature review was conducted to identify preliminary constructs and create a questionnaire for construct selection. Eleven experts were selected based on their qualifications and experience, and the questionnaire was distributed to them. After the constructs were selected, another questionnaire for element selection was developed and distributed to the experts to rate the importance and relevance of each element. Their responses were converted into fuzzy numbers and aggregated to form a consensus. The final consensus was determined by converting fuzzy numbers back to crisp values, resulting in a validated list of constructs and elements for the study.

Instruments

The research questionnaire for the FDM was developed through an in-depth literature review supplemented by insights from pilot studies and practical experiences. To ensure content validity, the questionnaire was evaluated by three expert panels from public universities in Malaysia who were knowledgeable in the Fuzzy Delphi Method approach to provide a preliminary assessment of the acceptability of the content. No amendment was required. The Content Validity Index (CVI) was employed as a quantitative measure of validity, in accordance with the issues discussed by Polit et al. (2007), who stipulate that a scale is considered to have excellent content validity if its items achieve an Item-Content Validity

Index (I-CVI) of 0.78 or higher, and the overall Scale-Content Validity Index/Average (S-CVI/Ave) is 0.90 or higher. CVI aims to assess the alignment of individual items and the overall scale with the construct being measured, ensuring the questionnaire's items are both relevant and accurate.

To identify suitable constructs and elements for developing the BioCT-PjBL framework, questionnaires utilising a 7-point Likert scale were distributed to experts to obtain consensus. This choice of a 7-point Likert scale for analysis was based on research findings indicating that it yields more accurate results with lower ambiguity compared to a 5-point Likert scale (Jamil & Noh, 2020; Saedah et al., 2020). Table 1 shows the differences between 7-point Likert scales and 5-point Likert scales.

Table 1 compares the 7-point Likert scale and the 5-point Likert scale. The 7-point Likert scale includes values such as m1 (indicating 90% agreement), m2 (indicating 100% agreement), and m3 (also indicating 100% agreement). This comparison helps assess the accuracy of experts' agreement, with the highest Fuzzy scale selected serving as an indicator.

Experts' Profile

Fuzzy Delphi studies generally recommend involving a minimum of ten experts to ensure a high level of consensus among them (Adler & Ziglio, 1996). The selection of nine experts in computer science and two experts in biology for this study was based on the unique nature of CT within the field of biology education. CT is a relatively new concept in the context of biology education, and its integration into biology curricula is an emerging area. Therefore, finding experts who possess both deep expertise in biology and a substantial background in CT proved challenging. The decision to include nine computer science experts stemmed from their well-established familiarity with CT

Table 1
Comparison between the 7-point Likert scale and the 5-point Likert scale

7 Likert scale			**5 Likert scale**		
Language Variable	**Fuzzy Scale (n1,n2,n3)**	**Average**	**Language Variable**	**Fuzzy Scale (n1,n2,n3)**	**Average**
7 – Strongly Agree	(0.9,1.0,0.9)	96.7%	5 – Strongly Agree	(0.6,0.8,1.0)	80.0%
6 – Agree	(0.7,0.9,1.0)	86.7%	4 –Agree	(0.4,0.6,0.8)	60.0%
5 – Somewhat Agree	(0.5,0.7,0.9)	70%	3 – Neutral	(0.2,0.4,0.6)	40.0 %
4 – Neutral	(0.3,0.5,0.7)	50%	2 – Disagree	(0.0,0.2,0.4)	20.0%
3 – Somewhat Disagree	(0.1,0.3,0.5)	30%	1 – Strongly Disagree	(0.0,0.0,0.2)	6.7%
2 – Disagree	(0.0,0.1,0.3)	13.3%			
1 – Strongly Disagree	(0.0,0.0,0.1)	3.3%			

Adapted from Jaya et al. (2022)

concepts and principles, given the inherent computational nature of their field. These experts are equipped with the knowledge and experience necessary to assess the effective integration of CT into educational settings. Their role in this study primarily focused on evaluating the appropriateness and effectiveness of CT skills within the context of biology education.

The inclusion of only two experts in biology was necessitated by the limited pool of individuals possessing both a deep understanding of biology and substantial experience with integrating Computational Thinking (CT). Due to the emerging nature of CT in biology education, these experts were selected for their unique insights into applying CT to enhance biology teaching. Their primary role is to ensure that the CT skills introduced are aligned with the content and educational goals of biology. According to Pohl et al. (2021), in developing any new interdisciplinary or transdisciplinary field, the quality of outcomes is crucial, irrespective of the number of researchers, disciplines, fields, and practitioners involved. Thus, the involvement of only two biology experts is justified as long as they are proven experts in their field. This aligns with the principles of this research, where the integration of diverse expertise and perspectives is valued more than the sheer number of contributors. The focus is on achieving impactful and comprehensive outcomes through effective collaboration, regardless of the number of experts from each discipline.

