



PREDICTIVE EFFECT OF PROJECT-BASED LEARNING QUALITY ON SCIENTIFIC PROBLEM-SOLVING ABILITY

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Abstract. *Many studies have examined the relationship between project-based learning (PBL) and scientific problem-solving ability, but few have addressed the issue of the quality of PBL (QPBL). This study analyzed two-wave data collected from 4,568 seventh-grade Chinese students. Pretest and posttest of scientific problem-solving ability were conducted through computer-based assessment featuring interactive tasks, and the students' QPBL scores were collected through a questionnaire. Hierarchical linear modeling (HLM) indicated that QPBL positively predicted students' scientific problem-solving ability. Specifically, "authenticity" positively predicted all three subcomponents of scientific problem-solving ability (design of scientific inquiry, scientific reasoning, and scientific explanation); "autonomy in research questions" negatively predicted all three subcomponents; and "group collaboration" and "project demonstration" positively predicted some of the subcomponents. These findings enrich the literature on the predictive effects of QPBL on scientific problem-solving ability in specific educational and cultural contexts and have practical implications for teachers seeking to apply PBL more effectively to enhance students' scientific problem-solving ability.*

Keywords: *project-based learning, scientific problem-solving ability, hierarchical linear modeling*

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Introduction

Given the numerous complicated problems in 21st-century society and the continuous emergence of new technologies such as artificial intelligence, people must learn quickly and be able to continuously solve new problems. Problem-solving ability is crucial for people as they face the challenges of the times (Adikayanti & Retnawati, 2022; Hasanah et al., 2023). The Science and Engineering Practices in the Next Generation Science Standards (NGSS) requires students to take the initiative to participate in problem discovery, inquiry, and solution, a process that mimics that adhered to by scientists and engineers (NGSS Lead States, 2013). The Science Curriculum Standards for Compulsory Education in China also focus on scientific inquiry and engineering practices, as well as the use of real-world scenarios and interdisciplinary practices to solve problems (MEPRC, 2022). It is evident that the learning of science is not limited to mastering concepts but also requires applying concepts in solving scientific problems (Hoellwarth et al., 2005).

Research has shown that students' problem-solving ability in different disciplines, including science, is categorized as low and therefore must be improved (Adikayanti & Retnawati, 2022; Harahap et al., 2022; Sugiarti et al., 2019; Tampubolon & Sipahutar, 2024). Some appropriate teaching methods, such as project-based learning (PBL), may facilitate the development of problem-solving ability (Hasanah et al., 2023; Zheng et al., 2021). PBL uses real-world problems that are integrated with daily life as the driving force for learning, enabling learners to formulate, develop, and execute plans to solve problems and promote learning (Bell, 2010; Muir et al., 2016). Teachers must guide students to discover practical problems, pay attention to problem discussions, design their own learning to answer questions, and then construct knowledge during the processes of continuous data collection and analysis, peer discussions, and idea correction (Zheng et al., 2021). Some research has shown that PBL is beneficial in the contexts of constructing students' knowledge, enhancing their learning interest, and promoting their academic development (Chen & Yang, 2019; Heo et al., 2010; Koh et al., 2010).



However, as the impact of PBL on academic achievement, such as problem-solving ability, in science classes varies significantly across different studies (Chen & Yang, 2019; Rehman et al., 2024), further exploration of the effects of the quality of PBL (QPBL) on scientific problem-solving ability is necessary. Additionally, computer-based interactive tasks are rarely used to assess scientific problem-solving ability in PBL-related research (Chistyakov et al., 2023). Hence, this study focused on the effects of the QPBL and each of its indicators on scientific problem-solving ability, as measured by computer-based assessment.

Literature Review

Scientific Problem-solving Ability

To understand the connotations of “scientific problem-solving ability,” we start by explaining what constitutes a “problem.” Accordingly, a problem is something that cannot be solved directly, requires deep understanding and requires time to analyze (Susilo & Retnawati, 2018). Problems in daily life that must be solved are often real and nonroutine problems that may have no obvious solution (Adikayanti & Retnawati, 2022; Mayer, 1992). Thus, problem-solving ability is the ability to solve nonroutine authentic problems that require the integration of learned knowledge and skills to find the best solution (Adikayanti & Retnawati, 2022; Susilo & Retnawati, 2018). Hence, scientific problem-solving ability refers to the capacity to apply scientific knowledge and a series of process skills to explore and seek solutions to problems related to science and technology (Zhao et al., 2023).

