Blended Problem-Based Learning for Enhancing COVID-19-Related Scientific Understanding and Critical Thinking in Thai Secondary School Students

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***Abstract*—The COVID-19 pandemic revealed substantial gaps in students' pandemic literacy and created a need for more resilient science education approaches. This study investigated the effectiveness of a four-stage blended Problem-Based Learning (PBL) module on COVID-19 sciences for enhancing conceptual understanding and critical thinking among 133 Thai secondary school students aged 13–15 years. The intervention combined structured online foundational learning through Google Classroom with collaborative hands-on construction of alcohol-based sanitiser dispensers. A quasi-experimental repeated-measures design was used across four assessment points (pre-test, mid-test, post-test, and one-week retention). Conceptual understanding was measured through a 36-item COVID-19, Sanitiser, and Dispenser Conceptual Test (CovSD-CT), while critical thinking was assessed using a rubric across three reasoning dimensions: Purpose, Mechanism, and Context. Mean (M) conceptual scores increased significantly from pre-test (M = 16.56) to post-test (M = 20.54) out of 35 points with a large effect size (Cohen's d, d = 0.96) and remained above baseline after one week. Critical thinking abilities showed substantial development across all dimensions, with Context reasoning showing the largest improvement (rank-biserial correlation, r_{rb} = 0.91) and significant retention gains (r_{rb} = 0.81). Purpose (r_{rb} = 0.77) and Mechanism (r_{rb} = 0.75) reasoning also improved significantly from pre-test to post-test despite greater decline at retention. The blended approach proved particularly effective, with the online phase establishing foundational knowledge and the hands-on phase reinforcing application-oriented understanding. These findings suggest that sequential blended PBL approaches offer considerable potential for pandemic science education while developing essential 21st-century reasoning skills.**

***Keywords*—blended Problem-Based Learning (PBL), COVID-19 pandemic, conceptual understanding, critical thinking, secondary school, pandemic literacy**

I. Introduction

The COVID-19 pandemic severely disrupted global education, affecting over 1.5 billion learners and necessitating rapid transitions to emergency remote teaching that often failed to support interactive science education effectively [1, 2]. While blended learning approaches combining online and face-to-face instruction have demonstrated efficacy in enhancing student engagement and outcomes, their integration with Problem-Based Learning (PBL) for pandemic-focused science education remains underexplored, particularly at the secondary level [3, 4].

Despite the pandemic's educational relevance as an authentic scientific context, age-appropriate instructional materials targeting COVID-19 science for early secondary students remain scarce [5]. This gap is particularly concerning given young learners' limited understanding of prevention measures and pandemic science, which extends beyond academic achievement to public health implications.

This study addresses these gaps by developing and evaluating a four-stage PBL module adapted for blended delivery (adapted from Windale *et al.* [6]) focused on COVID-19-related sciences for Thai secondary school students aged 13–15. While most blended learning and PBL research has focused on higher education or general science topics, few studies have explored pandemic-focused instruction at the lower secondary level. The intervention integrates structured online foundational learning with collaborative, hands-on activities centred on designing alcohol-based sanitiser dispensers, examining their effects on students' conceptual understanding and critical thinking across the Purpose, Mechanism, and Context reasoning dimensions. By providing empirical evidence for effective pandemic science education approaches, this research contributes to understanding how blended PBL can simultaneously address authentic societal challenges while developing essential 21st-century reasoning skills.

Although the acute phase of the COVID-19 pandemic has passed, it remains vital for education systems to consolidate lessons learned from this global disruption. Beyond immediate recovery, documenting and developing instructional models that capture this historical event ensures that schools are better prepared for future crises while also preserving their educational significance. By embedding pandemic-related content into science curricula, educators not only reinforce scientific literacy but also create opportunities for students to engage with real-world challenges that have shaped their generation.

Recent syntheses of problem-based and blended learning indicate consistent benefits for students' conceptual understanding and problem-solving across school and higher education settings [7–10], and post-pandemic research trends highlight a gradual shift from emergency remote teaching toward more sustainable blended models in science education [2, 11, 12]. However, these trend data rarely address COVID-19-related content at the lower secondary level, and very few studies have examined how distinct phases of blended problem-based learning, such as online and hands-on components, contribute differentially to learning gains and dimension-specific critical thinking over time. Building on this gap, the present study investigates the effects of a four-stage blended PBL module on COVID-19-related

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sciences among Thai lower secondary students by examining (1) changes in conceptual understanding across pre-, mid-, post-, and retention tests; (2) development of critical thinking through the Purpose, Mechanism, and Context reasoning framework; and (3) the respective contributions of the online and hands-on phases to these outcomes.

