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Original Article

Improving Undergraduate Science Education Students' Research Skills through STEM Learning Integrated with the Research Skill Development (RSD) Framework: A Quasi-Experimental Study

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Abstract: Research skills are an important competency in higher education, but various findings indicate that these skills are still developing unevenly among students. This study aims to examine the relationship between STEM-based science learning integrated with the Research Skill Development (RSD) framework and students' research skill achievement compared to conventional learning. The study used a quantitative approach with a quasi-experimental pretest–posttest control-group design involving 120 third-semester students in the science education study program at a university, who were divided into two experimental and two control classes. The experimental group received STEM learning structured according to the RSD stages and supported by a structured assessment rubric. In contrast, the control group followed the usual lecture-and-assignment-based learning practices. Data were collected using a research skills test developed in line with the RSD framework, then analyzed descriptively and inferentially using the Mann–Whitney U test. The pretest results showed no significant difference between the two groups ($p = 0.445$). In contrast, significant differences were found in posttest 1 ($p = 0.030$), posttest 2 ($p = 0.010$), and posttest 3 ($p = 0.011$), with the experimental group's average score increasing from 39.7 to 59.1 and the control group's from 37.1 to 54.7. These findings suggest a short-term performance advantage associated with STEM–RSD implementation, depending on the cohort and the instrument used.

Keywords :
Research skill development framework; Research-based learning; STEM curriculum integration; Science teacher education; Quasi-experimental study

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INTRODUCTION

Over the past decade, research competency has been increasingly recognized as a core graduate attribute in higher education. Nevertheless, the construct remains theoretically fragmented some scholars define research skills as procedural abilities in data collection and analysis, while others frame them as broader epistemic capacities involving problem formulation, methodological reasoning, critical interpretation, and independent knowledge production (Willison & Buisman-Pijlman, 2016; Winget & Persky, 2022). Consequently, claims about students' low research skills should be interpreted cautiously, as differing definitions shape measurement, pedagogy, and competence expectations. Thus, strengthening research skills requires not only assigning research tasks but also establishing a clear developmental framework that makes epistemic progression explicit.

STEM-based learning has been widely reported to foster critical thinking and evidence-based problem solving through interdisciplinary and authentic contexts (Fajrina *et al.*, 2020; Dare *et al.*, 2021). By integrating science, technology, engineering, and mathematics, STEM provides a rich environment for engaging with real-world problems that require analysis, design, and data-driven evaluation. Nevertheless, many implementations of STEM in higher education emphasize product development or contextual problem-solving without explicitly articulating how students' research competence develops across stages of increasing autonomy. As a result, students may engage in complex projects without systematically internalizing the epistemological principles underlying scientific inquiry.

In contrast, the Research Skill Development (RSD) framework conceptualizes research competence as a staged progression of cognitive responsibility and autonomy (Willison, 2018). Rather than a content model, RSD provides a developmental architecture guiding learners from structured inquiry to independent research design, implementation, and evaluation (Willison & O'Regan, 2007), making explicit the shift from instructor-directed procedures to student-owned methodological decision-making (Willison, 2018). While STEM supplies an authentic epistemic context, RSD clarifies how competence systematically develops within it, thereby bridging inquiry-rich environments and explicit developmental structuring (Willison, 2024). When STEM projects align with RSD autonomy levels, phases of problem identification, design, data collection, analysis, and interpretation become part of a measurable competence trajectory rather than isolated tasks (Torres, 2018). This integration reframes activity-based learning into competence-oriented learning through staged epistemic maturation (Willison, 2018; Willison, 2024).

Although STEM approaches have been widely adopted (Bybee, 2010; Kelley & Knowles, 2016) and RSD has been theoretically elaborated (Willison, 2018; Willison & O'Regan, 2007), empirical investigations that systematically examine STEM learning explicitly structured using RSD autonomy levels remain limited, particularly within quasi-experimental designs in science higher education (Torres, 2018). Existing studies tend to focus either on interdisciplinary integration (Vasquez, Sneider, & Comer, 2013) or on descriptive applications of RSD without rigorously evaluating their combined pedagogical effect (Brew, 2013). Consequently, it remains unclear whether embedding a structured research progression within STEM learning produces measurable differentiation in students' research competence compared to learning designs that do not incorporate such developmental architecture (Willison, 2018; Torres, 2018).