In line with Berliner's definition of expertise in 2004, which requires a minimum of five years of experience in a specialised field, the selected experts held at least a bachelor's degree and had no fewer than five years of experience in their respective areas of expertise. Gambatese et al. (2008) further emphasised the importance of high academic qualifications among experts. Table 2 shows the number of selected experts according to their expertise.

Table 2
Field and number of selected experts

Field of Expertise	Number of Experts
Biology Education - CT	2
Science Computer Education - CT	9

Data Analysis

The collected Likert Scale data were converted into numerical Fuzzy data using the FDM, employing Fuzzy triangular numbers (m1, m2, m3) to represent minimum, reasonable, and maximum values, as shown in Figure 1.

The data was then meticulously analysed using Microsoft Excel software, following recommendations by Jamil and Noh (2020). This analysis adhered to two primary prerequisites of the FDM: the use

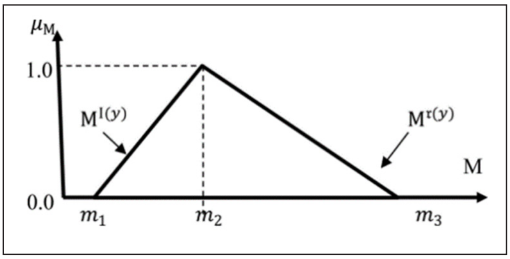

Figure 1. The Triangular Fuzzy Number
Source: Yasin et al., 2022

of Triangular Fuzzy Numbers (TFN) and the implementation of the Defuzzification Process. For TFN, the threshold (d) value should be ≤ 0.2. Expert agreement is considered achieved when the resulting value is ≤ 0.2, indicating consensus among the panel of experts in decision-making (Cheng & Lin, 2002). The following formula is used:

Threshold, d =

$$\sqrt{1/3\ [(m_1-n_1)^2 + (m_2-n_2)^2 + (m_3-n_3)^2]} \qquad [1]$$

n_1,n_2,n_3 = Fuzzy value

m_1, m_2,m_3 = Average of Fuzzy value (mean)

Another criterion for TFN involves achieving a consensus percentage among experts. It is considered acceptable when the agreement among the expert group is equal to or above 75% (Chu & Hwang, 2008).

The percentage of an expert agreement =

$$\frac{\text{The frequency of threshold value} < 0.2}{\text{The number of experts}} \times 100 \qquad [2]$$

The following requirement of the FDM pertains to the defuzzification process. The fuzzy (A) score must equal or exceed 0.5 in this process to determine item acceptance or rejection (Jamil & Noh, 2020). Items with a fuzzy score value (A) equal to or exceeding 0.5 are accepted, while those falling below 0.5 are rejected. The determination of the fuzzy (A) score value is made based on the following formula:

$$A, \text{Fuzzy score value} = (1/3) * (m_1 + m_2 + m_3) \qquad [3]$$

m_1, m_2,m_3 = Average of Fuzzy Value (mean)

RESULTS

The findings from the FDM analysis reveal critical criteria for item acceptance. These criteria include a TFN threshold value ‘d’ of equal to or less than 0.2 (d ≤ 0.2), a requirement for expert consensus to achieve 75% or above (Manakandan et al., 2017), and a defuzzification process that accepts items with a defuzzication value equal to or more than 0.5, where 0.5 serves as the alpha cut value (Defuzzification value (A) ≥ value α cut = 0.5; Bodjanova, 2006). The rank of an item within a similar construct was determined after the defuzzification process. These three requirements are essential to demonstrate which elements meet the experts’ criteria for acceptance, and any elements failing to meet these criteria will be eliminated. Table 3 summarises the analysis conducted using the FDM concerning the constructs and elements required to develop the BioCT-PjBL framework.

In Table 3, all four items under the first construct (CT skills) had a threshold value (d) of ≤ 0.2, signifying a consensus among experts, with 100% consensus achieved. When an item reaches a threshold value (d) of ≤ 0.2, it implies expert consensus (Jusoh, 2018). This unanimous consensus

Table 3
Construct and items' acceptability based on experts' consensus of the BioCT-PjBL framework

