



Enhancing Scientific Communication and Problem-Solving Skills through PBL-Integrated Digital Comics in Physical Optics

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Abstract

This study investigated the effect of integrating digital comics into Problem-Based Learning (PBL) on students' scientific communication and problem-solving skills in physical optics. A quasi-experimental non-equivalent control group design was employed involving 52 senior high school students divided into an experimental group ($n = 29$) and a control group ($n = 23$). The experimental group learned through PBL supported by digital comics, whereas the control group received conventional PBL using printed worksheets. Scientific communication and problem-solving skills were measured using validated essay-based assessments administered before and after the intervention. The data were analyzed using Multivariate Analysis of Covariance (MANCOVA), followed by univariate ANCOVA to examine the effect of the instructional treatment while controlling for pretest scores. The results revealed a significant multivariate effect of the intervention on both dependent variables ($p < .05$). Students in the experimental group achieved significantly higher posttest scores in scientific communication and problem-solving than those in the control group. The integration of digital comics into PBL facilitated clearer scientific explanations, evidence-based argumentation, and more effective application of physical optics concepts to authentic problems. These findings demonstrate that PBL-integrated digital comics constitute an effective instructional strategy for enhancing higher-order thinking and scientific communication in physics learning, particularly when teaching abstract concepts such as physical optics.

Keywords: Digital comics; Problem-based learning; Problem solving; Scientific communication

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INTRODUCTION

One of the major global challenges in science education today is the persistent difficulty students face in developing scientific communication and problem-solving skills, competencies emphasized as essential for success in 21st-century learning (OECD, 2022; Khoviriza et al., 2024). Empirical studies in science classrooms highlight that learners often struggle to express scientific ideas clearly, construct logical arguments, and apply disciplinary concepts such as physics to authentic problems (Khoviriza et al., 2024; Sari et al., 2024). These difficulties are compounded by the ongoing digital transformation of education, which requires students not only to grasp scientific knowledge but also to communicate it effectively in multimodal forms (Rutalianisa & Ellianawati, 2026). Despite continuous investments in digital instructional tools, many learning environments remain dominated by traditional text-based materials that fail to engage learners or support deep cognitive processing. As a result, educators are actively seeking instructional strategies that combine digital interactivity with inquiry-oriented

pedagogies to enhance meaningful learning outcomes. Integrating digital comics into Problem-Based Learning (PBL) is emerging as a promising approach, as recent studies show that multimodal narrative media support deeper engagement, conceptual visualization, and problem engagement in science learning (Rutalianisa & Ellianawati, 2026; Marpaung et al., 2022).

Empirical evidence from classroom-based studies consistently shows that students' scientific communication and problem-solving skills in physics—especially in complex topics such as physical optics—remain below expected standards. Recent observations in instructional settings reveal that many learners are unable to express scientific ideas clearly, construct coherent explanations, or justify their reasoning using appropriate physics principles (Khoviriza et al., 2024; Sari et al., 2024). Similarly, empirical studies indicate that students often struggle to identify core problems, formulate solution strategies, and apply conceptual knowledge when confronted with optical phenomena, reflecting persistent weaknesses in higher-order physics competencies (Suwanto et al., 2022). Although Problem-Based Learning (PBL) has been widely implemented, research shows that conventional applications frequently fail to stimulate meaningful discourse because learning materials are dominated by dense textual descriptions that provide insufficient conceptual visualization (Marpaung et al., 2022). While several studies have investigated PBL and digital comics as separate interventions, empirical findings on the integration of both approaches remain limited, particularly regarding how multimodal narratives can enhance students' scientific communication and problem-solving performance within inquiry-based learning environments (Rutalianisa & Ellianawati, 2026). This empirical gap highlights the need to examine whether PBL-integrated digital comics can more effectively address students' learning difficulties in physical optics.

Although both Problem-Based Learning (PBL) and digital comics have been theoretically associated with improved cognitive engagement and conceptual understanding, the theoretical relationship between narrative-based visualization and scientific communication processes within inquiry learning remains underdeveloped. Contemporary learning theories—such as multimedia learning, dual coding, and social constructivism—explain how visual and verbal information support comprehension, yet they do not explicitly address how digital narrative comics operate as scaffolds for students' reasoning, argumentation, and communication during PBL problem-solving cycles (Mayer, 2021; Fiorella, 2023). Recent studies on multimodal science learning also highlight the promise of narrative visualization but emphasize that existing frameworks still lack a clear explanation of how multimodal texts shape students' discursive practices in inquiry-rich environments (Aditomo & Klieme, 2023; Rutalianisa & Ellianawati, 2026). Similarly, PBL theory underscores collaborative inquiry and authentic problem contexts but offers limited theoretical elaboration on the role of multimodal narrative media in supporting metacognitive monitoring and scientific communication within physics learning (Khoviriza et al., 2024). Consequently, a theoretical gap persists regarding how and why digital comics, when integrated into PBL, may strengthen learners' scientific communication and problem-solving skills—particularly in abstract physics topics such as physical optics. This gap underscores the need for theoretical refinement to bridge multimodal learning principles with inquiry-based instructional frameworks.

This study offers a novel contribution by integrating digital comics directly into the structured phases of Problem-Based Learning (PBL) to enhance students' scientific communication and problem-solving skills in physical optics. While prior studies have examined PBL and digital comics independently, current evidence shows that their combined pedagogical potential—especially in advancing discursive and analytical competencies—remains largely unexplored (Marpaung et al., 2022; Rutalianisa & Ellianawati, 2026). This study uniquely investigates how narrative visualization serves as both a cognitive and discursive scaffold within PBL cycles, enabling students to articulate explanations, construct arguments, and reason through optical problems more effectively. In contrast to earlier research that focused predominantly on motivation or conceptual understanding, this work introduces a

dual-outcome orientation—scientific communication and problem-solving—which has received limited empirical attention in multimodal PBL contexts (Khoviriza et al., 2024). Furthermore, the study contributes a theory-informed integration model that links multimodal learning principles with inquiry-based instruction, providing new empirical and theoretical insights into the role of narrative digital media in strengthening higher-order science competencies (Fiorella, 2023).

