

TechDiscovery Inquiry Cycle Enhances Hydraulics Achievement and Narrows Score Dispersion in Vocational Education

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Abstract: Heavy-equipment hydraulics requires vocational students to connect pressure-flow relationships, component functions, circuit behavior, and technical reasoning. This study examined the integration of the TechDiscovery Inquiry Cycle, hereafter TDIC, which links technology discovery, inquiry formulation, experimentation, evidence interpretation, reflection, and application. A quasi-experimental pretest-posttest comparison-group design involved 70 Grade XI students at SMKN 1 Singosari, Indonesia. One intact class received TDIC and one received the school's comparison instruction, with 35 students in each class. Cognitive achievement was measured before and after instruction. Because most score distributions departed from normality, the primary analyses used Wilcoxon signed-rank and Mann-Whitney *U* tests. The TDIC mean increased from 55.00 to 91.29; 34 of 35 students improved and none declined. Posttest ranks were also significantly higher for TDIC than for comparison instruction, with both inferential tests yielding *p* values below .001. Score dispersion decreased by 64.5 percent under TDIC compared with 31.7 percent in the comparison group, while the TDIC posttest minimum rose to 85. These findings indicate that TDIC was associated with higher cognitive attainment and a narrower distribution of achievement, a pattern described here as achievement convergence. Intact-class allocation, the single-school setting, and possible ceiling effects limit causal and generalizable conclusions.

Keywords: TechDiscovery Inquiry Cycle; vocational education; heavy-equipment hydraulics; inquiry-based learning; achievement convergence.

Abstrak: Pembelajaran sistem hidrolik alat berat menuntut siswa sekolah menengah kejuruan menghubungkan hubungan tekanan dan aliran, fungsi komponen, perilaku rangkaian, serta penalaran pemecahan masalah. Penelitian ini bertujuan menguji integrasi TechDiscovery Inquiry Cycle, selanjutnya disebut TDIC, sebagai siklus pembelajaran yang menghubungkan penemuan teknologi, perumusan inkuiri, eksperimen, interpretasi bukti, refleksi, dan aplikasi. Penelitian menggunakan desain kuasi eksperimen pretest-posttest dengan kelompok pembandingan dan melibatkan 70 siswa kelas XI di SMKN 1 Singosari, Indonesia. Satu kelas mengikuti TDIC dan satu kelas mengikuti pembelajaran pembandingan, masing-masing terdiri atas 35 siswa. Hasil belajar kognitif diukur sebelum dan sesudah pembelajaran. Karena sebagian besar distribusi skor tidak memenuhi asumsi normalitas, analisis utama menggunakan uji Wilcoxon signed-rank dan Mann-Whitney *U*. Rerata kelompok TDIC meningkat dari 55,00 menjadi 91,29; sebanyak 34 dari 35 siswa meningkat dan tidak ada siswa yang mengalami penurunan. Hasil posttest kelompok TDIC juga lebih tinggi secara signifikan daripada kelompok pembandingan. Simpangan baku skor TDIC menurun 64,5 persen, dibandingkan 31,7 persen pada kelompok pembandingan, sedangkan skor minimum posttest TDIC meningkat menjadi 85. Temuan ini menunjukkan bahwa TDIC berkaitan dengan capaian kognitif yang lebih tinggi sekaligus distribusi hasil belajar yang lebih sempit, suatu pola yang dalam penelitian ini dideskripsikan sebagai konvergensi hasil belajar. Generalisasi

temuan tetap dibatasi oleh penggunaan kelas utuh, satu sekolah, dan kemungkinan efek batas atas instrumen.

Kata Kunci: TechDiscovery Inquiry Cycle; pendidikan vokasi; sistem hidrolik alat berat; pembelajaran berbasis inkuiri; konvergensi hasil belajar.

INTRODUCTION

Hydraulic Learning Challenges

Hydraulic systems are foundational to excavators, loaders, cranes, and other heavy equipment, where pumps, valves, actuators, reservoirs, lines, and pressure-control devices operate as an interdependent system. Contemporary hydraulics is also moving toward energy-efficient architectures, sensor-supported condition monitoring, and electro-hydraulic control associated with Industry 4.0, which increases the conceptual and diagnostic demands placed on future technicians (Li et al., 2023; Tao et al., 2024; Xu et al., 2020). For vocational students, learning hydraulics therefore requires more than naming components or reproducing circuit symbols. Students must develop a causal model of how pressure and flow are generated, regulated, transmitted, and converted into motion, and they must connect that model to observable machine behavior. The instructional challenge is made more acute by the abstract nature of hydraulic transmission. Recent work on immersive hydraulic laboratories likewise identifies theoretical complexity and abstraction as persistent obstacles and reports improved learning when component, disassembly, and circuit representations are made interactive (Wei et al., 2026).

This technical structure creates a persistent representational problem. Pressure exists within closed lines, flow paths change with valve states, and a local fault can alter behavior elsewhere in the circuit. Students may consequently remember isolated definitions while failing to infer system-level consequences. Similar difficulties are reported in other engineering subjects in which invisible or abstract phenomena must be coordinated across symbolic, visual, and physical representations. Interactive visualization has been used to reduce cognitive barriers in semiconductor physics (Akyüz et al., 2026), augmented-reality-guided inquiry has improved understanding of distributed forces (Giancaspro et al., 2024), and conceptual-modeling interventions have been developed to help engineering students connect theoretical constructs with observable electrochemical phenomena (Orozco et al., 2022). These studies do not establish effects for hydraulics directly, but they converge on an instructional principle relevant to hydraulic learning: abstract engineering relationships become more learnable when students can inspect, manipulate, explain, and test representations rather than receive them only as finished descriptions.

A further challenge is the theory-practice divide. Technical education is expected to support transfer from classroom knowledge to workshop decisions, but transfer is unlikely when students have few opportunities to ask questions, manipulate equipment, observe consequences, and justify conclusions. Experimental platforms have been proposed for hydraulic and pneumatic instruction precisely to connect theoretical principles with observable behavior (Peng et al., 2024). Indonesian studies have reported improved hydraulic-system learning under discovery and inquiry-oriented approaches (Keliat & Wiyogo, 2021; Tadu et al., 2022). Comparable evidence in vocational and engineering contexts points in the same direction: inquiry-based simulation has been proposed for motor-control practical skills (Butsadi et al.,



2025), guided inquiry integrated with electronic design automation has been associated with learning and motivation gains in engineering education (Rifai et al., 2020), and experiment-centered electronics instruction emphasizes hands-on investigation as a route to conceptual and technical learning (Peter et al., 2024). The core problem is therefore not simply how to present more hydraulic information, but how to organize learning so that technological observation, inquiry, evidence, and application become parts of the same reasoning process.