II. Literature Review

A. COVID-19 and Educational Opportunities

The COVID-19 pandemic, declared by the World Health Organisation in March 2020, led to unprecedented global school closures affecting more than 1.5 billion learners and up to 94% of the world's student population at the peak of disruption [1, 13–16]. Subsequent meta-analytic evidence shows substantial learning losses, roughly equivalent to one-third of a school year, with disproportionate effects on students with existing educational inequalities and posed challenges for vulnerable groups such as those in rural areas and low-income families [17, 18]. In Thailand, nationwide school closures and an adjusted academic calendar affected over 13 million students, contributing to declines in literacy, numeracy, and science learning, alongside reduced motivation and increased anxiety about academic futures [1, 19–22].

Emerging responses to this disruption initially took the form of emergency remote teaching. UNESCO launched emergency distance learning initiatives to reach at-risk students, while systems implemented varied modalities with limited preparation or resources [23, 24]. Education systems established agile leadership groups and steering committees to coordinate with public health, plan implementation, and reprioritise curriculum goals during social distancing [23–26]. Over time, countries began moving from short-term crisis management toward more sustainable models that emphasised teacher digital competence, system-level coordination, and the development of blended or hybrid learning ecosystems [27–33]. Within this trajectory, blended learning, combining online and face-to-face modalities, has gained prominence as a strategy for maintaining flexibility while restoring opportunities for interaction, practical activities, and collaborative learning.

Wong *et al.* [34] showed that crises can depict contemporary scientific practice by highlighting the tentative, theory-laden, and interdisciplinary nature of science and its relationships with society and technology, while Verran *et al.* [35] used simulation-based workshops to engage learners with disease transmission dynamics where engagement was high though perceived learning was moderate; Dantic [36] reported that secondary students' conceptual understanding of COVID-19 was fairly satisfactory and that teachers perceived pandemic content as valuable for Science, Technology and Society curricula, including addressing disparities, strengthening science communication, and considering broader societal implications.

B. Constructivist Learning Theory

Constructivism provides the theoretical foundation for understanding how learners build knowledge and meaning through their experiences. This learning theory posits that knowledge cannot simply be transmitted but must be actively constructed by learners through meaningful experiences and interactions [37]. Central to constructivist theory are two interconnected principles: cognitive assimilation or accommodation and socially mediated meaning-making.

The first principle, stemming from Piaget's theory of cognitive constructivism, suggests that, when faced with disequilibrium or a cognitive conflict driving conceptual change, learners actively construct new understandings by building upon their existing knowledge frameworks through the assimilation of new information into existing frameworks or accommodation when contradictions necessitate structural changes [37, 38].

The second principle, derived from Vygotsky's Zone of Proximal Development (ZPD), asserts that learning is the combination of cognitive processes and social interaction, enabling learners to surpass their limits zone of independent problem-solving abilities through guided collaborative support [38]. For instance, when working on real-world, ill-structured problem situations, students, as shown by Hmelo-Silver [39], not only have better causal reasoning but also have more coherent explanations of phenomena when compared to students in conventional instructional settings. Dantic [36] demonstrated that students who were actively involved in discussions about pandemic-related concepts achieved greater conceptual clarity when these discussions were grounded in students' existing mental models. In conclusion, constructivist learning environments emphasise authentic tasks that connect learning to real-world contexts, multiple perspectives through collaborative problem-solving, and opportunities for student autonomy [39].

C. Problem-Based Learning Development

Problem-Based Learning (PBL) was first developed in the late 1960s at McMaster University Medical School in Canada as a reaction to the fundamental dissatisfaction with conventional medical education practices, which featured the disconnect between preclinical education and clinical practice [40]. The emergence showed that within the educational context, PBL was gradually studied and refined while maintaining its core principles in student-centred, self-directed learning through authentic problem-solving [39, 41]. The evolution of PBL into science education has demonstrated significant promise beyond its medical origins. The effects of PBL in science education contexts have been validated through meta-analyses, with evidence suggesting a particularly strong impact on students' problem-solving abilities and conceptual understanding [7–9].

D. Four-Stage Problem-Based Learning Module

The four-stage PBL module, originally developed through the Problem Solving with Industry project at Sheffield City Polytechnic [6], provides a structured framework for implementing problem-based learning in science education. This module, as shown in Table 1, emphasises systematic progression through distinct stages that support both individual learning and collaborative problem-solving. In STEM education contexts, this approach integrates inquiry-based learning, scientific inquiry, and engineering design principles to address real-world problems through authentic contexts. The module's effectiveness lies in its structured activities, which are specifically designed to develop conceptual understanding, inquiry skills, and communication abilities through collaborative problem-solving processes [6].

