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Research Article

Beyond Mean Comparison: Assessing the Proportional Diostribution of Critical Thinking Mastery in Problem Based Learning on Pressure Concepts Using Chi-Square Analysis

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ABSTRACT

Purpose of the study: The study evaluates the effectiveness of Problem-Based Learning (PBL) in improving students' critical thinking mastery of pressure concepts by analyzing the proportional distribution of mastery rather than relying solely on mean score comparisons.

Methodology: A quasi-experimental pretest-posttest nonequivalent control group design was employed with 60 eighth-grade students selected through purposive sampling from intact classes. Students were assigned to a PBL group (n=30) or a conventional instruction group (n=30). Critical thinking was measured using a validated 10-item multiple-choice test adapted from Ennis's indicators. Baseline equivalence was tested with the Mann–Whitney U test, within-group mastery shifts with McNemar's test, and between-group distributional differences with the Chi-square test of independence. Reliability was confirmed (Cronbach's $\alpha = 0.86$).

Main Findings: The PBL group achieved a significantly higher mastery rate (83%) compared to the conventional group (60%), $\chi^2(1) = 4.02$, $p = 0.045$, with a moderate effect size (Cramer's $V = 0.26$). McNemar's test confirmed a statistically significant mastery transition within the PBL class ($p < 0.05$). The strongest gains occurred in analytical explanation and inferential reasoning dimensions.

Novelty/Originality of this study: Analyzing mastery distribution reveals equitable learning outcomes that mean comparisons obscure. The findings demonstrate that PBL systematically shifts categorical achievement toward competency thresholds, particularly in higher-order cognitive dimensions. In practice, this supports the adoption of distributional analysis in classroom assessment. The study's novelty lies in its methodological shift from continuous mean scoring to categorical mastery distribution, offering a more pedagogically relevant framework for evaluating instructional equity.

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1. INTRODUCTION

Critical thinking is a cornerstone of twenty-first-century science education, requiring students to engage in higher-order cognitive processes such as analysis, evaluation, interpretation, and inference [1]-[3]. In science contexts, these skills enable learners to connect theoretical principles with empirical phenomena, evaluate evidence-based claims, and draw logical conclusions [4], [5]. Despite its importance, international assessments consistently report suboptimal critical thinking performance among junior secondary students, highlighting a pressing need for instructional strategies that systematically cultivate these competencies [6], [7].

This underperformance is frequently linked to teacher-centered pedagogies that prioritize content delivery over active inquiry. Expository approaches often position students as passive recipients, limiting opportunities for scientific argumentation and reflective reasoning [8], [9]. Consequently, analytical and evaluative skills develop inadequately, while interpretation and inference remain under-practiced [10], [11]. To address this, instructional models that embed authentic problem-solving and collaborative inquiry are increasingly advocated [12], [13].

Problem-Based Learning (PBL) offers a structured framework where learning originates from contextualized problems, prompting students to identify variables, gather evidence, construct solutions, and reflect on outcomes [14], [15]. Empirical studies consistently report PBL's positive impact on critical thinking development [16]-[18]. However, the majority of these investigations rely on mean score comparisons or gain scores, which mask how learning outcomes are distributed across the student population [19]. A mastery-distribution approach provides a more equitable lens by examining the proportion of students who cross established competency thresholds, thereby revealing whether instructional interventions benefit the entire class or only a subset of high achievers.

The topic of pressure in matter exemplifies this need. Its conceptual complexity, particularly regarding the interplay between force and surface area across solid, liquid, and gaseous states, frequently triggers student misconceptions [20], [21]. These characteristics make pressure concepts highly suitable for PBL, as real-world contexts (e.g., hydraulic systems, footwear design, cutting tools) naturally stimulate analytical reasoning and evidence-based inference [22]. Yet, empirical research examining how PBL influences the categorical distribution of critical thinking mastery remains scarce, leaving questions about instructional equity and dimensional specificity unresolved.

Responding to this gap, the present study shifts the analytical focus from continuous mean scores to categorical mastery distribution using Chi-square analysis. By evaluating the proportion of students achieving minimum competency standards across five critical thinking indicators, this research provides a more nuanced assessment of instructional effectiveness. The study addresses the following research questions:

1. Is there a statistically significant association between instructional model (PBL vs. conventional) and the proportional distribution of critical thinking mastery?
2. Does PBL produce a significant within-group transition from non-mastery to mastery status?
3. Which specific critical thinking dimensions show the greatest proportional improvement under PBL?