Integrating Inquiry and Technology

Inquiry-based learning offers a relevant foundation because it shifts students from receiving final explanations to investigating questions and constructing warranted explanations. In a technical secondary school, black-box circuit investigations produced strong gains in conceptual understanding and application of circuit laws relative to lecture-based instruction (Abílio et al., 2026). In software engineering, a system that exposed students to multiple levels of inquiry produced stronger learning performance than a comparison application (Ahmed et al., 2025). Evidence from vocational education is also important: integrating inquiry and problem-based learning has been associated with increased student involvement (Rafiq et al., 2023), and a project-based inquiry model for electrical motor installation produced stronger technical, problem-solving, and collaborative outcomes than teacher-centered instruction (Simatupang et al., 2025). These findings support inquiry as a productive design principle, but they also show that inquiry is not a single method. Its effectiveness depends on how questions, guidance, experimentation, and reflection are sequenced.

Experience and technology add complementary affordances. Authentic hands-on simulations can support competence development when learners experience tasks as meaningful and self-directed (Khaled et al., 2014), while simulation-based experiential activities can make technical process relationships more visible and manipulable (Elbadawi et al., 2009). Recent reviews extend this logic to virtual laboratories and immersive environments. Virtual-laboratory research highlights the importance of combining technology with inquiry-oriented pedagogy rather than treating simulation as a substitute for instructional design (Anand & Tiwari, 2026; Budnyk et al., 2025; Hasibuan et al., 2025; Yindeemak et al., 2026). Collaborative virtual-reality research similarly suggests that immersive engineering environments can bridge theory and practice, although implementation cost, technical constraints, and pedagogical design remain important (Dunmoye et al., 2026). Digital twins and online engineering laboratories also show that virtual representations can support scientific inquiry, but hybrid arrangements may preserve more authentic learning than purely remote formats (Deniz et al., 2021; Ivanov et al., 2021; Olesen et al., 2022). A conceptual review of flipped learning in vocational education likewise suggests that active use of learning resources can support cognitive engagement, although outcomes depend on implementation (Zhou, 2023). Thus, digital technology is pedagogically useful when it enables students to inspect relationships, vary conditions, generate evidence, and connect virtual behavior with physical meaning.

The research problem addressed here emerges from fragmentation. Inquiry, experiential learning, questioning strategies, digital technology, and workshop practice are often implemented as separate pedagogical choices, yet complex technical reasoning requires them to work together. Scaffolding research suggests why



integration matters. Open-ended engineering tasks can overwhelm learners without structured support, whereas scaffolding can improve performance across different prior-achievement levels (Hughes et al., 2026). Inquiry behavior in interactive simulations also varies systematically among learners, implying that students need guidance that supports productive patterns rather than unrestricted exploration (Cock et al., 2025). Technology-enhanced inquiry studies likewise show benefits when collaborative annotation, structured systems, analytics, or other supports are deliberately aligned with inquiry goals (Chen et al., 2022; Chen et al., 2026). A learner confronted with a hydraulic malfunction must notice a phenomenon, ask what could explain it, propose a hypothesis, gather evidence, interpret the evidence, revise the explanation, and apply a decision. A learning model for technical reasoning should therefore integrate these actions into a coherent cycle rather than merely add disconnected active-learning elements.

The TechDiscovery Inquiry Cycle

In this study, the TechDiscovery Inquiry Cycle (TDIC) was implemented as a six-stage instructional sequence for heavy-equipment hydraulics. Technology Discovery starts with a hydraulic phenomenon, visual representation, or technical problem; Inquiry Formulation turns observations into investigable questions; Investigation and Experimentation generates practical observations or measurements; Data Analysis and Interpretation links these findings to causal explanations; Conclusion and Reflection makes students' evidence-based reasoning explicit; and Application and Skill Development connects explanations to vocational tasks. The operational sequence is illustrated in Figure 1.

This structure has several theoretical advantages. Questioning precedes explanation, creating an epistemic need for information. Experimentation then connects verbal and symbolic knowledge to observable consequences; data interpretation requires students to justify conclusions from evidence; reflection makes the reasoning process explicit; and application reconnects understanding to a vocational task. Such sequencing is consistent with experiential and inquiry-oriented work in engineering. Dynamic, interactive comparisons have been reported to improve comprehension particularly for learners with less prior knowledge in complex structural topics (Acican & Luyten, 2026). Take-home control-engineering laboratories provide repeated opportunities for experimentation and inquiry (Engmark et al., 2025), while student-designed laboratory work in tensile testing and heat transfer has been used to move learners beyond procedural compliance toward experiment design, interpretation, and engineering judgment (Johnson & Gurevich, 2025; Klehm et al., 2025). Inquiry-based biomedical engineering laboratories similarly emphasize design and troubleshooting as mechanisms for deeper appreciation of scientific process (Leo et al., 2025). TDIC draws on the same family of mechanisms but organizes them around a vocational technology-discovery cycle.

The model is particularly appropriate for hydraulics because a circuit can be represented at multiple levels: as a physical machine, a schematic, a simulated system, a set of measurements, and a causal explanation. Moving among these levels is a form of technical reasoning, not merely a change of media. Studies in engineering contexts caution that authentic or engineering framing does not automatically produce deeper conceptual learning if students attend to surface task features without connecting them to underlying science (Jiang et al., 2023). TDIC therefore makes evidence analysis



and reflection explicit rather than assuming that hands-on activity alone will generate conceptual understanding. This orientation also aligns with vocational efforts to connect school learning with authentic work contexts and competence development (Wahjusaputri & Bunyamin, 2022). Contextualized inquiry in vocational health education has been shown to improve conceptual understanding and reduce some initial differences between students (Fontana-Bria et al., 2025), while Indonesian vocational STEM modules that integrate theory, practice, experiment design, and technology illustrate the value of constructivist sequencing in local vocational settings (Azhari et al., 2023).