Based on this foundation, the present study compares research skills development between students engaged in STEM-based science learning explicitly structured by RSD levels and those experiencing conventional project-based learning without such integration (Torres, 2018; Willison, 2018). It examines students' ability to formulate research problems, design and justify methodologies, collect and analyze data, and interpret findings argumentatively (Willison & O'Regan, 2007). By emphasizing the structured transfer of epistemic responsibility from lecturer to student (Brew, 2013), the study aims to provide empirical evidence on the pedagogical value of integrating interdisciplinary problem contexts with staged autonomy in research development. staged research autonomy development (Kelley & Knowles, 2016; Willison, 2024).

METHOD

This study employed a quantitative approach with a quasi-experimental pretest–posttest control group design (Creswell, 2014; Shadish, Cook, & Campbell, 2002). The use of pre-existing classes (intact groups) precluded individual randomisation due to administrative limitations and the institution's academic structure (Fraenkel *et al*., 2012). To minimise potential selection bias, initial equivalence between groups was assessed using pretest scores collected before treatment (Campbell & Stanley, 1963; Shadish *et al*., 2002). The research design is shown in Table 1.

Table 1. design experiment (Creswell et al., 2012)

Class	Pretest	Treatment	Posstest
Experiment	P_1	Q_1	P_2
Control	P_1	Q1	P_2

Table 1 illustrates a pretest–posttest control group design (Creswell, 2012; Fraenkel *et al*., 2012), in which both experimental and control classes completed a pretest (P1) to assess initial ability prior to the intervention (Creswell, 2012). The experimental group then received the designated treatment (Q1), while the control group followed conventional instruction, and both groups subsequently undertook a posttest (P2) to measure learning outcomes and performance changes (Fraenkel, Wallen, & Hyun, 2012; Shadish *et al*., 2002). This design enables comparison while controlling baseline differences, thereby strengthening internal validity and supporting clearer evaluation of treatment effects (Campbell & Stanley, 1963). The population comprised all third-semester students in the Science Education Study Program at a state university in Indonesia, with a sample of 120 students across four classes two experimental and two control selected purposively based on curriculum uniformity, comparable learning outcomes, and similar academic backgrounds (Fraenkel *et al*., 2012).

Both groups engaged in project-based learning across the themes of environment, local wisdom, and sustainable technology; however, the experimental group received STEM-based instruction explicitly structured through the RSD framework (Willison & O'Regan, 2007; Willison, 2018), with each stage problem formulation, methodological design, data collection and analysis, and interpretation aligned to levels of research autonomy and supported by gradually reduced scaffolding to foster epistemic responsibility (Brew, 2013; Willison, 2018), whereas the control group completed similar projects without explicit STEM integration or systematic mapping of research autonomy, focusing primarily on task completion rather than articulated competency progression (Torres, 2018; Fraenkel *et al*., 2012; Willison, 2018; Willison, 2024). Research skills were measured using a case-based instrument grounded in RSD epistemic dimensions but employing a different context from the intervention to minimize bias, assessing six competencies problem formulation, information evaluation, methodological justification, data analysis and integration, evaluation of findings, and evidence-based argumentation with content validity established through expert judgment (five specialists), acceptable internal reliability (Cronbach's $\alpha > 0.70$), and exploratory factor analysis conducted to examine construct coherence.

A pretest was administered prior to the intervention to assess students' baseline research skills. Subsequently, three posttests were conducted sequentially after the completion of each thematic unit. These repeated posttests were intended to examine patterns of performance change across different topic contexts within a single semester, rather than to evaluate long-term retention. The study did not include a delayed posttest and, therefore, was not designed as a longitudinal investigation (Creswell & Creswell, 2018). The absence of long-term retention measures is acknowledged as a limitation. Descriptive statistics were employed to report the means and standard deviations of pretest and posttest scores, as recommended in educational research reporting (Field, 2018). The assumption of normality was examined using the Kolmogorov–Smirnov test (Ghasemi & Zahediasl, 2012). Because the data were not normally distributed, between-group comparisons were conducted using the nonparametric Mann–Whitney U test (Pallant, 2020). To control for the inflation of Type I error resulting from multiple posttest comparisons, a Bonferroni correction was applied, yielding an adjusted significance level of $\alpha = 0.017$ (0.05/3), consistent with established procedures for multiple testing adjustments (Armstrong, 2014).