2. RESEARCH METHOD

This study employed a quasi-experimental pretest–posttest nonequivalent control group design, appropriate for educational settings where individual randomization is impractical [23], [24]. Participants were 60 eighth-grade students selected through purposive sampling of two intact classes with comparable academic profiles at a public junior secondary school. Each class was assigned to either the experimental group (PBL, n=30) or the control group (conventional instruction, n=30). The sampling technique was chosen to preserve natural classroom dynamics while ensuring baseline academic comparability.

The overall research procedure is illustrated in Figure 1, and the experimental structure is presented in Table 1.

Table 1. Research Design.

Group	Pretest	Treatment	Posttest
Experimental	O_1	Problem Based Learning (PBL)	O_2
Control	O_1	Conventional Instruction	O_2

Independent Variable: Instructional model, operationalized as PBL (treatment) versus conventional teacher-centered instruction (control). Dependent Variable: Critical thinking mastery, measured categorically as mastery (score ≥ 75) or non-mastery (score <75), aligned with national curriculum standards. Dimensional mastery was analyzed across five indicators adapted from Ennis's critical thinking framework: (1) providing simple explanations, (2) building basic skills, (3) drawing conclusions, (4) providing further explanations, and (5) regulating strategies and tactics [25].

The assessment instrument was a 12-item multiple-choice test adapted from validated critical thinking indicators in science education [26]. Given the dichotomous scoring format (correct/incorrect), item validity was evaluated using point-biserial correlation. Items with coefficients ≥ 0.30 were retained; two items (0.21 and 0.16) were removed for low discrimination. The final 10-item instrument demonstrated strong internal consistency

(Cronbach's α = 0.86), confirming reliability for hypothesis testing. Homogeneity of variance was verified via Levene's test ($p > 0.05$ for pretest and posttest), satisfying parametric assumptions for subsequent analyses.

Data collection spanned three phases: (1) pretest administration to establish baseline equivalence, (2) instructional intervention over six sessions, and (3) posttest administration. The PBL group engaged in problem orientation, collaborative investigation, solution presentation, and reflection. The control group received direct instruction with guided practice and Q&A sessions. Data analysis was conducted using SPSS 26 and G*Power 3.1. Baseline equivalence was tested with the Mann–Whitney U test (nonparametric, robust to normality violations). Within-group mastery shifts were analyzed using McNemar's test for paired categorical data. Between-group distributional differences were examined via the Chi-square test of independence, with Cramer's V estimating effect size. A post-hoc power analysis confirmed adequate detection probability (power ≈ 0.74). Significance was set at $\alpha = 0.05$.

3. RESULTS AND DISCUSSION

Baseline equivalence analysis revealed no significant difference in pretest scores between groups ($p = 0.412$), confirming comparable initial critical thinking ability. Post-intervention data were analyzed to address the research questions.

Table 2 shows the posttest mastery distribution. A Chi-square test of independence yielded $\chi^2(1) = 4.02$, $p = 0.045$, with Cramer's V = 0.26, indicating a statistically significant and moderately strong association. The PBL group achieved an 83% mastery rate compared to 60% in the conventional group.

Table 2. Posttest Critical Thinking Mastery Distribution by Instructional Model

Class	Mastery (≥75)	Non-Mastery (<75)	Total
PBL	25 (83%)	5 (17%)	30
Conventional Class	18 (60%)	12 (40%)	30
Total	43	17	60

McNemar's test revealed a significant shift in the PBL class ($\chi^2 = 14.22$, $p < 0.05$), with 17 students transitioning from non-mastery to mastery. The conventional class showed no significant shift ($\chi^2 = 2.27$, $p > 0.05$). This confirms that PBL systematically promotes individual competency progression.

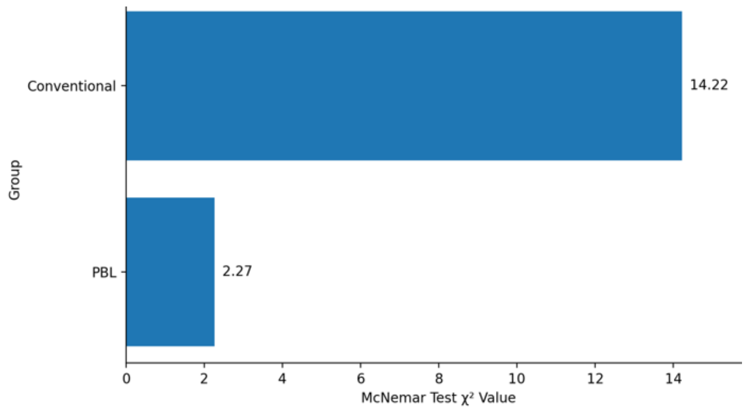

Figure 1. Comparison of McNemar χ^2 Values in the PBL and Conventional Classes

Chi-square analyses per indicator (Table 3) show that PBL significantly improved mastery in *providing simple explanations* ($p = 0.024$), *providing further explanations* ($p = 0.027$), and *regulating strategies and tactics* ($p = 0.024$). No significant differences emerged for foundational skills or conclusion drawing ($p > 0.05$).