Table 1. The four-stage PBL module

Stage	Learning Activity
1	Introducing the problem and context
2	Developing an understanding of the problem and background knowledge understanding and skills
3	Solving the problem
4	Communicating the solutions to the problem

E. Blended Problem-Based Learning

Integrating technology into the core principles of problem-based learning creates flexible digital study spaces where students can solve authentic problems through blended face-to-face and online learning formats. Aligning with constructivist views, this synergy between offline and online interactions enables learners to develop knowledge through active participation in social discussions and reflective practice [42]. Moreover, well-structured online components serve as scaffolding platforms to develop inquiry through feedback mechanisms while sustaining their interest in complex assignments [43]. Simultaneously, face-to-face activities complement the counterpart by offering immediate assistance, creating a sense of social presence and building group unity [44].

However, such dual-modality setups require learners to develop self-directed learning competencies as they navigate digital resources while also participating in hands-on, collaborative sessions [45]. Moreover, the design of problem-based e-learning platforms requires scaffolds that guide learners through ill-structured tasks to help them manage the cognitive load of such challenges [46, 47]. Hence, educators need to focus on learner scaffolding by providing consistent feedback loops, collaborative tools, and milestone-based tasks to cultivate metacognitive skills essential for navigating ill-structured problems [48].

Before the pandemic, research in Thai higher education had already demonstrated that blended learning could outperform traditional methods in content mastery, skill development, and information literacy [3, 4]. Moreover, this instructional approach is in line with Thai National Education Act B.E. 2542 (1999), which requires learning to be possible at any time and in any place [49, 50].

F. Critical Thinking Framework and Operationalisation

Critical thinking refers to the systematic process of collecting, analysing and evaluating information to develop sound judgments, select effective solutions, and reflect deeply on learning progressions [51]. To account for the multifaceted nature of critical thinking in science education, Paul-Elder's Critical Thinking Framework was selected as the primary theoretical framework for the study [52, 53]. However, as the model presents altogether 26 constructs: 8 Elements of Thought, 9 Intellectual Standards, and 9 Traits, it is often difficult for students to apply cohesively and for instructors to assess reliably in a specific disciplinary context, according to Thompson *et al.* [54].

In addition, Huneman's [55] explanation that scientific explanations are centred on discovering and describing the causal mechanisms of natural phenomena. Building on this framework, mechanistic explanations can be expanded into dual perspectives of constitutive explanations, which describe how the parts of a mechanism lead to a phenomenon, and contextual explanations, which represent the system or function in which the mechanism is found, as explained by Theurer [56]. Together, these perspectives highlight that high-quality scientific reasoning requires attention not only to purposes or goals, but also to the mechanisms by which those goals are achieved and the contexts in which they operate, providing a conceptual bridge between general critical thinking theory and the COVID-19-related scientific content of the present study.

Prior research has emphasized adolescence as a crucial period for the consolidation of critical thinking. Yet, most empirical applications of comprehensive reasoning frameworks, including adaptations of the Paul–Elder model, have been conducted in higher education rather than at the secondary level [57, 58]. At the same time, very few studies have integrated causal–mechanistic and contextual perspectives into problem-based learning designs focused on pandemic-related content, despite the clear relevance of such reasoning for understanding phenomena such as COVID-19.

Taken together, the literature shows that blended learning and problem-based approaches effectively promote understanding and reasoning skills. However, their use in pandemic-focused science education at lower secondary levels remains underexplored, especially concerning their impact on developing and retaining multi-dimensional critical thinking. In response to these gaps, the present study adopts an integrated critical thinking framework that combines Paul and Elder's systematic focus on purpose and quality of reasoning with mechanistic and contextual accounts of scientific explanation, and applies it within a four-stage blended PBL module on COVID-19-related sciences for Thai lower secondary students. This framework is operationalised through three dimensions (Purpose, Mechanism, and Context reasoning), which are used to examine how students' conceptual understanding and critical thinking develop over time in an authentic, pandemic-based instructional setting.