Several limitations should be acknowledged. First, the use of pre-existing classes restricts causal inference, even though initial group equivalence was statistically examined, because random assignment was not feasible and uncontrolled contextual variables may have influenced the outcomes. Second, the absence of a STEM-only comparison group limits the ability to isolate the unique contribution of the RSD framework; therefore, the findings should be interpreted as evidence of the effectiveness of the integrated STEM–RSD design compared to conventional project-based learning, rather than as confirmation of the independent effect of each component. Third, without a delayed posttest, conclusions regarding the long-term sustainability and transferability of research skills remain tentative, as the study primarily captures short-term performance changes during the intervention period. In addition, the research relied mainly on performance-based assessments and did not directly measure underlying cognitive, metacognitive, or motivational processes that may have contributed to skill development. Despite these constraints, the study provides ecologically valid evidence derived from authentic classroom implementation, demonstrating the practical potential of systematically integrating research autonomy development within a cross-disciplinary STEM learning context and offering a foundation for further longitudinal and mechanism-focused investigations.

RESULT AND DISCUSSION

The descriptive results of the study present the mean scores and standard deviations for both the experimental and control groups, as summarized in Table 2. These statistics provide an overview of students' research skill performance at each measurement stage and illustrate the distribution and variability of scores within each group. The mean values indicate the general level of achievement, while the standard deviations reflect the extent of score dispersion, thereby offering an initial comparison of performance trends prior to further inferential analysis.

Table 2. Descriptive results of the average value and standard deviation

Test description	Score Average	Standard deviation
experimental class pretest	39,7	11,2
post-test 1 experimental class	49,7	11,9
post-test 2 experimental class	49,8	8,4
post-test 3 experimental class	59,1	8,0
control class pretest	37,1	10,0
posttest 1 control class	44,5	13,1
post-test 2 control class	46,1	9,5
post-test 3 control class	54,7	11,7

Table 2. compares the means and standard deviations of research skills between the experimental and control groups at the pretest and three posttests. The pretest results showed no statistically significant differences between the two groups, suggesting relatively equal initial abilities (Field, 2018; Pallant, 2020). However, this equivalence does not eliminate the possibility of confounding variables, such as prior experience in research methodology or variations in lecturer teaching styles, potentially influencing the development of research skills during the intervention (Creswell, 2012; Fraenkel *et al*., 2012; Shadish *et al*., 2002).

In posttest 1 (after the environmental unit), both groups improved from the pretest, with the experimental group showing a statistically higher gain than the control group (Field, 2018). However, effectiveness was interpreted not only from significance values but also from effect size (Cohen, 1988; Ellis, 2010). The small-to-moderate effect sizes suggest practically meaningful yet still preliminary impact, positioning posttest 1 as an early indication of performance differentiation rather than conclusive evidence (Hattie, 2009). In posttest 2, the experimental group's mean remained stable with lower standard deviation than the control group (Pallant, 2020). Although reduced variability may signal greater performance consistency, this should be interpreted cautiously, as lower dispersion does not necessarily indicate equitable outcomes and may be influenced by ceiling effects, topic complexity, or instrument sensitivity (Creswell, 2012; Fraenkel *et al*., 2012). Similarly, higher variati on in the control group does not inherently reflect ineffective learning but may indicate heterogeneous responses to a less-structured project approach (Shadish *et al*., 2002).

In the results of posttest 3, the experimental class's superiority was further evident, with consistently higher average scores and less variance compared to the control class, indicating that the treatment's effects are consistent and sustainable, not merely transient improvements (Willison, 2018). This finding suggests that STEM learning integrated with the RSD framework can help students develop research skills more deeply and systematically, resulting in more stable and equitable outcomes than conventional learning methods (Kelley & Knowles, 2016; Willison & O'Regan, 2007). Overall, the data pattern suggests that the experimental group tends to maintain a higher mean and a more consistent distribution of scores than the control group (Tabachnick & Fidell, 2019). However, interpretation of this pattern is limited by the lack of learning process data that could directly verify the mechanisms of skill improvement, such as the quality of scaffolding or student participation levels (Creswell, 2012). Results from the pretest and posttest analysis, as well as a comparison of changes in research skills between the experimental and control groups, are presented in Table 3, which shows the normality test for the pretest, posttest 1, posttest 2, and posttest 3 data (Field, 2018).

Table 3. Results of normality test

		Kolmogorov-Smirnov		
	Class	Statistic	df	Sig.
Score	experimental class pretest	.129	70	.005
	control class pretest	.164	68	.000
	post-test 1 experimental class	.079	70	.200*
	posttest 1 control class	.135	68	.004
	post-test 2 experimental class	.172	70	.000
	post-test 2 control class	.262	68	.000
	post-test 3 experimental class	.162	70	.000
	post-test 3 control class	.203	68	.000

The normality test results in Table 2 show that the pretest and posttest scores were not normally distributed in either the experimental or control class, except for the experimental class posttest data. However, because the control group data were not normally distributed, non-parametric analysis was applied. Accordingly, the Mann–Whitney U test was used to examine group differences. The results of the comparative analysis for the pretest, posttest 1, posttest 2, and posttest 3 are presented in Table 4.