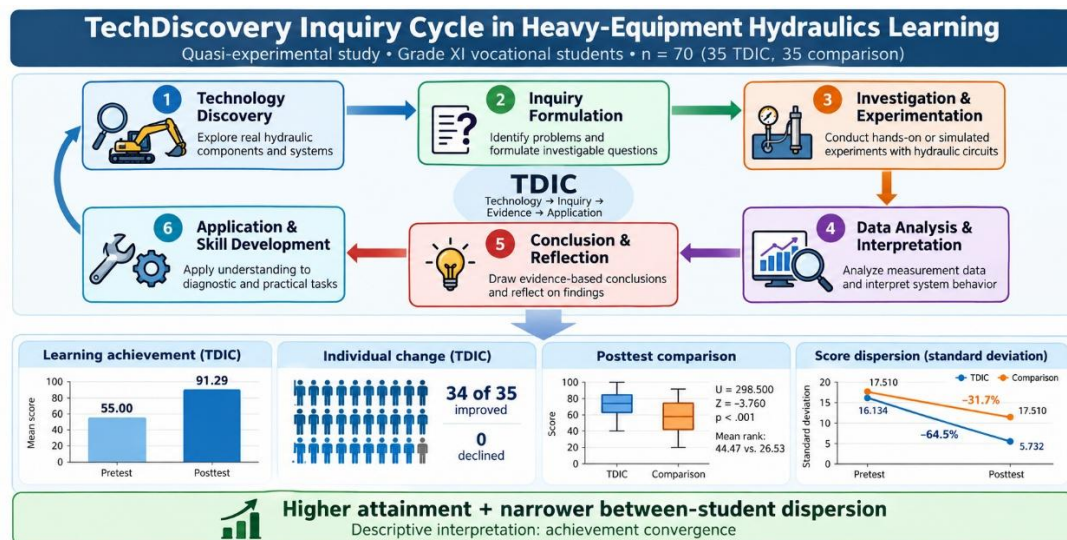


Figure 1. Operational sequence of the TechDiscovery Inquiry Cycle (TDIC)

Research Gap and Achievement Convergence

Many intervention studies in education emphasize whether a post-intervention mean is higher than a pre-intervention mean or whether one group has a higher average than another. Those comparisons are essential, but they can obscure a second issue that is especially important in vocational education: how competence is distributed across learners. A class may have a high average while retaining a subgroup with weak foundational understanding. Inquiry has been proposed not only as a route to performance but also as a way to reduce inequities in high-impact engineering and computing courses by incorporating learners' prior ideas, questions, and experiences into knowledge construction (Nath et al., 2023). Scaffolding evidence likewise indicates that structured support can improve engineering-design performance across academic levels rather than benefiting only high-achieving students (Hughes et al., 2026). For competence-based technical programs, these distributional questions matter because a high class mean cannot compensate for learners who remain below a functional threshold.

This study examines achievement as both a level and a distributional outcome. Achievement convergence is used descriptively to denote increasing attainment accompanied by decreasing between-student score dispersion; it is not proposed as a new psychometric index. The idea is related to variance reduction and achievement-gap reduction, but the present summaries cannot establish whether specific low-baseline subgroups benefited disproportionately. This distinction is consistent with

work on contextualized and interactive learning (Acican & Luyten, 2026; Chen et al., 2022; Fontana-Bria et al., 2025).

Research Questions and Hypotheses

This study examined the integration of TDIC in learning heavy-equipment hydraulic systems among Grade XI vocational students at SMKN 1 Singosari. The study addressed four questions: (1) how did learning outcomes change in the TDIC class; (2) how did learning outcomes change descriptively in the comparison class; (3) did posttest outcomes differ between TDIC and comparison instruction; and (4) did the two instructional conditions show different patterns of score dispersion?

Three hypotheses guided the analysis. H1 predicted that TDIC students would show significantly higher posttest than pretest achievement. H2 predicted that posttest achievement would be significantly higher in the TDIC group than in the comparison group. H3 predicted that TDIC would be associated with a stronger reduction in score dispersion, indicating greater convergence toward high achievement. The third hypothesis extends the usual effectiveness question by considering whether an intervention can raise attainment while simultaneously narrowing differences among students.

RESEARCH METHODS

Design and Participants

The study employed a quasi-experimental pretest-posttest comparison-group design at SMKN 1 Singosari, Malang Regency, East Java, Indonesia. Two intact Grade XI heavy-equipment classes participated: XI TAB 1 (TDIC; $n = 35$) and XI TAB 2 (comparison instruction; $n = 35$), giving 70 students in total. Table 1 identifies the instructional conditions. Individual assignment was not randomized, and scores were assessed on a 0–100 scale.

The TDIC and comparison classes had similar descriptive baseline means (55.00 and 54.86), but comparable averages are not evidence of equivalence. A baseline Mann–Whitney analysis and appropriate sensitivity models should be conducted from the original participant-level pretest scores before the manuscript is submitted; those records were not supplied with the materials evaluated here.

Study dates and research ethics. The study was conducted at SMKN 1 Singosari, Malang Regency, East Java, Indonesia, during the scheduled research period of January 26 to February 13, 2026. Research permission was requested through an official letter issued by the Faculty of Engineering, Universitas Negeri Malang (Letter No. 22.1.5/UN32.5.1/KM/2026, dated January 22, 2026). Permission to conduct the study was subsequently granted directly by the school administration without a separate written authorization letter. The research involved two intact Grade XI vocational classes participating in instructional activities related to heavy-equipment hydraulic systems.

Instructional Procedures

The experimental class followed six stages of TDIC. The following descriptions specify the documented learning functions of the stages rather than an assumed minute-by-minute implementation; a verified lesson plan is still required for replication.



Stage 1, Technology Discovery, introduced students to the hydraulic phenomenon or technical context. Learning resources could include system visualizations, digital representations, cases from heavy-equipment operation, and identification of component or circuit behavior. The purpose of this stage was to make the technological object of learning visible and problematic rather than beginning with a complete teacher explanation.

Stage 2, Inquiry Formulation, required students to transform observations into investigable questions and tentative hypotheses. In hydraulics, these questions can concern pressure behavior, flow direction, valve function, actuator response, or a possible source of system malfunction. The pedagogical function was to orient attention toward causal relationships that could subsequently be examined.

Stage 3, Investigation and Experimentation, engaged students in practical exploration, component testing, pressure-related observation or measurement, and analysis of hydraulic circuits. This stage provided the experiential bridge between a conceptual representation and physical system behavior.

Stage 4, Data Analysis and Interpretation, required students to examine observations and experimental evidence, compare expected and observed system behavior, and use technical reasoning to determine what the evidence implied.

Stage 5, Conclusion and Reflection, required evidence-based conclusions and reflection on the reasoning process. Students were expected to articulate not only what happened but why their evidence supported a particular interpretation.

Stage 6, Application and Skill Development, recontextualized the conclusion in a vocational task. Students applied their understanding to a realistic technical situation, with the broader aim of strengthening problem solving and readiness for later troubleshooting practice.

TDIC integrates inquiry-oriented teaching, initial questioning, experiential tasks, elements of the 5E cycle, scientific reasoning, hands-on activities, and technology-supported exploration. The six stages constitute the operational instructional sequence considered in this analysis.