When faced with a problem related to science and technology, students often need to design an experiment or investigation by combining relevant scientific concepts or principles, collect and analyze data to form effective evidence, conduct reasonable reasoning to form solutions, and then scientifically explain and evaluate the solutions. Therefore, scientific problem solving is, to some extent, a process of scientific inquiry (Gayford, 1989). Certain skills, such as formulating hypotheses and designing experiments, are involved in solving scientific problems. Moreover, problem solvers need to reason based on the data to further clarify the possible problem-solving solutions (Chang et al., 2007; OECD, 2013). Scientific reasoning involves evaluating the evidence, drawing inferences, and providing argumentation, and then, through these processes, verifying or refuting hypotheses or theories about scientific phenomena to form solutions for problems (Zimmerman, 2000). Researchers further claim that the process of problem solving involves generating and evaluating ideas to identify the most effective solution (Baumgartner, 2020; Plaillek et al., 2023). Ultimately, successful problem solvers are inclined to develop more explanations based on principles and rules to effectively connect the solution steps to the knowledge within the scientific field (Camacho & Good, 1989; Ferguson-Hessler & de Jong, 1990). In conclusion, in this study, the dimensions in assessing scientific problem-solving ability include design of scientific inquiry, scientific reasoning, and scientific explanation (Zhao et al., 2023).

Relationship between PBL and Scientific Problem-solving Ability

From the perspective of a teaching strategy, PBL involves designing, planning, and implementing project tasks to continuously explore authentic problems (Markham et al., 2003). As a learning methodology, PBL is defined as the process by which students must solve problems by defining problems, discussing ideas, collecting and analyzing data, and sharing findings with peers (Bell, 2010). In other words, PBL is a learning process that requires in-depth understanding of a topic based on higher-order thinking, enhances learning motivation, and promotes interaction and collaboration among students and between students and society (Adikayanti & Retnawati, 2022). Moreover, researchers have defined PBL as a systematic teaching and learning method that involves students in complex and authentic tasks and results in a product or presentation that enables students to acquire knowledge and improve life skills (Barron & Darling-Hammond, 2008). Although the conceptual definitions of PBL are diverse, there is a certain degree of consistency in the generalization of its core characteristics: centrality, driving question, constructive investigations, autonomy, and realism (Thomas, 2000). These characteristics have been highly recognized in subsequent studies and identified as the features that distinguish PBL from other activities (Helle et al., 2006). Researchers also believe that PBL should incorporate project outcomes, evaluations from multiple sources, and group collaborations (Kokotsaki et al., 2016; Krajcik et al., 1994) as essential characteristics of PBL.

PBL clearly encourages students to become active learners as they acquire core concepts and principles, investigate problems to produce products, and publicly communicate solutions (Adikayanti & Retnawati, 2022; Zheng et al., 2021). Research has determined that one of the benefits of PBL is that it increases students’ problem-solving ability (Hasanah et al., 2023; Retno et al., 2019). Moreover, a recent study highlighted notable differences in problem-solving



ability between students who participated in a 15-week project-based learning program and those who received non-project-based instruction (Zheng et al., 2021). The project-based module, which used a 4D developmental model consisting of define, design, develop, and disseminate, encouraged students to actively engage in solving problems through project activities and improved students' problem-solving skills in an animal development course (Tampubolon & Sipahutar, 2024). Research has also shown that PjBL-STEM is capable of improving students' problem-solving skills when open-ended problems are introduced into teaching scenarios (Adikayanti & Retnawati, 2022). Moreover, after using the HyFlex learning platform developed according to hybrid learning and flexible learning theory coupled with project-based learning, students' creative problem-solving ability reached the highest level (Plailek et al., 2023).