Table 4. Results of the Mann-Whitney U Test

The data tested	Test	Sig.a.b
Pretest score	Mann Whitney U Test	.445
Posttest Score 1	Mann Whitney U Test	.030
Posttest Score 2	Mann Whitney U Test	.010
Posttest Score 3	Mann Whitney U Test	.011

The Independent-Samples Mann–Whitney U Test results indicate no significant difference between the experimental and control groups at the pretest stage ($p = 0.445 > 0.05$), suggesting equivalent initial research skills. Establishing baseline equivalence is essential in quasi-experimental research to ensure that post-intervention differences can be attributed to the treatment rather than pre-existing disparities (J. W. Creswell & Cresswell, 2017). In contrast, all three posttest stages showed significance values below 0.05 (posttest 1 = 0.030; posttest 2 = 0.010; posttest 3 = 0.011), indicating statistically significant differences after the intervention. These findings demonstrate that the instructional treatment in the experimental group had a meaningful effect on improving students' research skills.

The consistent significant differences through the third posttest suggest that the treatment effect was relatively sustained, supporting gradual and deeper internalization of research skills. Learning models emphasizing active engagement, authentic problem-solving, and explicit scientific reasoning are known to produce more stable skill development than conventional approaches (Freeman *et al*., 2014; Kruit *et al*., 2018; Lamb *et al*., 2015). The findings indicate that STEM-based science learning integrated with the Research Skills Development (RSD) framework is associated with improvements in students' research skills during the intervention, as reflected in pretest–posttest gains and consistent performance across research skill indicators (Willison & O'Regan, 2007; Willison, 2018). However, these gains represent short-term development and should not be interpreted as evidence of advanced proficiency or long-term impact.

Pedagogically, the STEM–RSD integration demonstrates coherence between an authentic problem-solving context and a systematic structure for the development of research skills. Learning activities that require students to formulate research questions, design investigative procedures, analyze empirical data, and independently communicate findings reflect the explicit implementation of RSD stages within a STEM project context. Consistent improvement in indicators of data analysis and interpretation of findings also indicates student engagement in higher-order thinking processes, as theoretically expected in a STEM approach (Dare *et al*., 2021; English, 2016). Thus, the quantitative findings demonstrating significant differences between groups, along with developmental patterns aligned with the intervention structure, provide sufficient empirical support for the contribution of STEM–RSD integration to students' research skill development over the course of a semester.

The success of this learning approach can be attributed to the nature of STEM learning, which actively engages students in building knowledge through real-world and contextual problem-solving experiences. By integrating science, technology, engineering, and mathematics into science instruction, students are encouraged not only to grasp theoretical concepts but also to apply them as practical tools for analyzing, evaluating, and improving solutions grounded in empirical data. This process is inherently linked to scientific research practices, providing ample space for the development of research skills, such as problem-solving, data collection and analysis, and evidence-based conclusions (English, 2016; Y. Li *et al*., 2020; Thibaut *et al*., 2018). STEM integration serves as a pedagogical appr oach and a means of cultivating systematic scientific thinking. Students in the experimental class showed a stronger tendency to link empirical data with theoretical concepts and to reflect on the research process.

One of the results of the student project in STEM integration is the smart bin and peanut hulling tool shown in Figure 1. The creation of this project reflects the students' active involvement in all stages of research skills structured through the RSD framework.

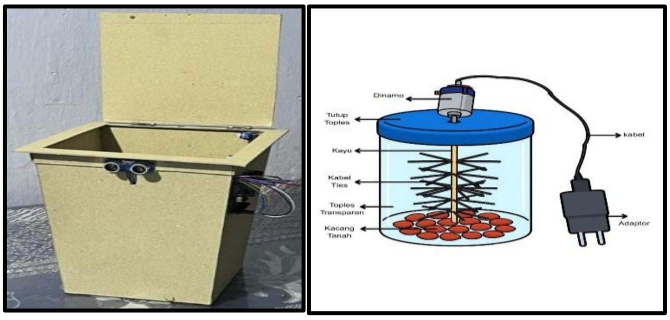

Figure 1. Results of STEM integration with the RSD framework in the learning process

In the initial stage, students identified contextual problems in their local environment, such as ineffective waste management and the manual peanut peeling process (Brundiers, Wiek, & Redman, 2010; UNESCO, 2017). These problems were formulated into operationally defined research questions and project objectives (Willison & O'Regan, 2007). These skills were assessed using a research skills rubric that included clarity of problem formulation, relevance of variables, and accuracy of objective formulation (Hafner & Hafner, 2003; Willison, 2018). Scores on the problem formulation indicator increased gradually from pretest to posttest, indicating development in research conceptualization skills (Torres, 2018).