The comparison class was described as receiving teacher explanation, question-and-answer activities, and limited demonstration. Although the instructional records also use the designation PBL, they do not establish implementation fidelity to a standard problem-based learning protocol; consequently, this paper uses the neutral term comparison instruction. The instructor assignment, instructional materials, exact number of meetings, teaching hours per meeting, and class-specific activity schedule require confirmation from the original teaching records.

Implementation dosage. The instructional intervention was implemented over four sessions, each lasting 180 minutes, resulting in a total instructional duration of 720 minutes (12 hours) per group. The experimental group ($n = 35$) received instruction through the six stages of the TechDiscovery Inquiry Cycle (TDIC): technology discovery, inquiry formulation, investigation and experimentation, data analysis and interpretation, conclusion and reflection, and application and skill development. The comparison group ($n = 35$) received conventional instruction over the same number of sessions and with an equivalent total instructional duration. Thus, both groups were allocated equal instructional time, allowing the study to compare cognitive achievement outcomes under two different instructional approaches without differences in the scheduled duration of instruction.



Cognitive Assessment

Cognitive achievement in heavy-equipment hydraulic systems was assessed using written pretests and posttests, with scores expressed on a scale ranging from 0 to 100. The assessments were administered before and after the instructional intervention to evaluate changes in students' cognitive learning outcomes. The original research documentation described the assessment instrument as validated; however, detailed evidence concerning item-level validity, internal consistency, and the distribution of perfect posttest scores was not available for independent verification. Accordingly, the psychometric properties of the instrument could not be fully evaluated, and this limitation should be considered when interpreting the findings.

Pretests preceded the instructional sequence and posttests followed it. The analysis reported here is based on the four sets of descriptive summaries, normality diagnostics, the TDIC paired Wilcoxon test, and the between-class posttest Mann–Whitney test. The individual-level data, original testing instruments, and detailed intervention logs were not included among the files available for revision.

Statistical Analysis

Analysis began with descriptive statistics: sample size, mean, standard deviation, minimum, and maximum scores for each group and measurement occasion. These statistics were used to describe both achievement level and score dispersion. In addition to raw mean gain, the percentage reduction in standard deviation from pretest to posttest was calculated as a descriptive index of convergence: Reduction in *SD* (%) = $[(SD_{pre} - SD_{post}) / SD_{pre}] \times 100$. This index is not an inferential statistic; it is used only to make the magnitude of dispersion change transparent.

Shapiro–Wilk diagnostics yielded $p = .047$ for TDIC pretest, $p < .001$ for TDIC posttest, $p = .291$ for comparison pretest and $p < .001$ for comparison posttest. Given the observed score distributions, the reported primary contrasts were nonparametric. These tests do not themselves establish baseline equivalence or rule out the effect of using two intact classes.

Within the TDIC class, the Wilcoxon signed-rank test evaluated paired pretest and posttest scores; the original statistical result included positive, negative and tied ranks, the standardized *Z* statistic and a two-sided *p* value. The reported rank descriptor was calculated as $r = |Z| / \sqrt{N}$, with $N = 35$ as used in the initial analysis.

The Mann–Whitney *U* test compared posttest ranks across the two classes. We report the original *U*, *Z* and *p* values, the rank-based $r = |Z| / \sqrt{70}$ descriptor, and an algebraically derived rank-biserial effect estimate of $1 - 2U/(35 \times 35)$, oriented so positive values favor TDIC. Student-level confidence intervals, covariate adjustment, and pairwise gain distributions require the authenticated raw scores and therefore are not reported here.

For H3, dispersion was summarized by the proportional change in within-class standard deviation and the observed score ranges. A formal posttest dispersion contrast (such as Fligner–Killeen or Levene's test), a ceiling-score frequency analysis, and the prespecified baseline-equivalence test all require the original score records. Thus, H3 is treated as a descriptive pattern rather than an inferentially established treatment effect.

Analyses still requiring authenticated data. Baseline Mann–Whitney *U*; posttest Fligner–Killeen/Levene sensitivity checks; ceiling-score frequency; item difficulty;



student-level effect-size uncertainty; and, if defensible, baseline-adjusted modeling. These are proposed analyses, not findings of the present report.

Table 1. Study design and instructional conditions

Feature	TDIC group	Comparison group
Class / sample	XI TAB 1; n = 35	XI TAB 2; n = 35
Design role	Experimental	Comparison
Instruction	Six-stage TDIC cycle	Teacher explanation, questions, limited demonstration; original PBL label unverified
Primary outcome	Cognitive pretest-posttest score	Cognitive pretest-posttest score
Setting	Heavy-equipment hydraulic systems, SMKN 1 Singosari	Heavy-equipment hydraulic systems, SMKN 1 Singosari

RESULTS AND DISCUSSION

Achievement Patterns

Before instruction, mean scores were almost identical: 55.00 ($SD = 16.134$; range 30–95) for TDIC and 54.86 ($SD = 17.510$; range 20–85) for comparison instruction. The baseline means differed by 0.14 points, but baseline equivalence was not tested. Table 2 reports the achievement summaries and available tests.

After instruction, both groups showed higher mean scores. The TDIC group increased by 36.29 points, from 55.00 to 91.29. The comparison group increased descriptively by 27.57 points, from 54.86 to 82.43. The posttest difference between groups was therefore 8.86 points. Figure 2 visualizes the pretest-posttest trajectories together with standard deviations. The greater vertical shift in the TDIC group is accompanied by a substantially shorter posttest variability bar.

The TDIC minimum increased from 30 to 85, with a posttest maximum of 100; by contrast, the comparison minimum increased from 20 to 35 and the posttest maximum was 95. These values suggest different lower tails, although aggregate minima cannot describe the full individual-level score distributions.