III. MATERIALS AND METHODS

A. Design and Setting

This study employed a pragmatic, quantitative, quasi-experimental repeated-measures design to track learning across four rounds: Pre-test (PRE), Mid-test after the online phase (MID), Post-test after the hands-on phase (POST), and One-week retention (RET), aligning the PRE–MID contrast with online learning effects and MID–POST with hands-on contributions while RET assessed maintenance beyond instruction. The intervention was implemented as a four-stage PBL module delivered in a blended format across three Thai secondary schools (coded as A, B, and C), with timeline adaptations by site due to institutional constraints, while preserving the core stage structure. Participants were Grades 7–9 students aged 13–15 under the Thai Basic Education Core Curriculum, with convenience sampling. 133 students completed PRE, MID, and POST, and 94 completed RET due to scheduling constraints and absenteeism. The participants were drawn from three schools selected by convenience, including one urban public school, one suburban school, and one peri-urban public school, all of which received the same instructional sequence and assessments.

B. Instructional Module

The module was adapted from the original four-stage PBL framework into two phases to suit blended delivery, as outlined in Table 2.

Table 2. The four-stage blended PBL module

Stage	Mode	Learning Activity	COVID-19 Scientific Concepts
1	Online	Problem & Context orientation	Authentic problem scenario
2	Online	Curated videos & Adaptive quizzes	Viral biology, sanitiser chemistry, dispenser mechanics
3	Onsite	Collaborative hands-on design challenge	Applied lever systems and alcohol formulation
4	Onsite	Prototype communication (written or spoken)	Integrated science-engineering solutions

Online phase (Stages 1–2): Google Classroom hosted structured topics with introductory videos, curated instructional media, and adaptive quizzes (illustrated in Fig. 1) designed to begin with understanding rather than recall, promote application when ready, and redirect to targeted review when needed, thereby scaffolding conceptual understanding before hands-on work. Content strands include COVID-19 biology (aetiology, transmission, screening and prevention), sanitiser chemistry (composition and functions), and dispenser mechanics (simple machines), arranged to highlight the progression from conceptual understanding to real-world problem analysis. This phase required approximately one hour of self-paced student engagement.

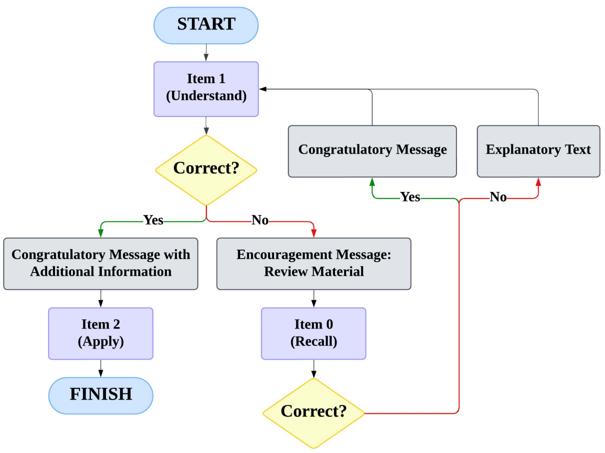

Fig. 1. Adaptive Google form's quiz structure showing differentiated learning paths based on student responses.

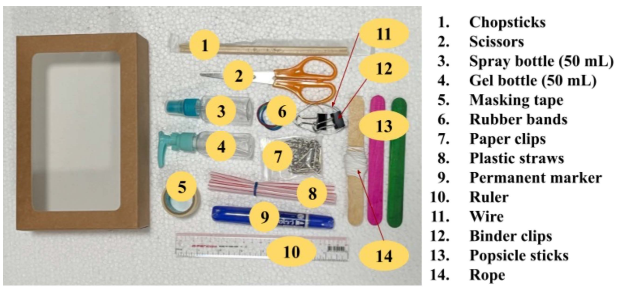

Fig. 2. Standardised box set containing dispenser construction materials.

Hands-on phase (Stages 3–4): Student groups of 4–5 constructed hands-free sanitiser dispenser prototypes using standardised box sets (shown in Fig. 2), iterating through brainstorming, building, testing, refinement, and concise justification of scientific principles in presentations or summaries. Regardless of site-specific timetabling constraints, the total contact time during the hands-on phase was approximately 1.5 to 2 hours. Across both phases, students engaged with the entire module for approximately 2.5 to 3 hours. Fig. 3 presents examples of students' prototype outputs produced during the hands-on phase.

Fig. 3. Examples of students' deliverables.

C. Measurements

Conceptual understanding: The COVID-19, Sanitiser, and Dispenser Conceptual Test (CovSD-CT) comprised 36 items: 35 objective items distributed across biology (20 true/false adapted from Students' Knowledge, Attitudes and Practices toward COVID-19 questionnaire, SKAPCOV-19 [59]), chemistry (5 multiple-choice on composition and functions), and physics (2 multiple-choice and 8 true/false on moments, levers, and mechanical advantage), plus a single open-ended item anchored to a hands-free dispenser image. Objective items provided continuous scores suitable for within-subject comparisons across PRE, MID, POST, RET, with content alignment to Thai curricular standards and the module's three content strands. For internal consistency, Cronbach's alpha for the objective scale was 0.76, indicating acceptable reliability for group-level inferences in this field context.