This study provides several important theoretical, practical, and methodological contributions to the field of science education. Theoretically, the study extends existing frameworks of Problem-Based Learning by integrating multimodal narrative principles through the use of digital comics, offering a deeper explanation of how visual storytelling supports scientific communication and reasoning within inquiry processes—an area receiving increasing attention in recent STEM education research (Fiorella, 2023; Lim & Hew, 2022). It also refines the understanding of dual coding mechanisms in problem-solving contexts by demonstrating how combined visual–verbal representations enhance students’ metacognitive regulation and argument construction, particularly in abstract physics topics such as physical optics (Khine & Areepattamannil, 2022). Practically, this research introduces an instructional model that teachers can readily implement, using digital comics as scaffolds throughout PBL phases to improve students’ communication and problem-solving performances. This approach provides an accessible, low-cost alternative for visualizing complex optical concepts while simultaneously increasing engagement, collaboration, and conceptual clarity, aligning with recent findings on the affordances of digital comics in science learning (Marpaung et al., 2022; Rutialianisa & Ellianawati, 2026). Methodologically, the study contributes by employing a quasi-experimental design to rigorously evaluate the effects of multimodal scaffolds within a PBL environment—an empirical gap noted in recent literature on inquiry and multimodal learning (Khoviriza et al., 2024). The use of dual outcome measures—scientific communication and problem-solving—and the application of robust statistical analyses further strengthen the reliability and generalizability of the findings. Collectively, these contributions offer a comprehensive model for integrating digital narrative media with inquiry-based learning and open new directions for future research in science education.

The rapid development of digital learning media has encouraged educators to integrate interactive technologies into science instruction. One promising medium is digital comics, which provide visual narratives that can simplify abstract scientific concepts and increase learner engagement. In science learning—especially in topics such as physical optics, which involve complex and often counterintuitive concepts—students frequently experience difficulties in communicating scientific ideas and solving conceptual problems. In addition, the Problem-Based Learning (PBL) approach has been widely recognized for promoting inquiry, collaboration, and problem-solving. However, PBL implementation often requires engaging materials to support students in exploring and discussing scientific problems. Integrating digital comics into the PBL framework is expected to strengthen students’ ability to construct explanations, communicate reasoning, and engage in deeper scientific discourse. Despite its potential, research combining digital comics and PBL specifically to improve scientific communication skills and problem-solving skills in physics—particularly in physical optics—remains limited. Therefore, this study aims to examine the impact of PBL-integrated digital comics on students’ scientific communication and problem-solving skills. The research question:

- (1) Does PBL-integrated digital comic learning significantly improve students’ scientific communication skills?
- (2) Does PBL-integrated digital comic learning significantly enhance students’ problem-solving skills in physical optics?

METHOD

Research Design

This study employed a quasi-experimental approach using a non-equivalent pretest–posttest control group design to investigate the effects of Problem-Based Learning (PBL) integrated with digital comics on students' scientific communication and problem-solving skills in physical optics. Two intact classes were assigned to the experimental and control groups without individual randomization. The experimental group received PBL instruction supported by digital comics developed using Pixton, whereas the control group participated in PBL instruction using conventional printed learning materials. Both groups followed the same instructional objectives, subject matter, and PBL stages, with the instructional media serving as the primary distinction between the two learning conditions. Pretests were administered before the intervention to assess students' initial competencies, while posttests were conducted after the instructional period to measure their scientific communication and problem-solving skills. The pretest scores were incorporated into the statistical analyses to account for differences in students' initial performance.

Participants

The participants consisted of 52 eleventh-grade students enrolled in a public senior high school in Indonesia. The study involved two existing classes, comprising 29 students in the experimental group and 23 students in the control group. Intact classes were used because the school's established classroom organization did not allow individual students to be reassigned. Both groups were selected from the same educational setting and participated in instruction covering identical physical optics content. Students' initial scientific communication and problem-solving skills were assessed through pretests administered before the instructional intervention. These baseline measurements were used as covariates in subsequent statistical analyses to control for potential differences in initial competencies between the groups.

Learning Intervention

The intervention was implemented over six instructional meetings covering physical optics concepts, including interference, diffraction, polarization, and optical instruments. Instruction in both groups followed five stages of Problem-Based Learning: problem orientation, investigation and information gathering, collaborative analysis and solution development, presentation of findings, and reflection and evaluation. The same instructional sequence was maintained across the experimental and control groups, while the learning materials differed according to the assigned treatment.

In the experimental group, digital comics developed using Pixton were integrated into the PBL activities. The comics incorporated contextual problems, scientific illustrations, visual narratives, and character-based dialogues related to physical optics phenomena. During problem orientation, students examined the comic scenarios to identify relevant scientific phenomena and formulate problems requiring investigation. During the investigation stage, students gathered information from the learning materials and other relevant sources to explore the underlying physics concepts. Collaborative analysis involved group discussions in which students interpreted information, applied physical optics principles, and developed possible solutions to the identified problems. During the presentation stage, students communicated their findings, explained their reasoning, and justified their solutions using scientific concepts and evidence. The final stage involved reflection and evaluation of the proposed solutions, including reviewing scientific explanations and considering alternative approaches.

The control group participated in the same PBL stages using conventional printed learning materials and worksheets without digital comics. The printed materials presented physical optics problems and guided students through investigation, collaborative discussion, solution development, presentation, and reflection. Both groups followed equivalent instructional stages and covered the same subject matter, allowing the instructional media to

function as the main distinction between the learning conditions.

Research Instruments

Two assessment instruments were used to measure the dependent variables: a scientific communication performance rubric and an open-ended problem-solving test. The instruments were developed or adapted to correspond with the instructional objectives and competencies addressed in physical optics learning. Assessments were administered before and after the instructional intervention using established scoring criteria.