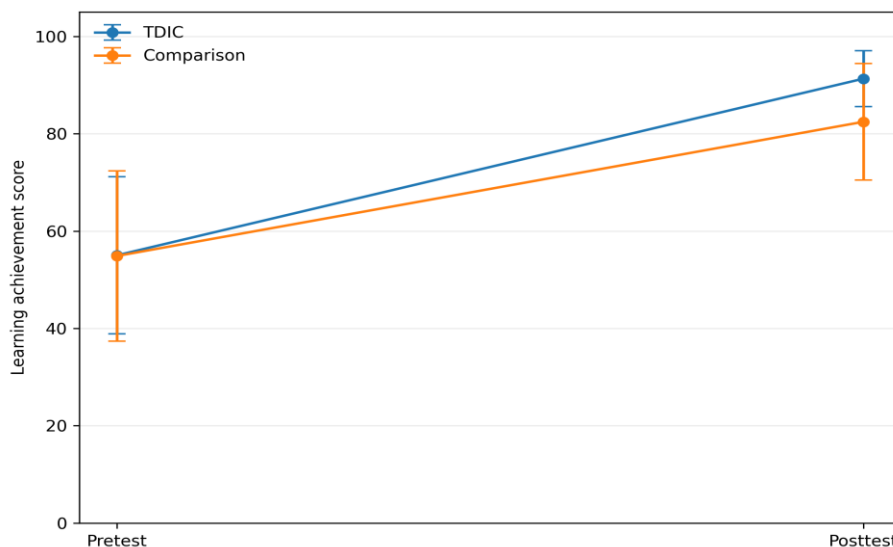


Figure 2. Pretest and posttest mean scores with standard-deviation error bars

Table 2. Learning outcomes and reported nonparametric statistics

Condition	Measure	Mean	SD	Min	Max	Inferential result
TDIC	Pretest	55.00	16.134	30	95	Wilcoxon paired: $Z = -5.097$, $p < .001$; 34 positive, 0 negative, 1 tie
TDIC	Posttest	91.29	5.732	85	100	
Comparison	Pretest	54.86	17.510	20	85	Posttest group comparison: $U = 298.500$, $Z = -3.760$, $p < .001$
Comparison	Posttest	82.43	11.966	35	95	

Nonparametric Findings

Three of the four assessed distributions had Shapiro–Wilk p values below .05 (TDIC pretest .047; TDIC posttest $< .001$; comparison posttest $< .001$); the comparison pretest did not ($p = .291$). Near-ceiling posttest scores in TDIC offer a plausible explanation for skewness, but normality diagnostics are not evidence of treatment effectiveness.

Importantly, departure from normality is not itself evidence that an instructional treatment was effective. It only describes the shape of the score distribution and informs the choice of statistical procedure. Effectiveness must be evaluated from the direction and magnitude of score changes and from the relevant hypothesis tests.

The Wilcoxon signed-rank analysis showed a highly consistent upward change in the experimental class. Of the 35 students, 34 had a higher posttest than pretest score, none had a lower posttest score, and one student was tied. Positive ranks therefore represented 97.1% of the class. The reported mean positive rank was 17.50 and the sum of positive ranks was 595.00.

The Wilcoxon analysis produced $Z = -5.097$, $p < .001$; 34 students improved, none declined and one tied. The reported $r = |Z|/\sqrt{35} = .862$ describes a strong standardized signed-rank contrast; it should not be interpreted as an independently estimated causal effect.

The consistency of individual change is pedagogically important. A mean gain can sometimes be produced by large gains among a subset of students while other students stagnate or decline. That pattern was not observed here: the rank table recorded no negative changes and only one tie. This finding supports the proposition that the intervention was associated with broadly distributed improvement across the class.

The Mann-Whitney U analysis compared the independent groups after instruction. The TDIC class had a mean rank of 44.47 and a sum of ranks of 1,556.50, whereas the comparison class had a mean rank of 26.53 and a sum of ranks of 928.50. The reported Mann-Whitney statistic was $U = 298.500$, with $W = 928.500$, $Z = -3.760$, and $p < .001$. The posttest score distributions therefore differed significantly, with ranks favoring the TDIC class.

The reported rank effect size was $r = |-3.760|/\sqrt{70} = .449$. From $U = 298.500$ and 35 observations per group, the rank-biserial effect favoring TDIC was approximately .513 ($1 - 597/1225$). This describes relative posttest rank dominance, not a covariate-adjusted impact; a confidence interval would require further information on the individual scores.

The Mann–Whitney result supports a distributional difference in posttest ranks, not the assertion that every TDIC student outperformed every comparison student. Because the score ranges overlap (TDIC 85–100; comparison 35–95), individual



outcomes cannot be reconstructed from the aggregate results. The subsequent dispersion profile is shown in Figure 3.

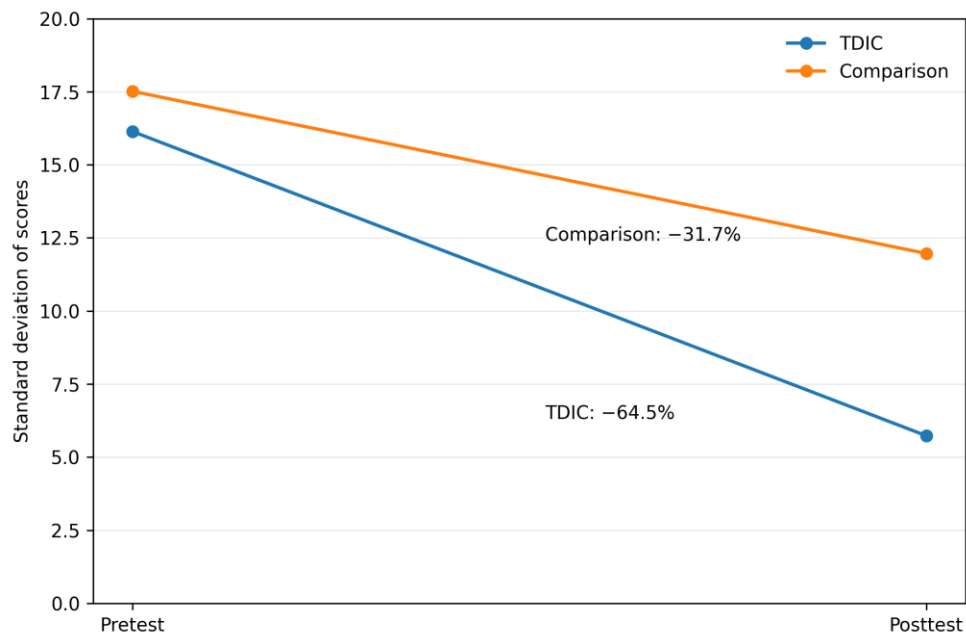


Figure 3. Reduction in score dispersion from pretest to posttest

Score Dispersion and Convergence

The most distinctive descriptive pattern concerns dispersion. In the TDIC group, the standard deviation decreased from 16.134 at pretest to 5.732 at posttest. This represents a 64.5% reduction in standard deviation. In the comparison group, standard deviation decreased from 17.510 to 11.966, a 31.7% reduction. Figure 3 illustrates the markedly stronger compression of variability under TDIC.

This result can be described as achievement convergence when interpreted jointly with the increase in the mean. A reduction in dispersion alone would not necessarily be desirable; scores could become more homogeneous at a low level. Here, however, lower dispersion occurred while the mean rose to 91.29 and the minimum rose to 85. The TDIC class therefore became both higher-achieving and more tightly clustered near the upper end of the scale.