Critical thinking: The open-ended CovSD-CT item was scored with a three-dimensional rubric derived from the literature: Purpose reasoning (mechanism linked to disease prevention), Mechanism reasoning (principles of simple machines), and Contextual reasoning (practical value and situational integration), each rated 0–2 by three raters and averaged in 0.33 increments. The three-dimensional rubric was designed for age-appropriateness and domain relevance in lower secondary science. Paul–Elder's 26 constructs, though comprehensive, are complex for adolescents to apply and for instructors to assess reliably. By drawing on prior work highlighting mechanistic and contextual explanation, the streamlined framework retains the essence of Paul–Elder reasoning about goals, mechanisms, and contexts, while ensuring practical feasibility and reliable interpretation of student growth [52–56]. Inter-rater reliability was established using Fleiss' kappa, showing substantial agreement for Mechanism reasoning (kappa, $\kappa = 0.81$) and Context reasoning ($\kappa = 0.71$), and moderate but acceptable agreement for Purpose reasoning ($\kappa = 0.48$). Rater preparation included rubric calibration on anonymised student responses, example-based consensus building, and independent scoring with remarks to ensure a consistent interpretation of age-appropriate reasoning evidence.

D. Procedures

PRE was administered before any module activity, MID immediately after completion of the online phase, POST after the hands-on phase, and RET approximately one week later, with School C constrained to omit RET. Online activities were delivered through Google Classroom, and hands-on tasks were conducted on-site. Implementation preserved the four-stage sequence across sites while accommodating compressed schedules in Schools B and C, maintaining fidelity to core activities despite reduced activity duration in certain settings.

E. Data Analysis

For conceptual understanding, repeated-measures analyses were conducted on objective scores, using parametric procedures when distributional checks supported their use and reporting Huynh–Feldt corrections when sphericity was violated; effect sizes were reported to characterise PRE–MID, MID–POST, PRE–POST, and RET-related differences, with separate analyses for complete PRE–MID–POST data (N = 133) and PRE–MID–POST–RET completers (N = 94). For critical thinking, ordinal rubric scores (rated 0–2) were analysed with nonparametric Friedman tests and Conover post hoc procedures with Holm adjustment, reporting Kendall's W for overall effects and rank-biserial correlations for pairwise contrasts across PRE, MID, POST, and RET, where available. Given the ordinal nature of the data, restricted scoring range, and violations of normality assumptions, Friedman tests were selected instead of repeated-measures ANOVA. Statistical analyses were conducted in JASP version 0.19.1 (for Apple Silicon), selected for repeated-measures ANOVA, Friedman's test, post-hoc comparisons, and effect size computation, all suitable for the study design.

F. Ethical Approval and Informed Consent

This study received ethical approval from the Institutional Review Board at Institute for Population and Social Research, Mahidol University (Protocol No. IPSR-IRB-2021-228). Written informed consent was obtained from all participating students and their guardians before data collection. Participation remained voluntary throughout the study period, with participants free to withdraw at any time without penalty. All data were anonymised and stored securely according to institutional protocols.

IV. Result and Discussion

Students demonstrated robust gains in conceptual understanding across the module with overall improvement and maintenance at retention, while critical thinking improved across Purpose, Mechanism, and Context with the strongest and most durable growth in Context reasoning.

A. Conceptual Understanding

Fig. 4 displays consistent improvement of mean scores from PRE (M = 16.56, SD = 3.68) to MID (M = 18.80, SD = 3.87), and further to POST (M = 20.54, SD = 4.84). With the addition of the retention test, though with a smaller sample size (N = 94), the improvement was maintained through the retention round (M = 21.01, SD = 4.45). This pattern suggests a positive overall impact of the intervention on student learning.

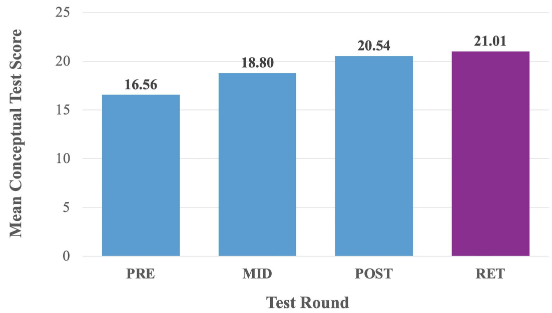

Fig. 4. Changes in mean conceptual test score across pre-test (PRE), mid-test (MID), post-test (POST), and one-week retention (RET) rounds. Note: RET round: N = 94. All other rounds: N = 133.