Scientific communication skills were assessed using a performance-based rubric adapted from scientific communication competency frameworks. The rubric evaluated five dimensions: accuracy of scientific explanations, appropriate use of scientific terminology, organization and coherence of ideas, evidence-based argumentation, and clarity of presentation. Each dimension was rated on a four-point scale ranging from 1 (Beginning) to 4 (Excellent). Students' communication skills were assessed through their explanations of scientific problems, presentation of proposed solutions, and participation in scientific discussions. Two independent raters evaluated student performance using the same rubric. Inter-rater reliability was assessed using the intraclass correlation coefficient (ICC) to examine agreement between the raters.

Problem-solving skills were measured using eight open-ended questions addressing concepts and applications of physical optics. The questions assessed students' abilities to identify scientific problems, analyze relevant information, apply appropriate physics principles, perform mathematical reasoning, evaluate alternative solutions, and justify their conclusions. Each question was evaluated using an analytical scoring rubric with a maximum score of five points. The scoring criteria considered the appropriateness of the problem-solving procedures, the accuracy of conceptual and mathematical reasoning, and the justification provided for the proposed solutions.

The instruments underwent content validation involving three experts in physics education and science education. The validation process focused on the relevance of assessment indicators, alignment with the intended competencies, clarity of instructions, appropriateness of the scoring rubrics, and suitability of the physical optics content. Item validity was examined using Pearson product-moment correlations, while internal consistency was evaluated using Cronbach's alpha. Item difficulty and discrimination indices were also examined as part of the instrument evaluation procedure. For the scientific communication rubric, inter-rater reliability was assessed using the ICC.

Data collection was conducted in three main phases. The first phase involved administering pretests to assess students' initial scientific communication and problem-solving skills. The second phase consisted of implementing the instructional intervention across six meetings in the experimental and control groups. The third phase involved administering posttests to assess students' competencies following the instructional activities. Scientific communication performance was evaluated using the established assessment rubric, while responses to the problem-solving test were scored according to the analytical scoring criteria. The assessment scores were subsequently organized and prepared for statistical analysis.

Data Analysis

Data analysis was conducted using descriptive and inferential statistical procedures with IBM SPSS Statistics. Descriptive statistics, including means, standard deviations, minimum scores, and maximum scores, were calculated for the pretest and posttest measurements of scientific communication and problem-solving skills in both groups. These statistics were used to describe the distribution and characteristics of students' assessment scores.

Before conducting inferential analyses, the assumptions underlying the statistical models were examined. The Shapiro-Wilk test was used to assess normality, while Levene's test was employed to examine the homogeneity of variances between groups. Box's M test was used to evaluate the equality of covariance matrices for multivariate analysis. The relationships

between covariates and dependent variables were also examined, including assessments of linearity and homogeneity of regression slopes. The latter was evaluated by testing interactions between treatment group and the corresponding pretest covariates.

Multivariate Analysis of Covariance (MANCOVA) was used to examine the effect of instructional treatment on scientific communication and problem-solving posttest scores simultaneously, with the corresponding pretest scores included as covariates. The multivariate group effect was assessed using Wilks' lambda (Λ). Outcome-specific analyses were subsequently performed to examine differences between the experimental and control groups for each dependent variable.

Analysis of Covariance (ANCOVA) was specified to evaluate between-group differences in scientific communication posttest scores while controlling for scientific communication and problem-solving pretest scores. For problem-solving skills, a moderated multiple regression approach was used to examine the relationship between treatment group, initial problem-solving performance, and posttest outcomes. The regression model included treatment group, mean-centered problem-solving pretest scores, mean-centered scientific communication pretest scores, and the interaction between treatment group and problem-solving pretest scores. Mean-centering was applied to the continuous predictors before constructing the interaction term. Simple slopes analysis was used to examine the relationship between initial and final problem-solving performance within each instructional group.

Effect sizes for MANCOVA and ANCOVA were expressed using partial eta squared (η^2_p), with conventional reference values of 0.01, 0.06, and 0.14 representing small, medium, and large effects, respectively. Cohen's *d* was calculated using the difference between group means divided by the pooled standard deviation to quantify standardized between-group differences in observed posttest scores. For the regression analysis, unstandardized coefficients (*B*), standard errors (*SE*), *t* statistics, coefficients of determination (R^2), and adjusted R^2 values were reported. Statistical significance was evaluated at an alpha level of 0.05 for all hypothesis tests.

RESULTS AND DISCUSSION

Descriptive Statistics

The descriptive analysis provides an overview of students' scientific communication and problem-solving skills before and after the instructional intervention. Pretest and posttest scores were examined for both the experimental group, which received Problem-Based Learning (PBL) integrated with digital comics, and the control group, which participated in PBL supported by conventional printed materials. The analysis included measures of central tendency and variability to characterize students' performance across the two learning conditions. Table 1 presents the descriptive statistics for both dependent variables.

Table 1. Descriptive Statistics of Scientific Communication and Problem-Solving Scores by Group

Variable	Group	n	Mean	SD	Min	Max
SC – Pretest	Experimental	29	60.86	12.29	30	78
	Control	23	59.96	13.63	30	86
SC – Posttest	Experimental	29	84.34	5.68	70	92
	Control	23	68.87	9.00	50	85
PS – Pretest	Experimental	29	62.28	11.24	40	86
	Control	23	56.65	14.80	29	85
PS – Posttest	Experimental	29	81.93	6.56	69	94
	Control	23	67.48	9.61	50	85

Note. SC = scientific communication; PS = problem-solving; n = sample size; SD = standard deviation; Min = minimum score; Max = maximum score. Higher scores indicate better performance.