The comparison group also improved and became less variable, but its final distribution remained broader. The posttest standard deviation of 11.966 was more than twice that of TDIC, and the minimum score remained at 35. This contrast suggests that the comparison instruction was associated with improvement that was less evenly distributed across students.

A bounded 0–100 assessment also creates a ceiling-risk interpretation: the TDIC mean was 91.29 and the maximum was 100. Without the raw number of perfect scores or item-difficulty statistics, reduced dispersion cannot be separated fully from upper-end score compression. Figure 4 juxtaposes minima, means and maxima without depicting an unobserved full distribution.

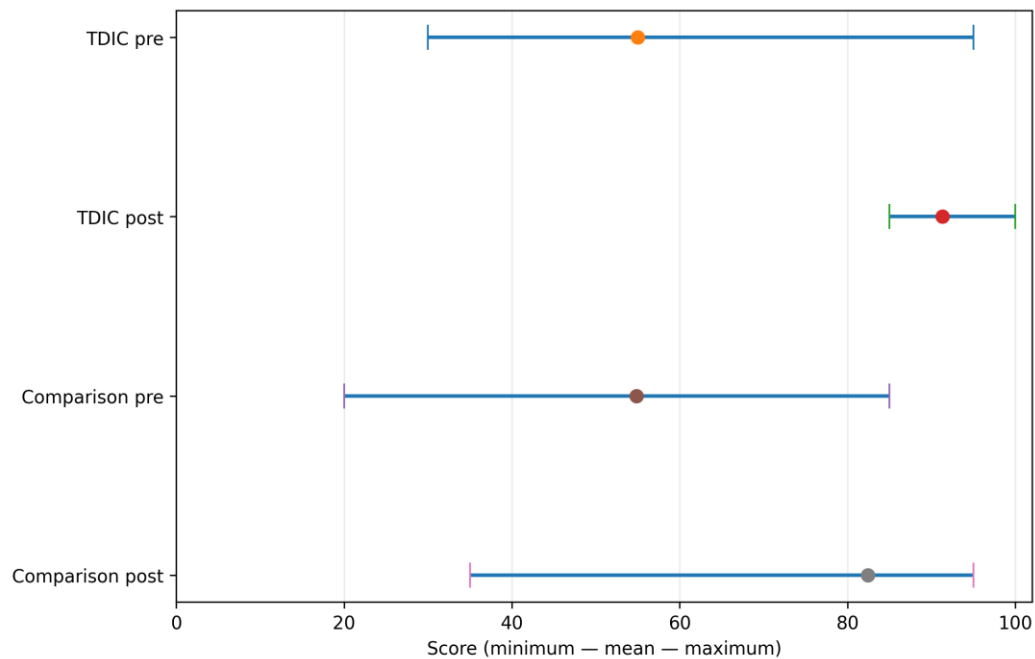


Figure 4. Minimum, mean, and maximum score profiles across groups and measurement occasions

H1 was supported by the paired TDIC result ($Z = -5.097, p < .001$; 34 increases, no declines). H2 was supported by posttest ranks favoring TDIC ($U = 298.500, Z = -3.760, p < .001$). H3 received descriptive support: the TDIC *SD* decreased by 64.5%, versus 31.7% in comparison instruction, but a raw-score variance test and explicit ceiling assessment remain necessary.

Interpretation and Implications

The central result is a class-wide upward shift rather than a mean increase alone. The TDIC mean rose by more than 36 points, 34 of 35 students improved, none declined, and the posttest distribution occupied a substantially higher region of the scale than the comparison class. Taken together, these observations are consistent with the proposition that sequencing technological discovery, questioning, investigation, evidence interpretation, reflection, and application can support conceptual learning in a technically demanding vocational subject. The design does not identify which stage caused the improvement, but it shows that the integrated sequence warrants further causal testing.

One reason TDIC may be effective is that it reorganizes when explanation occurs. In conventional exposition, students often receive the formal principle before encountering a problem that makes the principle necessary. TDIC reverses part of that sequence. Technology Discovery and Inquiry Formulation create an explanatory need; Investigation and Experimentation then provide evidence; and Data Analysis and Interpretation require students to connect that evidence to a conceptual account. This sequence is compatible with recent technical-education evidence. Black-box circuit inquiry enabled students to reason from observable outcomes toward electrical laws (Abílio et al., 2026), while guided inquiry with augmented reality improved engineering students' learning of distributed-force concepts (Giancaspro et al., 2024). In thermodynamics, a constructivist inquiry framework supported by generative AI was

associated with stronger conceptual understanding and fewer misconceptions than traditional instruction, although some quantitative misconceptions remained (El Fathi et al., 2025). Across these contexts, the common mechanism is not technology itself but the use of technology and evidence to make students' reasoning inspectable and revisable.

Hydraulics is especially suited to this logic. A pressure-control valve, cylinder, or directional circuit can be described symbolically, observed physically, represented digitally, and investigated through changes in system state. When those representations are coordinated, students can construct a more functional model of cause and effect. Experimental-platform work in hydraulic and pneumatic instruction emphasizes the value of linking theoretical knowledge to physical or simulated operation (Peng et al., 2024). More directly, an immersive hydraulic transmission laboratory that combined component, disassembly, and circuit modules reported substantially higher inquiry activity and test performance than traditional teaching among mechanical-engineering students (Wei et al., 2026). Indonesian studies on hydraulic systems have likewise reported positive outcomes from discovery and inquiry approaches (Keliat & Wiyogo, 2021; Tadu et al., 2022). The present study extends this line of work by testing a deliberately sequenced cycle in which discovery and experimentation are followed by evidence interpretation, reflection, and vocational application.

The observed effect should be attributed to the instructional package rather than to any single TDIC component. Question formulation may focus attention; hands-on investigation supplies concrete evidence; collaborative reasoning exposes alternative explanations; digital representations make otherwise hidden processes inspectable; reflection consolidates causal understanding; and application creates an opportunity for transfer. These mechanisms are theoretically complementary, but the present design does not isolate their individual contributions. TDIC should therefore be interpreted as an integrated treatment whose internal mechanisms remain to be experimentally decomposed.