With respect to students' scientific problem-solving ability, a mini review on PBL for science and STEAM education revealed that, on average, PBL improves students' learning outcomes in science and trains students to become problem solvers (Chistyakov et al., 2023). Additionally, integrating PBL into science education not only strengthens students' understanding of scientific concepts but also enables them to design innovative projects, supporting the development of crucial 21st-century skills such as problem-solving and creativity (Baran et al., 2021). STEM project-based learning is perceived as an effective approach to enhance students' problem-solving skills as it encourages students to integrate and apply the learned knowledge to solve real-world challenges (Kartini et al., 2021). Research has also determined that the application of the PBL learning model with the STEM approach has a positive effect on students' creative problem-solving ability (Fiteriani et al., 2021). The results of a study adopting a quasi-experimental nonequivalent control group design revealed that there was a meaningful difference in the mean problem-solving score between an experimental classroom that used an E-STEM project-based learning model and a control classroom that applied conventional teaching methodology (Muzana et al., 2021). The test instrument, which included essay questions that were conducive to identifying a problem, designing and making a plan to solve the problem, and evaluating the solution, was used to measure students' ability to solve problems. Additionally, a project-based digital storytelling approach was applied to the learning activity of a science course in an elementary school. The experimental results revealed that PBL with digital storytelling effectively enhanced students' problem-solving competence (Hung et al., 2012). A 5-point Likert scale for problem-solving competence was adopted to collect student feedback. Moreover, the findings of a quasi-experimental design revealed that students' scientific problem-solving skills in the science classroom could be improved through science project-based learning with the help of local-based teaching materials (Kundariatia et al., 2022). To measure students' scientific problem-solving skills, data were collected using instruments such as essay tests. Therefore, the application of PBL generally improved students' scientific problem-solving ability, and the instruments for assessing this ability in the current PBL-related study mainly included essay assessments and questionnaires. While the majority of studies reveal a positive impact of PBL on academic achievement in science classes, this impact varies significantly across different studies, indicating the need for further research on the implementation of PBL, including the quality of project-based learning (Rehman et al., 2024).

Quality of Project-based Learning (QPBL)

If an activity that is identified as "project-based learning" has neither realistic driving questions nor procedures that promote student exploration, can it be categorized as PBL? A meta-analytical study by Ferrero et al. (2021) on the effectiveness of PBL at the primary school and kindergarten levels revealed that there is a lack of description in empirical research regarding whether teachers and students comply with the basic requirements of PBL, such as driving questions and project outcomes. Whether the PBL implemented in the classroom conforms to its core characteristics is important for determining its effectiveness and holds great significance for evaluating whether PBL is conducive to student learning. Therefore, we believe that it is not sufficient to merely apply PBL in the classroom. Rather, an objective evaluation of the quality of PBL requires more attention.

With respect to the evaluation of PBL, the Buck Institute for Education has developed the 6A Framework that includes six aspects: authenticity, academic rigor, applied learning, active exploration, adult connection, and assessment practices (Markham, 2003). According to the framework, projects can be classified into three levels: unqualified, basically qualified, and excellent. Following the development of the framework, the gold standard (GS) project design elements were developed, which included seven dimensions: challenging problems or questions, sustained inquiry, authenticity, student voice and choice, reflection, critique and revision, and public product (Larmer et al., 2015). On the basis of the aforementioned GS, the end result is a high-quality project-based learning framework based on students' experiences (Evans, 2019). This framework was then used to develop a survey in the form of a scale plus open-ended questions to investigate students' experiences during the implementation of PBL. Moreover, in combination with the teachers' cases, a comprehensive evaluation of the quality of PBL was conducted that assessed



factors such as project design, teachers' practices, students' experiences, and students' learning outcomes. Moreover, an observation scale for PBL classrooms was developed that encompasses six dimensions: the structure of PBL, the advancement of PBL, students' participation, resources, evaluation, and classroom learning atmosphere (Capraro et al., 2016). In conclusion, first, the evaluation of the quality of PBL involves various aspects that are strongly related to the definition and core characteristics of PBL; second, when evaluating the quality of PBL, researchers have adopted several evaluation methods, including qualitative research methods such as classroom observations and textual analysis based on teachers' lesson plan designs for PBL and quantitative research methods such as questionnaires.