As presented in Table 1, the experimental and control groups had similar mean scientific communication pretest scores of 60.86 and 59.96, respectively, representing an initial difference of 0.90 points. Following the intervention, the experimental group's mean increased

to 84.34, whereas the control group's mean reached 68.87. The corresponding mean increases were 23.48 and 8.91 points, respectively. The observed posttest difference between groups was 15.47 points. In addition, the experimental group's standard deviation decreased from 12.29 at pretest to 5.68 at posttest, while the control group's standard deviation decreased from 13.63 to 9.00. These descriptive patterns indicate greater mean improvement and lower posttest score variability in the experimental group.

A similar pattern was observed for problem-solving skills, although the groups differed more noticeably at baseline. The experimental group obtained a pretest mean of 62.28, compared with 56.65 in the control group. At posttest, the experimental group's mean increased to 81.93, while the control group's mean reached 67.48. The corresponding mean increases were 19.65 and 10.83 points, producing an observed posttest difference of 14.45 points. The experimental group also exhibited a smaller posttest standard deviation of 6.56 compared with 9.61 in the control group. Although these descriptive results favor the experimental group, the initial differences in problem-solving performance require consideration when evaluating between-group differences through inferential analyses.

Assumption Testing

Before examining the treatment effects, statistical assumption tests were evaluated to determine the suitability of the multivariate and outcome-specific analyses. The assessment included normality, homogeneity of variances, equality of covariance matrices, and homogeneity of regression slopes. Particular attention was given to the interactions between instructional group and pretest covariates because these relationships are relevant to the interpretation of covariance-adjusted comparisons. The results of the assumption tests are summarized in Table 2.

Table 2. Assumption Tests for MANCOVA and Follow-Up Analyses

Assumption	Test/Interaction	Statistic	p	Decision
Normality	SC Pretest – Experimental	W = .919	.028	Violation
	SC Pretest – Control	W = .987	.988	Satisfied
	SC Posttest – Experimental	W = .888	.005	Violation
	SC Posttest – Control	W = .955	.374	Satisfied
	PS Pretest – Experimental	W = .964	.417	Satisfied
	PS Pretest – Control	W = .968	.651	Satisfied
	PS Posttest – Experimental	W = .959	.309	Satisfied
	PS Posttest – Control	W = .962	.501	Satisfied
Homogeneity	SC Posttest	F(1,50) = 3.405	.071	Satisfied
	PS Posttest	F(1,50) = 3.722	.059	Satisfied
Covariance matrices	SC and PS Posttests	M = 7.536; $\chi^2(3) = 7.203$	.066	Satisfied
Regression slopes	Group $\times$ SC Pretest $\rightarrow$ SC Posttest	F(1,46) = 2.214	.143	Satisfied
	Group $\times$ PS Pretest $\rightarrow$ SC Posttest	F(1,46) = 3.806	.057	Satisfied
	Group $\times$ SC Pretest $\rightarrow$ PS Posttest	F(1,46) = 2.861	.097	Satisfied
	Group $\times$ PS Pretest $\rightarrow$ PS Posttest	F(1,46) = 7.636	.008	Violation

Note. SC = scientific communication; PS = problem-solving; W = Shapiro–Wilk statistic. Decisions are based on $\alpha = .05$.

As shown in Table 2, the Shapiro–Wilk tests identified significant deviations from normality for scientific communication pretest scores ($W = .919$, $p = .028$) and posttest scores ($W = .888$, $p = .005$) in the experimental group. The remaining score distributions did not show statistically significant deviations from normality. Levene's tests were non-significant for both scientific communication, $F(1,50) = 3.405$, $p = .071$, and problem-solving, $F(1,50) = 3.722$, $p = .059$, indicating no statistically detectable differences in variances between the groups. Similarly, Box's M test was non-significant, $M = 7.536$, $\chi^2(3) = 7.203$, $p = .066$, providing no statistically significant evidence of unequal covariance matrices.

The tests of homogeneity of regression slopes revealed an important difference between

the two outcome variables. For scientific communication, the interactions between instructional group and the scientific communication and problem-solving pretest covariates were not statistically significant, with $p = .143$ and $p = .057$, respectively. For problem-solving, the Group $\times$ Scientific Communication Pretest interaction was also non-significant ($p = .097$). However, the Group $\times$ Problem-Solving Pretest interaction was statistically significant, $F(1,46) = 7.636$, $p = .008$. This result indicates that the association between initial and final problem-solving scores differed across the instructional groups. Consequently, the outcome-specific analysis of problem-solving incorporated this interaction through moderated regression, while scientific communication was examined using ANCOVA.

Multivariate Analysis

A multivariate analysis of covariance (MANCOVA) was conducted to examine the combined differences in scientific communication and problem-solving posttest scores between the experimental and control groups, with the corresponding pretest scores included as covariates. The analysis evaluated the instructional group effect across the two dependent variables simultaneously. Wilks' lambda was used to assess multivariate significance, while partial eta squared was reported to describe the magnitude of the group effect. The reported multivariate results are presented in Table 3.

Table 3. Multivariate Effect of the Instructional Treatment on Scientific Communication and Problem-Solving

Effect	Wilks' Λ	F	df	p	η^2p
Group	.430	31.141	2, 47	< .001	.570

Note. Λ = Wilks' lambda; η^2p = partial eta squared.

Table 3 shows a statistically significant multivariate difference between the experimental and control groups, Wilks' $\Lambda = .430$, $F(2,47) = 31.141$, $p < .001$, $\eta^2p = .570$. The partial eta squared value exceeded the conventional threshold for a large effect, indicating a substantial multivariate group difference in the reported model. This result suggests that instructional group membership was associated with differences in the combined posttest outcomes after accounting for the included pretest covariates.