In the discovery and information processing stage, students conduct literature reviews, collect field data, and integrate concepts from science, technology, engineering, and mathematics relevant to the project (Kelley & Knowles, 2016; Vasquez *et al*., 2013). In the innovative trash bin project, students integrate sensor concepts, simple programming logic, and mathematical calculations to design an automated sorting system (Bers, 2018; Sullivan & Heffernan, 2016). Meanwhile, in the peanut shelling tool project, students apply principles of mechanics and engineering design to improve the tool's efficiency and ergonomics (Crismond & Adams, 2012; Katehi, Pearson, & Feder, 2009). The development of analytical skills and concept integration is assessed through indicators of the methodological design's accuracy, the rationality of the selection of scientific principles, and the coherence between the data and the proposed solution (Willison & O'Regan, 2007; Willison, 2018).

The analysis synthesis phase, involving prototype testing, empirical evaluation, and iterative revision, led to improved data analysis and interpretation, reflecting evidence-based reasoning beyond product completion. Despite persistent variation particularly in synthesis and argumentation the experimental group showed higher means and lower deviations, indicating more consistent development. Within the RSD framework, project-based STEM learning functions as structured, rubric-aligned stages connecting problem identification, design, testing, and reflection to measur able research skill indicators

(Willison & O'Regan, 2007; Willison, 2018). Iterative design–test–evaluate cycles grounded in measurable data further strengthened systematic research management (Crismond & Adams, 2012; Katehi *et al*., 2009), as seen in variable testing and performance calculations in both projects (Bers, 2018; Sullivan & Heffernan, 2016; Mullis, 2018; Wicklein, 2006). Assessed through analytical rubrics emphasizing variable clarity, quantitative processing, argumentation, and design revision (Hafner & Hafner, 2003; Willison, 2018), the largest gains appeared in data analysis and justification, indicating evidence-informed decision-making (Willison & O'Regan, 2007; Torres, 2018).

Quantitative design and modelling activities in this context require students to explicitly test assumptions, compare measurement results with established success criteria, and justify design changes. The pattern of improvement in evaluation and synthesis indicators suggests that this iterative process correlates with the development of evidence-based reasoning skills. This finding is consistent with research reporting that engagement in engineering design and quantitative modelling can improve analytical skills and understanding of the relationship between theory and empirical data (Estapa & Tank, 2017; Guzey *et al*., 2016). The strengthening of research skills in this learning is supported by evidence of measurable improvements in students' abilities to design procedures, analyse test results, and systematically revise solutions.

In the analysis and synthesis stage, students repeatedly tested prototypes, evaluated tool performance based on quantitative data, and revised the design based on measurement results, with this iterative process documented in project reports that included cross-experiment comparisons, performance analyses, and data-based design justifications (Crismond & Adams, 2012; Kolodner *et al*., 2003). Assessment used an analytical rubric addressing accuracy of data interpretation, coherence between empirical findings and design revisions, and quality of synthesis in conclusions, with improved scores on evaluation and synthesis indicators indicating that students were increasingly able to integrate test results into systematic design decision-making (Hafner & Hafner, 2003; Willison, 2018). This finding aligns with literature suggesting that learning environments emphasizing reflection, feedback, and iterative improvement support the development of self-regulation and conceptual synthesis in scientific research contexts (Panadero, 2017; Schunk & Zimmerman, 2011; Winne, 2016).

However, in this study, this development was interpreted based on measurable evidence of academic performance rather than through specific psychometric instruments such as think-aloud protocols or structured reflection journals (Ericsson & Simon, 1993; Zimmerman, 2008). Furthermore, individual variation in achievement was still identified, particularly in depth of argumentation and consistency of data use as a basis for revision, suggesting that the effectiveness of the iterative process is not uniform and is likely influenced by student engagement and the quality of instructional feedback (Hattie & Timperley, 2007; Shute, 2008). Thus, while the STEM–RSD approach in this phase is supported by measurable improvements in data-driven analysis and revision skills, implications for the development of metacognition and learning independence are positioned as findings consistent with the theoretical framework but not claimed as directly verified results (Willison & O'Regan, 2007; Winne, 2016).