However, with respect to evaluating PBL in large-scale quantitative studies, instruments for measuring the QPBL are lacking (Condliffe et al., 2017; Leggett & Harrington, 2019). In empirical studies with large samples, evaluation methods such as classroom observations and textual analyses require a great deal of time for data collection, data coding, and analysis. Moreover, these methods require scorers to possess a high level of professionalism, accuracy, and stability. Compared with the aforementioned methods, questionnaires are convenient for collection and collation. Although the amount of information collected is relatively limited, a general survey of the QPBL can be conducted from a macro perspective. Therefore, this study suggests that the QPBL be evaluated through questionnaires in large-scale assessments. Because the core characteristics of PBL, such as authenticity, are strongly correlated with students' prior experiences, we evaluate the QPBL from the students' perspective by exploring their feelings about PBL in the classroom, which is consistent with previous studies (Evans, 2019). Given that the GS developed by the Buck Institute for Education offers a clear, publicly available, and verifiable framework for evaluating the implementation of PBL, this study used GS as the conceptual blueprint to develop a student questionnaire for evaluating the QPBL.

Problem Statement

As mentioned, there is still much room for exploration in analyzing the impact of PBL on scientific problem-solving ability. First, current research on how the QPBL and its indicators affect scientific problem-solving ability and its subdimensions remains relatively limited. Second, the instrument for measuring scientific problem-solving ability in existing PBL-related studies rarely adopts computer-based assessment methods, even though they have prominent advantages in assessing higher-order abilities (Zhao et al., 2023). Third, although some studies have focused on the pretests and posttests of scientific problem-solving ability when exploring the impact of PBL (Hung et al., 2012; Muzana et al., 2021), large-scale longitudinal tests are rare. Therefore, in accordance with the aforementioned research gaps, this study aims to investigate how QPBL and its indicators predict scientific problem-solving ability and its subdimensions measured in a large-scale computer-based assessment, providing practical implications for teachers seeking to apply PBL more effectively to enhance students' scientific problem-solving ability. Accordingly, this study was administered with the intent to answer the following research questions:

RQ1: Does the QPBL have significant predictive effects on students' scientific problem-solving ability?

RQ2: Which indicators of the QPBL have significant predictive effects on students' scientific problem-solving ability and its subdimensions (design of scientific inquiry, scientific reasoning, and scientific explanation)?

Research Methodology

Design

This study employed a quantitative research design. To analyze the predictive effect of the QPBL on scientific problem-solving ability, a pretest and posttest of scientific problem-solving ability in the form of computer-based assessment were administered to the same student participants in both May 2022 and May 2023, respectively. All student participants had been enrolled in at least one science project-based learning program between the autumn semester of 2022 and the spring semester of 2023 in their respective schools. Descriptive statistics and correlation analyses were conducted to describe the basic properties of the variables and examine their interrelationships, thus providing a foundation for model construction, and hierarchical linear modeling (HLM) was subsequently used to answer the research questions.

Participants

A total of 4,698 students were recruited from 286 classes in 77 lower-secondary schools in three regions of China (City B in northern China, City W in eastern China, and City J in central China). Cities were selected through conve-



nience sampling based on the willingness of local education authorities to participate. Participating schools were selected by local education authorities and generally comprised public schools within their jurisdiction. Within each selected school, two classes were randomly sampled, and all students in those classes participated in the assessment. All participants were provided with a clear description of the study's purpose and adequately informed about their participation and right to withdraw during the study.

All participants engaged in science PBL activity during the pretest and posttest of scientific problem-solving ability. At the student level, approximately 30% of students participated in one science project, 45% participated in two to three projects, and 25% participated in four or more projects. At the project level, 46% of the projects were implemented for one class hour per week (1 class hour = 45 minutes), 26% for two class hours per week, 21% for three class hours per week, and 7% for four or more class hours per week. All participating students were required to take the pretest and posttest of scientific problem-solving ability and complete a questionnaire for QPBL during the posttest period. After excluding 130 cases with missing data on both the test and questionnaire, the final valid sample consisted of 4,568 students (response rate = 97.2%; 48% female). Specifically, 669 students were from 12 schools in City B, 1,986 students were from 30 schools in City W, and 1,913 students were from 35 schools in City J.