The multivariate finding provides an initial assessment of the relationship between instructional condition and the two learning outcomes considered jointly. However, the significant Group $\times$ Problem-Solving Pretest interaction identified in the assumption analysis indicates that the relationship between initial and final problem-solving performance was not homogeneous across groups. Accordingly, the reported MANCOVA result is interpreted with this qualification, rather than as evidence of a uniform group effect across all levels of initial problem-solving ability. Separate outcome-specific analyses are presented below to describe the scientific communication difference and the interaction-dependent pattern in problem-solving performance.

Scientific Communication Skills

To examine the scientific communication outcome separately, an analysis of covariance (ANCOVA) was performed using scientific communication posttest scores as the dependent variable and instructional group as the between-group factor. Scientific communication and problem-solving pretest scores were included as covariates. The analysis assessed the adjusted group difference while accounting for initial performance on both competencies. Table 4 summarizes the ANCOVA results for scientific communication.

Table 4. ANCOVA Results for Scientific Communication

Effect	F(1,48)	p	η^2p
Group	54.504	< .001	.532
SC Pretest	2.898	.095	—
PS Pretest	1.421	.239	—

Note. SC = scientific communication; PS = problem-solving; η^2p = partial eta squared.

The ANCOVA results in Table 4 indicate a statistically significant instructional group effect on scientific communication posttest scores, $F(1,48) = 54.504$, $p < .001$, $\eta^2p = .532$. The effect size was large according to conventional interpretation criteria. In contrast, neither scientific communication pretest scores, $F(1,48) = 2.898$, $p = .095$, nor problem-solving pretest scores, $F(1,48) = 1.421$, $p = .239$, showed a statistically significant association with scientific communication posttest scores in the reported model.

The significant group effect indicates that scientific communication posttest performance differed between the instructional groups after accounting for the included pretest scores. To describe the direction and magnitude of this difference, estimated marginal means were examined. These adjusted means provide a comparison of scientific communication performance at the covariate values used in the ANCOVA model. The adjusted group means are presented in Table 5.

Table 5. Adjusted Mean Scores for Scientific Communication

Group	Adjusted Mean
Experimental	84.04
Control	69.25

As presented in Table 5, the experimental group achieved an adjusted scientific communication mean of 84.04, compared with 69.25 in the control group. The adjusted mean difference was 14.79 points, indicating higher scientific communication performance among students who participated in PBL integrated with digital comics. This adjusted comparison is consistent with the direction of the observed posttest difference reported in Table 1, suggesting that the between-group difference remained substantial after adjustment for the included pretest scores.

The magnitude of the observed difference was further described using Cohen's d , which was reported as 2.11. This value represents a very large standardized mean difference between the experimental and control groups. Unlike the adjusted mean comparison, Cohen's d was based on the observed posttest scores and therefore represents an unadjusted effect-size estimate. Considered alongside the ANCOVA findings, the results indicate that the experimental group demonstrated higher scientific communication performance than the control group, with a substantial difference in both adjusted and observed posttest outcomes.

Problem-Solving Skills

The analysis of problem-solving skills accounted for the statistically significant interaction between instructional group and problem-solving pretest scores identified during assumption testing. Because this interaction indicated that the relationship between initial and final problem-solving performance differed across groups, a moderated multiple regression model was used to examine the posttest outcome. The model included instructional group, mean-centered problem-solving pretest scores, mean-centered scientific communication pretest scores, and the Group $\times$ Problem-Solving Pretest interaction. The regression coefficients are presented in Table 6.

Table 6. Moderated Regression Analysis Predicting Problem-Solving Posttest Scores

Predictor	B	SE	t	p
Intercept	68.738	1.533	44.833	< .001
Group	13.477	2.040	6.606	< .001
PS Pretest (centered)	0.400	0.130	3.089	.003
Group $\times$ PS Pretest	-0.516	0.187	-2.763	.008
SC Pretest (centered)	0.009	0.100	0.094	.925

Note. B = unstandardized coefficient; SE = standard error; SC = scientific communication; PS = problem-solving. Control is the reference group.

The moderated regression model was statistically significant, $F(4,47) = 17.378$, $p < .001$, with $R^2 = .597$ and adjusted $R^2 = .562$. The model accounted for approximately 59.7% of the

observed variance in problem-solving posttest scores. Instructional group was a significant predictor, $B = 13.477$, $SE = 2.040$, $t(47) = 6.606$, $p < .001$, indicating a predicted difference of approximately 13.48 points between the experimental and control groups at the centered covariate values. Problem-solving pretest scores were also a significant predictor, $B = 0.400$, $SE = 0.130$, $t(47) = 3.089$, $p = .003$, whereas scientific communication pretest scores were not statistically significant, $B = 0.009$, $SE = 0.100$, $t(47) = 0.094$, $p = .925$.

The interaction between instructional group and problem-solving pretest scores was statistically significant, $B = -0.516$, $SE = 0.187$, $t(47) = -2.763$, $p = .008$. This finding indicates that the slope relating initial problem-solving performance to posttest performance differed between groups. The negative interaction coefficient indicates that this relationship was less positive in the experimental group than in the control group. Because the interaction was significant, the group coefficient represents the predicted difference at the centered pretest values rather than a constant difference across all levels of initial problem-solving performance. To examine the interaction more closely, simple slopes were evaluated separately for the experimental and control groups. In the control group, problem-solving pretest scores were positively associated with posttest scores, $B = 0.400$, $SE = 0.130$, $t(47) = 3.089$, $p = .003$. In contrast, the corresponding slope in the experimental group was negative but not statistically significant, $B = -0.116$, $SE = 0.122$, $t(47) = -0.954$, $p = .345$. These findings show that higher initial problem-solving scores were associated with higher final scores in the control group, whereas no statistically significant linear association was detected in the experimental group.

The difference between the simple slopes provides additional information about the relationship between initial ability and subsequent performance. Specifically, the experimental group's posttest scores exhibited a weaker association with initial problem-solving scores than those of the control group. Nevertheless, the non-significant slope in the experimental group does not establish that initial ability had no influence on students' learning outcomes. Rather, the regression findings indicate that the association between pretest and posttest scores varied according to instructional condition within the observed sample.