As shown in Table 3, the statistical analyses revealed significant main effects in both the main analysis and retention subset (N = 94), indicating that the four-stage blended PBL module successfully enhanced students' conceptual understanding of COVID-19-related sciences. The intervention demonstrated large effect sizes, with partial eta-squared values of 0.28 for the main analysis and 0.37 for the retention analysis, suggesting that the module accounted for approximately 28% and 37% of the variance in student learning outcomes, respectively. These substantial effect sizes indicate not only statistical significance but also practical educational significance, demonstrating that the blended approach produced meaningful improvements in student understanding that persisted over time.

Table 3. Statistical test results for conceptual understanding across rounds

Analysis	Test Statistics	Effect Size[1]	Significant Changes[2]
Main (N = 133)	50.90***	0.28	PRE < MID (0.54)*** MID < POST (0.42)*** PRE < POST (0.96)***
Retention (N = 94)	53.42***	0.37	POST > RET (–0.27)** PRE < RET (0.97)*** MID < RET (0.54)***

Note: [1] η^2_p = partial eta-squared effect size.
[2] Cohen's d effect size.
Main Analysis used Huynh-Feldt correction (W = 0.90, $X^2(2) = 13.53$, p = 0.001). Retention analysis maintained sphericity (W = 0.91, $X^2(5) = 9.07$, p = 0.11). **p < 0.01 or ***p < 0.001. All p-values for *post hoc* comparisons were Holm-adjusted.

Repeated-measures ANOVA indicated significant main effects with practical impacts (partial η^2 effect size = 0.28 for main analysis and 0.37 for retention subset), with moderate effect sizes observed for consecutive comparisons (PRE < MID, d = 0.54; MID < POST, d = 0.42), culminating in a large effect size for overall improvement (PRE < POST, d = 0.96). After introducing the retention round into analysis with a smaller sample size (N = 94), there was a small decline during the retention period (POST > RET, d = –0.27); however, students maintained substantially higher performance compared to their initial levels (PRE < RET, d = 0.97).

The progression reveals how each phase contributed distinctly to conceptual development. The larger gain in the online phase (d = 0.54) likely stemmed from adaptive pathways that enabled students to engage with complex pandemic science at their own pace, building foundational schemas without time pressure or social demands. The hands-on phase produced a smaller gain ($d = 0.42$) because students simultaneously managed group coordination and physical manipulation while applying knowledge, constraining new content acquisition but enabling practical consolidation. A slight decline but substantial net gain ($d = 0.97$) during retention suggests formation of relatively durable mental models rather than superficial memorisation.

The online phase accounted for the largest single-phase gain, consistent with self-paced multimedia scaffolding of foundational contents, whereas the hands-on phase consolidated application despite higher cognitive demands, yielding a smaller but meaningful increment.

B. *Critical Thinking*

The stacked bar chart in Fig. 5 shows Mechanism progressing steadily, Purpose increasing but less stably, and Context shifting at POST from predominantly basic responses toward more varied reasoning levels.

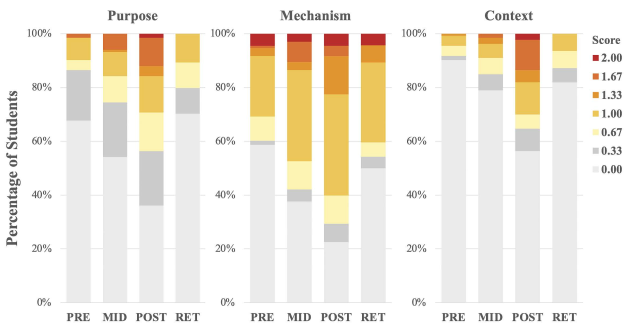

Fig. 5. Critical thinking dimension score distribution across pre-test (PRE), mid-test (MID), post-test (POST), and one-week retention (RET) rounds.

Nonparametric Friedman tests showed significant development across dimensions with small-to-moderate overall magnitudes, as shown in Table 4.