Construct		Elements	Threshold (d) Value d≤0.2	% Expert Consensus ≥ %75	Defuzzification Value (A) ≥ 0.5	Ranking	Outcome
Computational Thinking Skills	B1	Decomposition	0.05	100%	0.95	1	Accepted
	B2	Pattern Recognition	0.08	100%	0.92	4	Accepted
	B3	Abstraction	0.06	100%	0.94	2	Accepted
	B4	Algorithmic Thinking	0.07	100%	0.93	3	Accepted
Activities	D1	Unplugged	**0.38***	**0%***	0.69		**Rejected**
	D2	Plugged-In	**0.36***	**45%***	0.74		**Rejected**
	D3	Unplugged & Plugged -In	0.06	100%	0.94	1	Accepted
Assessment	E1	Portfolio	0.19	**73%***	0.85		**Rejected**
	E2	Projects	0.08	100%	0.92	1	Accepted
	E3	Reflection Report	0.13	**73%***	0.86		**Rejected**
	E4	Presentation	0.09	91%	0.92	1	Accepted
	E5	Artefacts	0.17	91%	0.84	3	Accepted

Note. *Item with threshold value d ≥ 0.2 and experts' consensus ≤ 75%

confirms that the elements of CT skills (decomposition, pattern recognition, abstraction, and algorithmic thinking) are universally considered crucial for learning. Regarding the fuzzy score (A), a 0.5 threshold determined item acceptance. Items with a defuzzification value (A) ≥ 0.5 were accepted, while those below 0.5 were rejected. Importantly, all items in the CT skills construct achieved a defuzzification value (A) ≥ 0.5, demonstrating overall expert consensus and a 100% consensus on item acceptance.

In the construct of CT activities, experts unanimously agreed that unplugged and plugged-in activities should be combined to effectively introduce and teach CT. This consensus leads to the rejection of using unplugged or plugged-in activities separately. The criteria for this decision include a threshold (d) value of 0.061, a 100% expert consensus, and a defuzzification value of 0.939.

Three out of the five elements received approval from the experts in the assessment technique for evaluating CT. Projects emerged as the highest-ranked element, achieving a threshold value (d) of 0.076, 100% expert consensus, and a defuzzification value (A) of 0.921. Additionally, presentation and artefacts were also accepted, with threshold values of 0.099 and 0.171, respectively. Both garnered expert consensus exceeding 75%, specifically 91%. The defuzzification process revealed a value of 0.915 for presentation and 0.839 for artefacts. On the other hand, the portfolio and reflection report were rejected by the experts.

Ultimately, all CT skills items met the threshold for expert consensus ($d \leq 0.2$) and had defuzzification values (A) ≥ 0.5, confirming their importance. Experts also agreed that unplugged and plugged-in activities should be combined, with a threshold (d) of 0.061 and a defuzzification value (A) of 0.939. Projects, presentations, and artefacts were approved for assessment techniques, while portfolios and reflection reports were rejected.

DISCUSSION

This research sheds light on the efficacy of incorporating CT into Biology instruction via a PjBL paradigm, culminating in the BioCT-PjBL framework. The framework's robustness is validated through key performance indicators: a threshold 'd' value below 0.2, expert agreement exceeding 75%, and defuzzification value above 0.5. Utilising PjBL fosters an interactive, learner-centric environment that amplifies critical thinking, problem-solving, and the practical application of CT skills within the biological sciences. This pedagogical approach elevates student engagement and enables a more authentic evaluation of CT competencies. Moreover, the collaborative nature of PjBL enhances peer-to-peer learning and instils a sense of accountability among students, enriching their educational journey.

The overwhelming concurrence among experts accentuates the universal significance of foundational CT skills—specifically, decomposition, pattern recognition, algorithmic thinking, and abstraction—in educational effectiveness. This expert alignment resonates with the Malaysian Computer Science curriculum, underscoring these pivotal CT skills as integral to secondary education (Ministry of Education Malaysia, 2015). The imperative for educators to master these skills prior to teaching is further corroborated by scholarly literature. For instance, decomposition is emphasised as a mechanism for simplifying complex biological systems, substantiated by Peters-Burton et al. (2022). Similarly, pattern recognition is vital for identifying recurring elements in biological datasets, as affirmed by the same study. Algorithmic thinking, as expounded by Rich et al. (2019), transcends mere procedural adherence and involves the creation of systematic methodologies, particularly relevant in biological experimentation. As delineated by the same authors, abstraction involves focusing on essential information while omitting irrelevant details, thereby making intricate biological systems more manageable.