In addition to the regression results, the observed problem-solving posttest scores were examined to describe the magnitude of the between-group difference. Table 7 presents the posttest means and standard deviations, together with the reported standardized mean difference.

Table 7. Problem-Solving Posttest Scores by Instructional Group

Group	Mean	SD
Experimental	81.93	6.56
Control	67.48	9.61

Note. SD = standard deviation. The reported unadjusted standardized mean difference was Cohen's $d = 1.80$.

As shown in Table 7, students in the experimental group achieved a mean problem-solving posttest score of 81.93 ($SD = 6.56$), compared with 67.48 ($SD = 9.61$) in the control group. The observed mean difference was 14.45 points, favoring the experimental group. The smaller standard deviation in the experimental group also indicates less variability in posttest scores compared with the control group. These descriptive findings are consistent with the direction of the conditional group difference estimated in the moderated regression analysis.

The reported Cohen's d value of 1.80 indicates a very large unadjusted standardized difference in problem-solving performance. However, this effect-size estimate should be distinguished from the regression coefficient because the latter accounts for the pretest covariates and their interaction with instructional group. The regression results indicate that the magnitude of the predicted between-group difference depends on initial problem-solving performance, while the observed posttest means describe the overall difference between groups without covariate adjustment.

The principal statistical findings for the combined outcomes, scientific communication, and problem-solving skills are summarized in Table 8. This synthesis brings the multivariate,

outcome-specific, and interaction analyses into a single presentation while preserving their distinct statistical interpretations.

Table 8. Summary of Main and Follow-Up Analyses of Instructional Group Effects

Outcome/Predictor	Analysis	Statistic	p	Interpretation
Combined outcomes	MANCOVA	$\Lambda = .430$; $F(2,47) = 31.141$	< .001	$\eta^2p = .570$
Scientific communication	ANCOVA	$F(1,48) = 54.504$	< .001	$\eta^2p = .532$; $d = 2.11$
Problem-solving	Moderated regression	$F(4,47) = 17.378$; $R^2 = .597$; adj. $R^2 = .562$	< .001	$d = 1.80$ (observed)
Group effect on PS	Moderated regression	$B = 13.477$; $SE = 2.040$; $t = 6.606$	< .001	Conditional group difference
Group $\times$ PS Pretest	Interaction	$B = -0.516$; $SE = 0.187$; $t = -2.763$	.008	Significant interaction
PS Pretest – Control	Simple slope	$B = .400$; $SE = .130$; $t = 3.089$	.003	Positive association
PS Pretest – Experimental	Simple slope	$B = -.116$; $SE = .122$; $t = -.954$	.345	Non-significant association

Note. SC = scientific communication; PS = problem-solving; η^2p = partial eta squared; d = Cohen's d . Cohen's d values refer to observed posttest differences.

Table 8 consolidates the major statistical results and highlights the differences between the analytical approaches used for the two learning outcomes. The MANCOVA identified a significant difference in the combined outcomes, while the ANCOVA indicated higher adjusted scientific communication scores in the experimental group. The moderated regression analysis further showed that instructional group was associated with problem-solving performance and that the relationship between initial and final problem-solving scores differed significantly between groups.

Taken as a whole, the reported results indicate higher posttest performance in scientific communication and problem-solving among students who received PBL integrated with digital comics compared with those who received PBL supported by conventional printed materials. The scientific communication difference remained significant after adjustment for the included pretest covariates, while the problem-solving analysis revealed an interaction-dependent relationship between instructional group and initial ability. These findings provide the empirical basis for the subsequent discussion of instructional differences, the potential role of digital comics within PBL, and the methodological limitations associated with the observed results.

Discussion

The findings of this study indicate that students who participated in Problem-Based Learning (PBL) supported by digital comics demonstrated higher scientific communication and problem-solving performance than those who received PBL instruction using conventional printed materials. The ANCOVA results revealed a significant difference in scientific communication after accounting for students' pretest scores, whereas moderated regression demonstrated that problem-solving performance was associated with instructional condition and its interaction with initial problem-solving ability. These findings extend the literature on problem-centered instruction by examining multimodal narrative materials in relation to two related scientific competencies. Previous studies have demonstrated that PBL creates opportunities for applying conceptual knowledge, developing reasoning, and constructing solutions to meaningful problems, although its outcomes depend on instructional design and implementation (Barrows, 1986; Dochy et al., 2003; Hmelo-Silver, 2004; Walker & Leary, 2009). Since both groups followed PBL, the differences should primarily be interpreted in relation to the additional support provided by digital comics rather than as evidence of the superiority of PBL over other pedagogical approaches.

The higher scientific communication performance in the experimental group can be interpreted through the relationship between multimodal representations and the construction of scientific explanations. Scientific communication requires students to organize ideas, use appropriate scientific terminology, interpret evidence, and justify conclusions. These competencies are closely related to scientific reasoning and the connection of claims to evidence. Research on scientific explanation has emphasized the need for explicit instructional support to produce coherent arguments and justify scientific reasoning (McNeill & Krajcik, 2008). In this study, digital comics presented contextual physical optics problems through illustrations, dialogue, and narrative sequences for students to examine before discussing and presenting solutions. Such representations may have supported the organization of scientific information and provided concrete contexts for communicating abstract concepts. However, changes in individual communication dimensions were not analyzed separately, so this explanation remains an interpretation of overall performance rather than a directly tested mechanism.

The potential contribution of digital comics can also be explained through the cognitive functions of multiple representations. Multimedia learning theory proposes that meaningful learning involves selecting, organizing, and integrating visual and verbal information (Mayer, 2021). The DeFT framework similarly emphasizes that the value of multiple representations depends on their design, purpose, and the cognitive tasks learners perform when interpreting them (Ainsworth, 2006). Thus, the instructional value of digital comics does not arise automatically from combining pictures and text. Representations must complement one another, emphasize relevant relationships, and support coherent explanations. The visual narratives may have provided representational support when students connected observable physical situations with wave-related concepts. Further evidence is nevertheless required to determine the influence of specific visual and narrative features on scientific communication.