Table 4. Statistical test results for critical thinking across rounds

Dimension	Analysis	Stat.	ES[1]	Significant Changes[2]
Purpose	Main (N = 133)	51.32***	0.19	PRE < MID (0.62)*** MID < POST (0.51)*** PRE < POST (0.77)***
	Retention (N = 94)	37.03***	0.13	POST > RET (–0.50)***
Mechanism	Main (N = 133)	50.30***	0.19	PRE < MID (0.63)*** MID < POST (0.43)*** PRE < POST (0.75)***
	Retention (N = 94)	55.23***	0.20	POST > RET (–0.77)***
Context	Main (N = 133)	56.19***	0.21	PRE < MID (0.68)* MID < POST (0.71)*** PRE < POST (0.91)***
	Retention (N = 94)	24.22***	0.09	PRE < RET (0.81)* POST > RET (–0.52)

Note: [1] Kendall's W effect size.
[2] r_{rb} = rank-biserial correlation based on individual signed-rank tests.
An r_{rb} value presented without asterisks denotes a non-significant comparison. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. All p-values for *post hoc* comparisons were Holm-adjusted.

Friedman tests indicated significant development across dimensions with small-to-moderate overall magnitudes; Context showed the strongest PRE-POST change ($r_{rb} = 0.91$) and retained a significant gain ($r_{rb} = 0.81$), whereas Mechanism and Purpose gains were smaller during the hands-on phase and decayed at retention.

The dimension-specific trajectories reflect the differing cognitive demands of each reasoning type. During the online phase, all dimensions improved relatively uniformly ($r_{rb} = 0.62$–0.68) because scaffolded content addressed each explicitly without extraneous load. During hands-on collaboration, Context reasoning thrived ($r_{rb} = 0.71$) because practical considerations emerged naturally from design challenges. In contrast, Mechanism and Purpose reasoning showed limited gains because the simultaneous management of social coordination, physical manipulation, and formal concepts created competing cognitive demands. The differential retention, in which Context reasoning was maintained while technical details diminished, suggests that reasoning based on salient real-world concerns led to more durable memories than purely abstract technical reasoning.

The retention patterns revealed an important contrast in how different aspects of critical thinking were maintained. While all dimensions showed some decline from POST to RET, only the Context dimension maintained significant overall improvement from PRE to RET ($r_{rb} = 0.81$), albeit from an extremely low baseline. While this shows the intervention's effectiveness in developing previously minimal contextual thinking skills, the substantial gain may partially reflect this floor effect.

This pattern of development and retention differed notably from the conceptual understanding results, suggesting that while factual knowledge about COVID-19 remained stable, critical thinking abilities on this matter might require more consistent practice to maintain.

C. *Discussion*

The four-stage blended PBL module demonstrated effectiveness in promoting conceptual understanding while revealing complex, dimension-specific patterns in critical thinking development among secondary students engaged with COVID-19-related sciences.

Students achieved robust improvements ($d = 0.96$), substantially exceeding Xu *et al.*'s [10] meta-analytic benchmark of 0.69 for online learning interventions, with the online phase yielding the greatest single gain ($d = 0.54$), complemented by hands-on activities that reinforced knowledge ($d = 0.42$). Retention at one week indicated sustained mastery ($d = 0.97$), aligning with constructivist principles where knowledge is actively built through problem engagement [60]. The online component's adaptive design fostered self-paced engagement and multimedia learning, consistent with Warren *et al.*'s [61] observation that online platforms enable multiple mastery experiences through immediate feedback without performance pressure. Hands-on work enhanced practical application, aligning with Zheng *et al.*'s [62] finding that hands-on components contribute to knowledge integration but depend on adequate time and facilitation, though compressed timelines at some sites limited depth while still contributing to durable learning.

Critical thinking exhibited complex developmental patterns across the three measured dimensions (Purpose, Mechanism, and Context reasoning), with all dimensions showing statistically significant improvement (all $p < 0.001$) but varying considerably in extent and stability, fitting within Liu and Pásztor's [63] meta-analytic finding (ES = 0.64) that PBL enhances critical thinking though with smaller and more variable effects than for factual knowledge. The online phase fostered balanced growth across dimensions, supported by scaffolding and real-world contextual challenges [39]. Hands-on activities notably advanced Context reasoning (r_{rb} = 0.71), reflecting collaborative negotiation of practical considerations; however, Mechanism and Purpose gains were comparatively limited by competing cognitive and social demands during construction. This pattern aligns with Shehab and Nussbaum's [64] demonstration that complex learning environments requiring students to coordinate disparate elements in working memory can create cognitive overload that prevents the consolidation of technical reasoning. Simultaneous management of social coordination, physical manipulation, and conceptual understanding creates competing demands that constrain the development of technical reasoning [64].