STEM learning structured through the RSD framework facilitates students' shift from procedural activity to deeper conceptual understanding by embedding collaborative inquiry, data-driven argumentation, and iterative design within explicitly staged research processes. Such collaborative and design-based approaches enhance scientific reasoning and evidence-based communication (Johnson & Johnson, 2018; Osborne, 2014; Volet *et al*., 2009). Within this structure, RSD functions as operational scaffolding that systematically guides planning, implementation, and evaluation, with each phase aligned to clear assessment indicators problem formulation, methodological rigor, data analysis quality, and argumentative coherence measured through rubric-based evaluation (Willison & O'Regan, 2007; Willison, 2018; Hafner & Hafner, 2003). Final presentations and reports further assess argument structure and theoretical integration (Willison, 2018), and improvements in communication and evidence-based justification scores indicate measurable gains in academic research performance (Torres, 2018). However, these gains represent observable performance development rather than direct evidence of metacognitive transformation verified through specialized psychological measures (Zimmerman, 2008; Winne, 2016).

Theoretically, the RSD framework clarifies stages and skill expectations across research phases, helping students view research as a set of competencies that can be developed progressively (Bandaranaike, 2018; Gyuris, 2018). An explicit research-skill framework also supports self-regulation and critical reflection in higher education (Visser-Wijnveen, van der Rijst, & van Driel, 2016; Zimbardi *et al*., 2013). In this study, this support is reflected in students' greater consistency in following research stages and aligning methodological decisions with research objectives (Willison, 2018). Nevertheless, framework clarity does not ensure uniform mastery, as individual differences persisted, influenced by prior ability, task complexity, and feedback quality (Hattie & Timperley, 2007; Shute, 2008). Thus, RSD is positioned here as a pedagogical structure that guides measurable research skill development rather than as the sole determinant of competence gains or direct evidence of psychometrically verified metacognitive growth (Winne, 2016; Zimmerman, 2008). Documentation of student research activities is presented in Figure 2.

Figure 2. Documentation of student activities during research implementation

It reinforces the argument that research skills are not optimally developed through instruction focused solely on imparting knowledge. It also highlights the need for a learning environment that encourages students to participate in authentic and meaningful scientific processes as shown in figure 3. STEM-based learning with an RSD framework provides learning experiences that mimic real-world experiences, enabling students to simultaneously "learn about research" and "learn through research." This approach is more effective in fostering academic confidence, research skills, and the ability to face future academic and professional challenges (Brew, 2013; Healey & Jenkins, 2009; Rodríguez *et al*., 2019) and the integration of research in learning enhances student agency, academic identity, and complex problem-solving capacity (Healey *et al*., 2014; Shanahan *et al*., 2015; Walkington, 2015). This effectiveness arises because students understand research procedures and directly experience the scientific decision-making process, resulting in a deeper and more sustainable internalization of research skills.

The findings show that score development in the experimental class was non-linear, with a plateau between posttest 1 (49.7) and posttest 2 (49.8), followed by a marked increase in posttest 3 (59.1). This pattern suggests a cumulative learning effect, where performance gains become visible only after consolidation of understanding rather than through steady incremental improvement. Such an interpretation aligns with perspectives that mastery of complex skills requires repeated practice, structured guidance, and sustained cognitive engagement in authentic tasks (Chi *et al*., 2014; Hmelo-Silver *et al*., 2007; Belland *et al*., 2017; Jong, 2019). Nevertheless, as this study did not directly measure cognitive mechanisms, adaptation processes, or transfer, this explanation remains theoretical rather than causal. Accordingly, the key contribution of this finding lies in identifying performance differences emerging at later implementation stages, providing a basis for further investigation into the dynamics of research skill development within RSD-based STEM learning.