This distinction is scientifically important because current literature supports several elements individually but does not establish that any one element explains the TDIC result. Inquiry can strengthen engagement and systematic reasoning in vocational settings (Rafiq et al., 2023), and combining inquiry with problem-based learning has produced gains in motivation and creativity relative to PBL alone in an engineering FEM course (Huang, 2026). Integrated pedagogical frameworks are increasingly being proposed for engineering and design education; for example, the EPIC model combines experiential, paired, inquiry-based, and collective learning to address Industry 5.0 skill demands (Ang & Domingo, 2025), while a BOPPPS-6E design integrates structured lesson architecture with inquiry and technology to reduce fragmented learning in interdisciplinary design (Hsu, 2026). These studies support the rationale for pedagogical integration, but they also caution against treating integration as inherently effective. The contribution of the present study is narrower: it provides initial empirical evidence that the specific TDIC package, as implemented in heavy-equipment hydraulics, was associated with a large achievement shift and lower score dispersion.

A useful future research program would therefore move from package evaluation to mechanism evaluation. For example, researchers could compare TDIC with a

condition that includes hands-on experimentation but not inquiry formulation, or with a condition that includes inquiry but not technology discovery. Process data could also examine which stages generate the most student explanation, conceptual conflict, or revision of hypotheses. Such work would clarify whether TDIC's value comes from the complete cycle, from one high-leverage stage, or from interactions among stages.

The Meaning of Convergence

The reduction in score dispersion provides a second contribution. Educational effectiveness is commonly summarized by changes in means, yet vocational programs also need to know whether instruction leaves a low-performing subgroup behind. In safety-sensitive and competence-based technical fields, a high class average can conceal students who have not reached foundational understanding. The TDIC group's posttest minimum of 85, together with a reduction in *SD* from 16.134 to 5.732, indicates that the observed improvement was not confined to the upper end of the class. This issue connects to broader work on participation and equity in engineering learning. Nath et al. (2023) argue for inquiry as a means of drawing learners' prior knowledge and questions into high-impact courses, and Hughes et al. (2026) found that structured scaffolding supported engineering-design performance across academic levels. The present study cannot identify which prior-achievement subgroup benefited most, but the upward movement of the minimum score makes distributional outcomes difficult to ignore.

We describe this pattern as achievement convergence: the simultaneous upward movement of performance and reduction of between-student dispersion. It should be distinguished from simple homogenization. If all students converged at a low score, the result would not represent instructional success. Here, lower dispersion occurred near a high mean and high minimum. Related studies suggest that structured, contextualized, or interactive instruction can sometimes support learners who begin with weaker knowledge. Dynamic comparisons in architecture structures education were particularly helpful for students with less prior knowledge (Acican & Luyten, 2026), a web-based inquiry environment with collaborative annotation showed greater benefits for students with low prior knowledge in some outcomes (Chen et al., 2022), and contextualized inquiry in vocational health education eliminated an initial gender difference observed at baseline (Fontana-Bria et al., 2025). These studies do not validate the specific convergence construct used here, but they provide a plausible educational context for examining whether active learning can improve not only central tendency but also the breadth of successful participation.

Several TDIC features could plausibly contribute to such convergence. First, the cycle provides multiple entry points into the same concept: a learner who struggles with verbal explanation may benefit from visual representation, manipulation, or measurement, while another may deepen initially procedural knowledge during interpretation and reflection. Second, inquiry questions expose misunderstandings before final assessment. Third, the cycle revisits the same causal relationship as phenomenon, hypothesis, experimental evidence, explanation, and application. Simulation research shows that inquiry behaviors can be stable and patterned across tasks, meaning some learners may require explicit support to engage productively (Cock et al., 2025). Scaffolding studies similarly show that open-ended engineering design benefits from structured supports (Chang, 2023; Hughes et al., 2026). TDIC



can therefore be interpreted as a structured inquiry architecture rather than an invitation to unguided discovery.

Nevertheless, the convergence interpretation requires caution. The test is bounded at 100, and the TDIC posttest mean was already 91.29. Scores concentrated near a maximum have less mathematical room to vary, creating potential ceiling compression. The strongest evidence against a purely mechanical ceiling explanation is the rise in the minimum from 30 to 85 and the near-universal pattern of positive ranks. Even so, future research should use more discriminating posttests, performance assessments, or item-response models to determine whether convergence persists when upper-end measurement is less constrained.

The comparison group also improved descriptively, from 54.86 to 82.43. This is important because the study is not a contrast between learning and no learning. Students in both classes received instruction, and both classes finished with higher means. The scientific question is therefore whether TDIC was associated with a different magnitude and distribution of achievement.

The comparator was designated PBL in some planning records but described through teacher explanation, questions and limited demonstration. This ambiguity cannot be resolved simply by relabeling the pedagogy: authentic PBL in mechanical-engineering laboratories has supported nontechnical skills (Sanchez-Gomez, 2022), and integrating inquiry with PBL has been linked to engagement or creativity outcomes in engineering and vocational education (Huang, 2026; Rafiq et al., 2023). Implementation protocols, teacher exposure and lesson fidelity are therefore needed to specify the treatment contrast. Our conclusions concern TDIC versus the observed comparison instruction, not an independently verified canonical PBL protocol.

Treatment precision strengthens rather than weakens the study. Labels such as “PBL,” “inquiry,” “active learning,” or “simulation-based learning” can conceal substantial differences in student agency, teacher guidance, task structure, and opportunities for evidence-based reasoning. Active-learning studies in engineering report positive outcomes across a range of designs, but the operative mechanisms differ by implementation (Reddy et al., 2024). Future TDIC trials should therefore report a treatment-fidelity matrix specifying lesson duration, teacher actions, student actions, technology used, physical equipment, questions posed, evidence collected, and assessment opportunities in each condition. Such documentation would make replication possible and would allow researchers to separate the effect of an integrated cycle from differences in instructional time, teacher attention, or resource exposure.

The statistical results are clear for the tests that were reported. The TDIC pretest-posttest comparison was significant at $p < .001$, and the posttest group comparison was also significant at $p < .001$. The rank effect-size descriptors calculated from the reported Z statistics were 0.862 for the paired TDIC change and 0.449 for the posttest between-group contrast. These values indicate that the observed differences were not merely statistically detectable; the rank shifts were substantial.

Practical meaning, however, should be expressed in the metric of the learning task. An 8.86-point difference in posttest means is directly interpretable on the reported 0-100 score scale. Even more striking is the difference in the lower boundary: the TDIC minimum was 85 compared with 35 in the comparison class. A single minimum is sensitive to individual cases and should not be overgeneralized, but in conjunction with the smaller SD it indicates a different class-level profile. For vocational



instructors, this profile may be more consequential than a p value because it speaks to how many learners may still require remediation before progressing to more complex technical tasks.