Context reasoning demonstrated superior durability, maintaining significant gains post-intervention (r_{rb} = 0.81), while Mechanism and Purpose reasoning declined markedly (r_{rb} = −0.77 and −0.50, respectively), indicating differential stability among reasoning facets. Context reasoning's connection to salient public health implications likely contributed to stronger memory consolidation, whereas more technical reasoning proved susceptible to decay without reinforcement, consistent with Ramdani *et al.*'s [65] observation that inferential skills require ongoing engagement. Moreover, it aligns with Radvansky *et al.*'s [66] finding that application-oriented cognitive processes demonstrate enhanced durability compared with technical skills.

Regarding educational implications, sequencing is critical: online phases effectively build foundational knowledge and initiate multi-dimensional reasoning, while hands-on phases develop applied reasoning and collaborative skills but require explicit scaffolding for technical dimensions. To counteract the decline in Mechanism and Purpose reasoning, integrating reflective prompts and spaced practice during and after construction is advised.

D. Limitations of the Study

Nevertheless, several limitations warrant consideration when interpreting these findings. Adaptations were required due to eased public-health restrictions and tight school timetables. Although all sites followed the same four-stage sequence, used identical materials and assessment instruments, and maintained fidelity to core collaborative problem-solving activities, compressing multi-week plans to single-day or dual-period implementations in two schools could raise interpretive caution about time-on-task differentials and depth of engagement with the PBL process, particularly during critical thinking development [67].

The present study aggregated data across three school sites to maintain adequate statistical power. While this approach provided insight into overall intervention effects, future research with larger sample sizes per site could examine whether school context (urban, suburban, peri-urban) or the implementation schedule moderates learning outcomes in blended PBL implementations.

The sample size reduction between the post-test (N = 133) and the retention test (N = 94) creates challenges for comparing findings across test points and potentially introduces selection bias. In addition, the use of convenience sampling limits the extent to which findings can be generalised nationally. While the sample included schools of differing types and locations, results should be interpreted with caution and validated in larger, representative cohorts.

The critical thinking assessment rubric's limited scoring range (0–2 points) potentially masked nuanced progression in students' reasoning abilities, as noted by Liu and Pásztor [63] regarding common constraints in rubric-based assessments.

In addition, although the conceptual test was adapted from validated sources and reviewed by curriculum experts for alignment with Thai national standards, the absence of pilot psychometric testing and back-translation procedures limits the strength of the validity evidence. The streamlined three-dimensional rubric was chosen to ensure age-appropriateness and practical feasibility, but this inevitably reduced the breadth of Paul–Elder's complete framework and may have omitted subtler reasoning constructs. Despite these limitations, inter-rater reliability indices showed substantial agreement, providing confidence in the consistency of scoring. Future work should extend validation with pilot testing, back-translation, and expanded scoring scales.

Finally, the retention test was conducted after only one week, which limits conclusions about the long-term durability of learning outcomes. Longer retention intervals would be necessary to evaluate whether conceptual and reasoning gains persist across academic terms or transfer into other contexts.

V. Conclusion

This study demonstrates that carefully sequenced blended PBL can effectively promote both conceptual understanding and critical thinking in secondary science education, with differential effects across reasoning dimensions that inform instructional design. The findings reveal that online scaffolding optimally establishes knowledge foundations and initiates multi-dimensional reasoning, while collaborative construction preferentially advances contextual argumentation but requires targeted support for technical reasoning stability.

Theoretically, the current study contributes empirical evidence for phase-specific affordances in blended learning environments by extending the four-stage PBL framework to a blended, pandemic-focused secondary science context and by operationalising critical thinking as three complementary dimensions that can be examined longitudinally. Practically, for educators implementing crisis-responsive or socio-scientific curricula, these results suggest that sustainable reasoning development requires intentional progression from individual digital engagement to collaborative application, supplemented by explicit maintenance strategies for complex analytical skills. As educational systems continue adapting to technological integration and real-world problem contexts, especially in the field of pandemics, this research provides foundational insights for designing pedagogically coherent blended approaches that balance immediate learning gains with retention.

Future research should employ more sensitive measurement instruments with expanded scoring ranges to detect subtle changes in critical thinking development, implement consistent timelines across sites, and incorporate extended retention assessment periods to evaluate durability over meaningful educational intervals. The differential retention patterns observed suggest investigating whether they reflect temporary implementation effects or fundamental characteristics of blended PBL approaches for the development of technical reasoning.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

TP conducted the research, performed data analysis, and prepared the initial manuscript draft. PY and PC provided guidance, critical feedback, and support throughout the research process. All authors reviewed and approved the final version of the manuscript.

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