The difference test

The results of the difference test indicate a statistically significant difference in research skills between students who participated in STEM-based science learning integrated with the Research Skill Development (RSD) framework and those who participated in conventional learning (Field, 2018; Pallant, 2020). Both groups showed increases from pretest to posttest, but the average increase in the experimental group was higher and more stable across the three post-intervention measurements (Willison, 2018; Torres, 2018). However, interpretation of these findings requires a proportional analysis, as the study did not report effect sizes or confidence intervals, so the magnitude of the impact and the practical relevance of the improvement cannot be comprehensively assessed (Cohen, 1988; Ellis, 2010). Furthermore, claims regarding the sustainability of improvements are limited to a single semester, with no long-term follow-up data (Creswell, 2012; Shadish *et al*., 2002). Improvements in the control group also indicate skill development, although not as significant on some indicators as in the experimental group (Fraenkel *et al*., 2012). These differences cannot be attributed solely to the learning model, as other factors, such as prior ability, studen t engagement, material complexity, and instructional dynamics, can also influence outcomes (Hattie & Timperley, 2007; Shute, 2008). Thus, the results of this study provide initial empirical support for the claim that STEM–RSD integration is associated with greater research skill gains in this context (Kelley & Knowles, 2016; Willison & O'Regan, 2007). Still, broader generalizations and causal claims require further analysis and longitudinal data to strengthen the validity and practical significance of the findings.

In the control group, project-based learning was still implemented, but without explicit integration of the STEM approach and the Research Skills Development (RSD) framework (Kelley & Knowles, 2016; Willison, 2018). Based on assessment using a research skills rubric, students in this group generally demonstrated adequate achievement in product completion, but relatively lower performance in indicators such as data-based problem formulation, methodological justification, and results synthesis (Hafner & Hafner, 2003; Torres, 2018). This suggests that project activities were more focused on completing the final artefact than on systematically developing the research process (Barron & Darling-Hammond, 2008; Thomas, 2000). However, this finding should not be interpreted as an inherent weakness of project-based learning, but rather as a difference in the level of emphasis and structure in the development of research skills (Blumenfeld *et al*., 1991; Kokotsaki, Menzies, & Wiggins, 2016). Variations in performance between individuals persisted, indicating that factors such as initial ability, motivation, and instructional guidance also contribute to student achievement (Hattie & Timperley, 2007; Shute, 2008).

This situation suggests that project activities alone are insufficient to develop in-depth research skills without being accompanied by a conceptual framework that explicitly guides students' research process. Without explicit scaffolding, students approached projects as a series of technical tasks, rather than as a scientific inquiry process that demands evidence-based decision-making. It aligns with the view that unstructured project-based learning has the potential to result in surface learning, where students mechanically grasp research steps but fail to develop in-depth conceptual and reflective understanding (Biggs *et al*., 2022; Chi *et al*., 2014). Learning projects without explicit scaffolding often make students oriented towards completing the final product, rather than on the process of scientific inquiry and evidence-based decision-making, so that the transfer of research skills is limited (Kirschner & Hendrick, 2024; Lazonder & Harmsen, 2016; Loyens *et al*., 2008).

In contrast, the experimental class engaged in STEM learning integrated with the RSD framework, explicitly aligned with targeted research skill stages and requiring authentic problem-solving through hypothesis formulation, data-driven decision-making, and argumentative interpretation. These processes were operationalized via rubric-based tasks emphasizing data analysis, synthesis, and justification of conclusions, with score increases on these indicators during the intervention (see Figure 4) reflecting performance development consistent with the learning demands. Conceptually, this design aligns with the ICAP framework, which posits that constructive and interactive engagement fosters deeper learning than merely active participation (Chi *et al*., 2014), and is supported by evidence that knowledge construction and collaborative interaction enhance conceptual understanding and highe r-order thinking (Freeman *et al*., 2014; Hernández *et al*., 2019;

Menekse *et al*., 2013). However, as the study inferred outcomes from performance gains rather than direct measures of cognitive or metacognitive processes, the findings are presented as empiric. As for how the score changes occurred during the research, it can be seen in Figure 3.