Within the academic landscape of CT, a growing scholarly consensus advocates for a balanced amalgamation of unplugged and plugged-in activities for effective teaching and learning. Unplugged activities, devoid of digital device requirements, serve as potent introductory exercises for new subject matter. Empirical studies validate their constructive influence on cultivating CT abilities (Busuttil & Farmosa, 2020). In certain research endeavours, these activities have even demonstrated superior outcomes compared to their plugged-in alternatives (Kite & Park, 2024). Conversely, plugged-in activities, which necessitate technological engagement, offer distinct merits. They are especially advantageous for mastering programming (Sigayret et al., 2022) and achieving a nuanced understanding of conceptual frameworks (Aytekin & Topçu, 2023). These tech-centric activities leverage computational capabilities as essential tools for a more intricate grasp and application of CT principles (Caeli & Yadav, 2020). Interestingly, while individual preferences for one modality exist, most participants exhibit a favourable inclination towards unplugged and plugged-in activities (Erumit & Sahin, 2020). This collective evidence compellingly suggests that a harmonised instructional methodology incorporating both activity types is well-received and offers a comprehensive and efficacious strategy for imparting CT skills.

In the realm of evaluating CT, expert opinions diverge on the various assessment methodologies at hand. Notably, projects received universal endorsement from the expert panel, attaining a 100% consensus. This unanimous approval is ascribed mainly to the active learning paradigm that projects embody, aligning seamlessly with the foundational tenets of CT. This modality enables students to deploy CT skills in real-world scenarios, thereby nurturing problem-solving (Durak, 2020), critical thinking (Giannakoulas et al., 2021), and creativity (Liu et al., 2022; Saidin et al., 2021). Alongside projects, presentations, and artefacts, they also garnered significant expert approval, achieving a 91% consensus. These methods are commended for their ability to furnish tangible proof of students' CT proficiencies, offering educators invaluable insights into their cognitive processes and problem-solving acumen. In contrast, portfolio and reflection reports were met with expert disapproval, likely due to their dependence on self-reporting and documentation, which are deemed less objective and comprehensive for CT skill assessment. The absence of expert endorsement for these techniques highlights the necessity for a more nuanced CT assessment strategy, likely involving a blend of methodologies tailored to specific educational objectives and settings.

CONCLUSION

In conclusion, this comprehensive study serves as a pivotal contribution to the evolving field of CT in educational settings, particularly within the context of Biology instruction. The BioCT-PjBL framework, validated through rigorous empirical metrics, emerges as a robust model for integrating CT into Biology education. It not only enhances pedagogical effectiveness but also enriches the learning experience for students. The framework's alignment with expert consensus and established curricula further underscores its relevance and applicability.

Moreover, the study delves into the nuances of teaching methodologies and assessment techniques, advocating for a balanced and holistic approach. It highlights the merits of both unplugged and plugged-in activities, as well as the importance of employing diverse assessment methods, each with its unique strengths and limitations. The unanimous expert agreement on the core CT skills and their applicability in Biology education adds another layer of validation to the framework.

The collective insights from this research offer a multidimensional perspective on CT education. They validate and enrich the academic discourse surrounding the integration of CT skills into Biology education. The study thereby provides educators with a well-rounded, empirically backed framework and assessment strategies, equipping them with the necessary tools to meet the complex educational challenges of the 21st century.

Implications

Developing a CT framework for teachers in Malaysia using the FDM has significant implications. The framework tailors theoretical principles to the Malaysian education system, aligning with its goals and curriculum. The methodology, involving experts, ensures the framework meets teachers' needs. Empirical data analysis strengthens the framework's research foundation, making it theoretically sound and practical. The framework is designed to be easily integrated into existing curricula, benefiting teachers and students alike.

Limitations of the Study

This study heavily relies on the cooperation and idea contributions of the participants (expert groups). The validity of the study findings is highly dependent on the level of cooperation, commitment, and earnestness demonstrated during the FDM in their phase of designing and developing the module.

Recommendations for Future Studies

In light of the strong consensus among experts regarding the BioCT-PjBL framework, it is imperative for educational authorities to consider its integration into the national Biology curriculum as a pivotal step in enhancing CT skills within the discipline. Concurrently, to ensure the framework's effective implementation, developing targeted professional development programs for educators is essential. These programs would serve as a conduit for equipping teachers with the requisite skills and knowledge to integrate CT seamlessly into biology education.

While the current study has been instrumental in gathering expert opinions, further empirical validation is warranted. Therefore, future research endeavours could focus on pilot studies or randomised controlled trials to gauge the framework's efficacy in real-world educational settings. Alongside this, the advent of the BioCT-PjBL framework necessitates the creation of innovative student assessment tools designed to accurately measure both CT skills and Biology comprehension.

Moreover, the study's findings carry substantial policy implications, urging policymakers to consider them carefully when shaping educational policies, particularly those related to STEM education and the broader application of CT. Given the global challenges that education faces, examining the framework's applicability in various cultural and educational contexts is crucial to ensure its universal relevance and effectiveness. Lastly, to capture the long-term impact of the BioCT-PjBL framework, longitudinal studies are recommended, which would monitor changes in educators' pedagogical approaches and students' academic performance over an extended timeframe.

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