At the same time, causal language should remain proportional to the design. The classes were intact and were not reported as randomly assigned. Teacher effects, class culture, prior experiences, or other unmeasured differences may have contributed to the outcome. Similar pretest means reduce one obvious concern but do not eliminate all confounding. The data support a strong association between TDIC implementation and improved outcomes under the study conditions, while broader causal claims require replication with stronger allocation procedures or statistical controls based on student-level data.

For teachers, the findings suggest that inquiry in technical education should be designed as more than asking students to “discover” a principle without structure. TDIC provides a sequence that can be translated into lesson planning: begin with visible or simulated system behavior, elicit an investigable question, require a prediction, structure safe experimentation, ask students to interpret observations or measurements, and then require application to a different circuit or fault scenario. This sequence is consistent with laboratory innovations that place design and reasoning at the center of technical learning. Student-designed tensile testing has been used to deepen comprehension of material behavior (Klehm et al., 2025), inquiry-oriented heat-transfer laboratories emphasize hypothesis formation and experimental judgment (Johnson & Gurevich, 2025), and challenge-based inquiry laboratories ask engineering students to design and troubleshoot experimental procedures rather than follow recipes (Leo et al., 2025). TDIC adapts that logic to secondary vocational hydraulics while preserving teacher scaffolding.

For hydraulic-system instruction specifically, Technology Discovery can exploit the representational richness of the subject. A circuit schematic, cutaway component, digital simulation, pressure gauge, and machine behavior each offer a different view of the same causal system. The instructional goal is to help students move between these views and explain their correspondence. Digital and virtual laboratories are valuable when they enable repeated manipulation and feedback, especially where physical equipment is costly or access is limited (Anand & Tiwari, 2026; Hasibuan et al., 2025; Yindeemak et al., 2026). At the same time, evidence from digital-twin and live-lab research suggests that virtual environments are strongest when connected to authentic laboratory reasoning or physical experience rather than treated as ends in themselves (Deniz et al., 2021; Olesen et al., 2022). For TDIC, this implies a deliberate virtual-real progression: use digital visualization to make hidden hydraulic relationships inspectable, then connect those representations to measurements, components, or workshop cases.

The findings also align with broader vocational efforts to connect classroom learning to industrial relevance. Teaching-factory and competence-based models emphasize authenticity and alignment with workplace requirements (Wahjusaputri & Bunyamin, 2022). Vocational STEM modules in Indonesia have similarly combined theory, experiment design, technology use, and practical activity to support meaningful learning (Azhari et al., 2023), while project-based inquiry in electrical motor installation has been evaluated specifically for technical competence, problem solving, and collaboration (Simatupang et al., 2025). TDIC may complement such



models by supplying a micro-level reasoning cycle within larger workshop, teaching-factory, or work-based environments. It does not replace authentic practice; rather, it organizes how students observe, question, test, interpret, and act during that practice.

Priorities for Replication

Future studies should measure technical diagnosis, psychomotor performance, and transfer rather than inferring these outcomes from a cognitive test; delayed posttests would distinguish immediate attainment from retention.

Process indicators such as observation rubrics, task records and reflection quality would allow researchers to examine whether every TDIC stage operated as intended.

Larger samples across multiple schools, classes and teachers, with explicit comparison-group documentation, would improve causal and contextual inference. The present two-class design does not distinguish effects of the instructional package from possible class- or instructor-level differences.

To investigate convergence formally, raw-score analyses should include baseline-adjusted posttests, change-score distribution, ceiling frequencies, test difficulty, and robust variance comparisons. Authentic diagnostic tasks would also help determine whether cognitive improvements transfer to unfamiliar hydraulic problems.

TDIC also requires expert validation of its conceptual stages, operational rubrics and fidelity indicators. Integrated design frameworks have emphasized these alignments in experiential and inquiry principles (Ang & Domingo, 2025), structured technology-supported lessons (Hsu, 2026), and simulation-based technical inquiry (Butsadi et al., 2025).

Additional interpretive context is necessarily indirect: other instructional studies examine physics inquiry and vocational motor tasks (Abílio et al., 2026; Simatupang et al., 2025), while simulation and collaborative-inquiry research highlights the importance of structured questioning, learning paths and evidence use (Cock et al., 2025; Chen et al., 2022; Chen et al., 2026; Jiang et al., 2023). A vocational history intervention (Huang et al., 2026) offers a broader vocational comparator, not direct evidence concerning hydraulics.

Study Limitations

Several limitations define the scope of the conclusions. First, the research used two intact classes in one vocational school. Without individual random assignment, unmeasured class-level differences cannot be ruled out. The similarity of pretest means is encouraging but is not equivalent to randomization or comprehensive baseline balance.

Second, the principal outcome was a cognitive achievement test. The conceptual rationale for TDIC includes problem solving, technical diagnosis, hands-on competence, and industry readiness, but these outcomes were not directly quantified in the statistical results available for this manuscript. Claims about them should therefore remain theoretical or prospective.

Only aggregate summary statistics and selected nonparametric tests were available for the present revision. Individual data are necessary for baseline testing, confidence intervals, adjusted models, formal variance comparisons and distributions of change; none of these missing analyses is represented as completed.

Fourth, the TDIC posttest scores approached the upper boundary of the scale. The mean of 91.29 and maximum of 100 indicate a plausible ceiling effect, which may



partly contribute to the reduced standard deviation. Future assessment instruments should include sufficient upper-end difficulty to distinguish high-performing students.

The comparator was not documented sufficiently to identify a verified PBL protocol, and the original lesson timetable and fidelity logs were not available. Such implementation details are required for a fully replicable trial.

Finally, longer-term retention was not reported. Immediate posttest gains can differ from durable learning. Delayed assessment and transfer tasks should therefore be incorporated into subsequent TDIC evaluations.

CONCLUSION

The two intact Grade XI classes showed improvement in hydraulics achievement, with larger gains under TDIC. The TDIC mean rose from 55.00 to 91.29 (34 of 35 students improved), whereas the comparison mean rose from 54.86 to 82.43. The TDIC within-class Wilcoxon result ($Z = -5.097$, $p < .001$) and the between-class posttest Mann–Whitney result ($U = 298.500$, $Z = -3.760$, $p < .001$) support the corresponding rank-based comparisons.

Beyond higher average attainment, TDIC scores showed a 64.5% reduction in standard deviation, versus 31.7% under comparison instruction, with the TDIC posttest minimum rising to 85. This pattern is descriptively consistent with achievement convergence. However, ceiling compression, the nonrandomized two-class design and incomplete participant-level records preclude strong causal or subgroup-specific claims. The six-stage cycle merits replication with verified lesson protocols, calibrated assessments and formal dispersion tests.

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