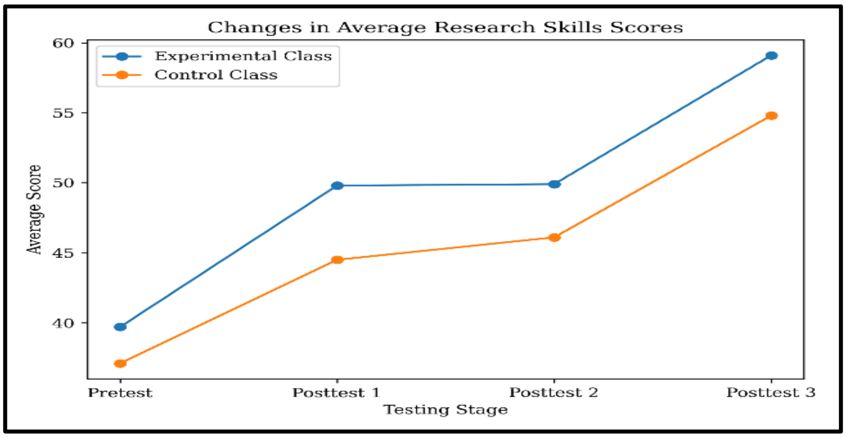

Figure 3. Changes in scores during the research

The pattern of increasing research skill scores demonstrated in the experimental class indicates changes in the quality of students' thinking processes. The steady increase in scores from the pretest to the third posttest indicates that students not only experienced short-term gains but also developed increasingly mature procedural and conceptual understanding. It aligns with the view that research skills are complex cognitive skills that develop through repeated engagement in authentic and reflective research cycles, rather than through linear exposure to material (Froyd *et al*., 2012; Schunk & Zimmerman, 2011).

The integration of STEM learning with the Research Skills Development (RSD) framework in this study was implemented through assessment indicators and rubrics that explicitly map the stages of problem formulation, methodology design, data analysis, and communication of research results. Based on this operationalization, the experimental class demonstrated more consistent score increases on the indicators of investigation, synthesis, and scientific argumentation than the control class, indicating a link between the more explicit structure of the research assignment and performance on instruments aligned with the RSD framework. Conceptually, this clarity of stages aligns with the theoretical view that scaffolding and structured guidance can support self-regulation in learning (Dignath & Veenman, 2021; Panadero, 2017); however, this study did not directly measure metacognitive awareness, student perceptions of research, or self-regulation processes through specific instruments such as surveys or interviews. Therefore, the findings presented are limited to observed performance differences based on rubric-based assessments, without extending claims to psychological constructs or cognitive processes that were not empirically measured.

In the control group, although scores increased, the more fluctuating pattern and relatively larger standard deviations indicated wider variation in achievement across individuals. Analysis of the score distributions showed that some students with high initial abilities continued to show good progress, while s tudents with lower initial abilities tended to experience more limited improvement in advanced indicators such as synthesis and data-based justification. This finding is not interpreted as an inherent weakness of conventional learning, but rather suggests that without explicit scaffolding of research skill stages, competency development can be uneven. This aligns with the literature, which emphasizes that learning without a clear-structure-risks producing procedural rather than conceptual understanding (Biggs *et al*., 2022; Dolmans & Loyens, 2016).

Intergroup differences were also evident in the data analysis and synthesis indicators, with students in the experimental class showing higher mean scores in linking empirical findings to theoretical frameworks and constructing evidence-based arguments. This improvement was interpreted as resulting from alignment between the learning design and the assessed skill indicators, rather than solely from the learning model itself. Conceptually, the role of scaffolding in supporting the development of problem-solving and self-directed learning has been widely supported in the literature (Hmelo-Silver *et al*., 2007; Willison, 2018); however, in this study, these implications were limited to evidence of improved written argumentation quality and consistent use of data in student reports.

Thus, the observed differences in research skill achievement between the two groups are more appropriately interpreted as reflecting variations in the degree of explicit structure, alignment, and coherence between learning activities and assessment indicators. The STEM–RSD integration was associated with more consistent improvements across targeted research skill dimensions, suggesting the value of a systematically designed autonomy-development framework. Nevertheless, causal claims should be made cautiously, as performance outcomes may also have been influenced by prior ability, classroom interaction patterns, and the quality and fidelity of instructional implementation.

CONCLUSION

Based on the results of this study, students in the STEM–RSD group achieved posttest scores that averaged 1.8 points higher than those in the conventional learning group on three immediate posttest measures, with statistically significant differences at each stage. Within the limits of the instrument used which was developed and aligned with the RSD framework this finding suggests a measurable performance advantage for the experimental group in this study. However, this study did not directly measure analytical thinking, data synthesis, or evidence-based decision-making as separate constructs, nor did it include transfer tasks, delayed posttests, or external validation. Therefore, interpretation of the results should be limited to the observed differences in scores and not extended to claims about the development of comprehensive research skills. Furthermore, although the control group showed lower improvements, the study design does not allow causal inferences attributing these differences solely to the learning model, as other factors, such as prior knowledge, motivation, and learning conditions, could also influence the results. Thus, these findings suggest short-term performance differences associated with the implementation of STEM–RSD in the studied cohort. At the same time, further research with broader measurement, longitudinal designs, and replication across contexts is needed before drawing stronger conclusions about i ts effectiveness and generalizability.

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