Visual narratives may also be understood in relation to generative learning. Meaningful learning occurs when students actively organize information, construct explanations, and integrate new knowledge with prior understanding. Generative learning theory identifies self-explanation, drawing, mapping, and teaching others as activities that can support these processes (Fiorella & Mayer, 2015). Research on drawing in science education also emphasizes the role of visual representation in reasoning and communication (Ainsworth et al., 2011). Although students did not necessarily create the comics, their learning activities involved interpreting illustrations, discussing phenomena, and presenting explanations. These activities may have provided opportunities for generative processing, but the study did not directly observe or test these mechanisms through process measures or mediation analyses.

The collaborative nature of PBL provides another explanation for the communication results. PBL organizes learning around meaningful problems that require investigation, discussion, and evaluation of proposed solutions. These processes encourage learners to negotiate interpretations and communicate reasoning. Theoretical accounts of PBL emphasize activating prior knowledge, elaborating explanations, and integrating information through problem-centered learning (Norman & Schmidt, 1992; Savery, 2006). Instructional scaffolding can help learners approach complex tasks that may exceed their independent capabilities (Hmelo-Silver et al., 2007). In this context, comic scenarios may have served as shared reference points during discussion and presentation. Their potential role is thus to support, rather than substitute for, collaborative inquiry.

The relationship between collaboration and communication can be considered through the Interactive, Constructive, Active, and Passive (ICAP) framework. This framework distinguishes activities according to the forms of cognitive engagement they encourage and highlights the value of constructive explanation and interactive knowledge building (Chi & Wylie, 2014). Students interpreted the comic narratives and then investigated, discussed, and presented solutions. This sequence may have supported progression from receiving

information to constructing and negotiating explanations. Nevertheless, the study did not classify classroom activities using ICAP, and increased cognitive engagement should not be treated as a directly established finding.

The problem-solving findings complement the communication outcomes. The experimental group obtained higher observed posttest scores, and moderated regression identified a significant group difference at the centered pretest values. Problem-solving in physical optics requires identifying phenomena, interpreting representations, selecting physical principles, applying mathematical relationships, and evaluating solutions. Prior research suggests that problem-centered instruction can support knowledge application, although outcomes differ according to problem types, implementation, and assessment (Dochy et al., 2003; Dolmans et al., 2016; Walker & Leary, 2009). Digital comics may have provided additional context for interpreting problems before selecting solution strategies. However, this study cannot isolate which features of the comics were most influential.

The interpretation of visual narratives in problem-solving is also connected to conceptual development. Scientific problems may require learners to revise everyday interpretations in response to more adequate scientific explanations. Conceptual change research emphasizes the accommodation of existing ideas to explanations consistent with scientific evidence (Posner et al., 1982). In physical optics, interference, diffraction, and polarization involve wave phenomena that students often interpret through abstract diagrams and formulas. Comic narratives may have supplied familiar contexts from which students could identify physical relationships and move toward formal explanations (Ainsworth, 2006; Mayer, 2021). Because conceptual change was not measured independently, the findings do not demonstrate transformation of students' conceptual frameworks.

Instructional scaffolding offers another possible explanation. Scaffolds support learners as they address tasks involving substantial cognitive and reasoning demands. A meta-analysis reported positive effects of computer-based scaffolding on cognitive outcomes in STEM problem-centered learning environments (Belland et al., 2017). Digital comics may have provided representational scaffolds through contextual scenarios, sequenced illustrations, and scientific dialogue. These features could help learners identify information and organize problem-solving steps. Nonetheless, the present study did not compare specific types or levels of scaffolding, and the evidence does not establish universal superiority of comic-based support.

The cognitive demands of visual learning materials require equally careful consideration. Cognitive load theory emphasizes limitations of working memory and the importance of instructional designs that support relevant processing without unnecessary complexity (Sweller et al., 2019). Coordinated illustrations and explanatory text may make complex physical phenomena easier to interpret. Conversely, decorative images, poorly sequenced narratives, and redundant information can increase processing demands. Because cognitive load was not measured, the higher performance cannot be attributed specifically to reduced cognitive load. The results establish a difference under the investigated instructional conditions, not the processing mechanism responsible for it.

One particularly important result was the significant interaction between instructional group and initial problem-solving performance. In the control group, higher pretest scores were positively associated with posttest scores, whereas the corresponding simple slope in the experimental group was not statistically significant. This pattern indicates that the relationship between initial and final problem-solving performance was less positive under digital comic-supported PBL. A potential interpretation is that representational scaffolds may offer support across differing levels of initial competence (Belland et al., 2017; Hmelo-Silver et al., 2007). However, the non-significant slope does not establish that initial ability ceased to matter or that students with lower baseline scores benefited more. Those claims require explicit conditional comparisons across the pretest range and preferably replication in larger samples.

The interaction also has methodological significance. An instructional difference cannot be assumed constant across initial problem-solving levels when a group-by-pretest interaction is present. The moderated regression therefore describes the observed problem-solving outcome more appropriately than a standard covariance adjustment that assumes homogeneous slopes. Educational effects can vary across task demands, assessment conditions, and instructional implementations (Walker & Leary, 2009). Similarly, the suitability of learning supports depends on task complexity and learners' needs (Belland et al., 2017). The significant interaction is thus an informative finding, but its generalizability requires further testing.

Narrative media may additionally be relevant to learners' situational interest and engagement. Educational comics have been associated with learning and attitudes toward science in particular educational contexts (Hosler & Boomer, 2011). Interest development theory proposes that learning materials can trigger situational interest, although sustaining interest depends on continuing experiences and instructional conditions (Hidi & Renninger, 2006). School engagement also includes behavioral, cognitive, and emotional dimensions that should not be treated as interchangeable (Fredricks et al., 2004). The comic format may have helped make scientific problems engaging, but interest, motivation, and engagement were not directly measured. Accordingly, these factors are hypotheses for subsequent research rather than measured explanatory variables in the present study.