Table 3. Mastery Distribution by Critical Thinking Indicator

Indicator	χ^2	p-value	Cramer's V
Providing Simple Explanation	5,11	0,024	0,29
Building Basic Skills	2,03	0,154	0,18
Drawing Conclusions	1,87	0,171	0,17
Providing Further Explanation	4,87	0,027	0,28
Regulating Strategies and Tactics	3,87	0,024	0,27

Sensitivity analysis across mastery thresholds (≥70, ≥75, ≥80) confirmed result stability at moderate cutoffs, strengthening internal validity (Table 3 in supplementary material). The findings confirm that PBL significantly alters the categorical distribution of critical thinking mastery, with 83% of students reaching competency thresholds compared to 60% under conventional instruction. This distributional advantage aligns with prior meta-analyses reporting PBL's efficacy in fostering higher-order cognition, but extends the literature by demonstrating that its impact is not merely additive (raising averages) but transformative (shifting categorical achievement). The moderate effect size (Cramer's V = 0.26) indicates pedagogically meaningful improvement, consistent with studies emphasizing PBL's role in promoting equitable learning outcomes [24].

The strongest gains occurred in analytical explanation and inferential reasoning dimensions. This pattern theoretically aligns with PBL's core mechanics: contextual problems require students to dissect variables, construct evidence-based arguments, and compare alternative solutions [27]-[34]. Conversely, foundational skills and conclusion drawing showed minimal proportional shifts, suggesting that procedural competencies may be equally developed through direct instruction, or that evaluative dimensions require extended scaffolding beyond the intervention period. These differential outcomes highlight that critical thinking development is multidimensional and non-uniform, reinforcing calls for indicator-specific assessment [35]-[39].

This study's primary novelty lies in shifting evaluation from mean comparisons to proportional mastery distribution. Mean-based analyses often obscure equity concerns by averaging out non-mastery cases. Distributional analysis, by contrast, reveals whether instructional models lift the entire cohort toward competency standards. This approach offers a more pragmatic framework for teachers and curriculum designers aiming to minimize achievement gaps [40]-[44].

Educators should integrate PBL not merely as an engagement strategy but as a structured vehicle for categorical competency attainment. Assessment practices should incorporate mastery distribution metrics alongside traditional scores to monitor instructional equity [45]-[48]. Policymakers and teacher trainers should emphasize PBL fidelity, particularly in scaffolding analytical and inferential tasks. The quasi-experimental design limits causal certainty despite baseline equivalence testing [49], [50]. Future studies should employ randomized designs or multilevel modeling to control for latent variables (e.g., motivation, prior knowledge). The single-school sample restricts external generalizability; cross-institutional replication is recommended. Additionally, post-hoc power (0.74) suggests larger samples would enhance detection sensitivity. Future research should also incorporate mixed-methods designs to capture qualitative shifts in student reasoning and examine long-term retention of critical thinking gains.

4. CONCLUSION

This study demonstrates that Problem-Based Learning significantly influences the proportional distribution of critical thinking mastery on pressure concepts, moving 83% of students to competency thresholds compared to 60% under conventional instruction. McNemar's test confirms meaningful individual progression within the PBL group, while indicator-level analysis reveals disproportionate gains in analytical and inferential dimensions. Theoretically, the study advances assessment methodology by validating mastery distribution analysis as a more equitable and pedagogically relevant alternative to mean score comparisons. Practically, it provides evidence that PBL systematically restructures classroom achievement patterns, supporting its integration into science curricula aimed at closing competency gaps. Future research should expand sample diversity, extend intervention duration, and employ multivariate models to isolate mechanisms driving mastery transitions.

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AUTHOR CONTRIBUTIONS

M., H.A., S.M.S., and K.W. conceptualized the study, designed the methodology, collected and analyzed data, and drafted the manuscript. All authors reviewed and approved the final version.

CONFLICTS OF INTEREST

The author(s) declare no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

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