The findings also underscore that the educational contribution of digital media depends on instructional integration. Research on computer simulations in science education has emphasized the importance of pedagogical guidance when learners encounter technological representations (Rutten et al., 2012). Although comics and simulations differ in interactivity and representation, the general instructional principle is relevant. Here, comics were used within the stages of PBL rather than as standalone materials. Their possible contribution may therefore involve connecting contextual problem presentation with collaborative investigation, explanation, and evaluation. This interpretation should not be confused with evidence that the digital format itself is uniquely responsible for improved outcomes.

The theoretical contribution of this study lies in considering multimodal representation, scaffolding, and problem-centered learning in relation to scientific communication and problem-solving. Multimedia and multiple-representation perspectives provide accounts of how visual-verbal materials can support conceptual organization; generative learning and PBL emphasize active explanation and construction of knowledge (Ainsworth, 2006; Fiorella & Mayer, 2015; Hmelo-Silver, 2004; Mayer, 2021). The present findings are consistent with the possibility that digital comics function as contextual representational resources within inquiry-oriented activities. However, the research did not directly test an integrated theoretical model or causal pathways among the proposed mechanisms. The contribution should therefore be characterized as empirical evidence motivating further mechanism-focused research.

Practically, teachers may consider comics as supplementary materials for presenting authentic problems, illustrating abstract phenomena, and prompting explanation within PBL. Their design should emphasize scientific accuracy, relevant contextual problems, coherent sequencing, and opportunities for collaborative reasoning. The significant interaction also suggests that learners' initial competencies deserve attention when designing instructional support. Research on scaffolding and cognitive load indicates that clarity and task appropriateness matter more than visual novelty alone (Belland et al., 2017; Sweller et al., 2019). Digital comics should therefore be designed as purposeful resources rather than assumed to be beneficial merely because they are visually attractive.

Several limitations qualify the interpretation of these findings. The sample comprised 52 students from two intact classes in one school without individual randomization, limiting causal inference and generalizability. With only one class per condition, classroom-level influences cannot be distinguished clearly from the instructional treatment. The six-meeting intervention focused solely on physical optics, leaving the durability of the differences and transfer to other

topics unknown. The study assessed communication and problem-solving, not cognitive load, engagement, motivation, conceptual change, or other proposed mediators. Moreover, significant deviations from normality were found in scientific communication scores, and the homogeneity of regression slopes assumption was violated for problem-solving. These issues warrant caution in interpreting covariance-adjusted and multivariate effects.

Future research should include larger samples across multiple schools and educational levels, longer observation periods, and designs supporting stronger causal inference. Longitudinal assessments could investigate retention, while direct measures of representational comprehension, engagement, cognitive load, and scientific argumentation could clarify potential mechanisms. In view of the interaction with baseline problem-solving ability, subsequent research should evaluate conditional effects across the initial-competence range. Comparisons with other visual or printed formats could help identify the separate contributions of narrative structure, representation, and pedagogical integration.

The findings indicate that PBL supported by digital comics was associated with higher scientific communication and problem-solving performance than PBL supported by printed materials in the investigated physical optics context. The interaction involving initial problem-solving skills also suggests that students' baseline competencies should be considered when interpreting their final performance. The study consequently supports further investigation of digital narrative resources as part of structured problem-based instruction, while the methodological and statistical limitations caution against broad causal or universal claims.

CONCLUSION

This study examined differences in scientific communication and problem-solving skills between students who participated in Problem-Based Learning (PBL) integrated with digital comics and those who received PBL instruction supported by conventional printed materials in physical optics. The findings indicated that the experimental group achieved higher posttest performance in both competencies. ANCOVA revealed a significant difference in scientific communication after controlling for pretest scores, while moderated regression identified a significant conditional group difference in problem-solving performance. The significant interaction between instructional group and problem-solving pretest scores further demonstrated that the relationship between initial and final problem-solving performance differed across instructional conditions. These results suggest that integrating digital comics into PBL may provide additional support for students' scientific communication and problem-solving performance in the investigated learning context.

The study contributes empirical evidence concerning multimodal narrative materials within problem-based physics instruction, particularly in relation to scientific communication and problem-solving as complementary learning outcomes. Contextual illustrations and scientific dialogues may serve as useful resources for organizing explanations and supporting problem-oriented learning. However, the quasi-experimental design, limited sample, short intervention period, and identified statistical assumption issues restrict the generalizability and causal interpretation of the results. The findings should therefore be regarded as evidence of the instructional potential of digital comic-supported PBL rather than definitive proof of effectiveness across educational settings. Further investigation is needed to establish the consistency, underlying mechanisms, and long-term implications of this approach.

RECOMMENDATION

Physics teachers may consider incorporating digital comics into Problem-Based Learning (PBL) activities as supplementary instructional materials, particularly when introducing abstract physical optics phenomena, presenting contextual problems, and facilitating scientific explanations and collaborative problem-solving. The selection and development of digital comics should prioritize scientific accuracy, clarity of visual representations, relevance to learning objectives, and alignment with the stages of PBL. Classroom implementation should

also consider students' digital literacy, technological access, and opportunities for active discussion and reflection. Future research is recommended to examine this instructional approach using larger and more diverse samples, multiple schools, longer intervention periods, and research designs that provide stronger support for causal inference. Further investigations should explore differences in outcomes across students' initial ability levels, evaluate the persistence of learning outcomes, and examine potential explanatory mechanisms such as cognitive processing, learning engagement, and scientific argumentation. These investigations would help clarify the conditions under which digital comic-supported PBL contributes to scientific communication and problem-solving in physics education.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding the publication of this article.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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