Measurement

Scientific Problem-solving Ability. Scientific problem-solving ability was assessed through computer-based interactive tasks, which took 45 minutes to complete. There were 7 subtasks for the design of scientific inquiry, 10 subtasks for scientific reasoning, and 5 subtasks for scientific explanation. Two of the tasks were original and belonged to physics and geography. Another task, belonging to biology, was adapted from the Problem Solving and Inquiry blocks of TIMSS 2019 (<https://timss2019.org/psi/index.html>). The tasks were formed using the programming tool JavaScript and then embedded in the test system (<https://pbl.bnunet.com/>). Under the technical assistance provided by two professional technicians, the tasks were designed and completed by a research team consisting of three researchers (the first, second, and third corresponding authors). To improve the assessment instrument, the study conducted three rounds of student interviews with eighteen seventh-grade students and two rounds of expert interviews with three professors proficient at designing science tasks. The instrument demonstrated good reliability and validity ($\alpha = .830$, CFI = .882, TLI = .871). To facilitate an intuitive understanding of this instrument, one subtask for the design of scientific inquiry in the Chinese version was translated into English and is presented in Figure 1.

Figure 1
One Subtask for the Scientific Problem-solving Ability Test

Instruction > Subtask1 > Subtask2 > **Subtask3** > Reading > Subtask4 > Subtask5 > Subtask6 > Subtask7 > Complete

Subtask 3 To investigate which type of fertilizer (Fertilizer A or Fertilizer B) can promote plants to produce more chili peppers, please continue to design an experiment.

Please perform the following operations on the left-side interface:
Select the type of fertilizer you want to add to each seedling tray, and click with the mouse to choose the amount of fertilizer to spray (unit: ml).
After you have set the type and amount of fertilizer for the three seedling trays, click "Observe" to view the fertilizer spraying status. If you want to redesign the experiment, click the "Reset" button.

Note: After clicking "Next", you will not be able to modify your answer.

Previous Next

Quality of Project-based Learning. The QPBL was measured using a self-report questionnaire consisting of seven items. The items were developed on the basis of the gold standard (GS) project design elements proposed by the Buck Institute for Education (Larmer et al., 2015) and were adapted to align with the context of science education at secondary schools in China. The adaptations were as follows: (1) Owing to the large-scale assessment, the measurement of “reflection” was difficult to create; thus the “reflection” and “critique and revision” in the GS were combined into “evaluation and feedback,” with a greater emphasis on enabling students to receive evaluations and feedback from different sources during the process of implementing project. (2) Owing to the important role of group collaboration when students design and carry out projects based on the definition of PBL, the dimension of “group collaboration” was added. (3) Recognizing the crucial role of students’ independent choice in PBL and considering this study’s emphasis on driving questions based on the actual implementation of PBL in China, “student voice and choice” in the GS was replaced by “autonomy in research questions”. (4) Regarding the “project products” in the GS, whether and how to demonstrate the project products is vital. Therefore, “project demonstration” was used in this study. The indicators of the QPBL in this study included seven dimensions: challenging problems or questions, authenticity, sustained inquiry, autonomy in research questions, evaluation and feedback, group collaboration, and project demonstration (see Table 1). Each item represented one indicator and was scored on the basis of student responses. Higher scores indicated higher levels of perceived quality in the corresponding aspect of PBL.

Table 1
Indicators of the QPBL and Responding Items

Indicators	Items and Options	Rating
Challenging problems or questions	Regarding the level of challenge in the project, which of the following statements best reflects your actual experience? The problems to be solved in the project were A = Relatively easy for me. B = Moderately challenging for me. C = Too difficult for me, making it difficult to get started.	A=1 B=2 C=1
Authenticity	To what extent were the problems addressed in the project related to real-life situations? The problems addressed in the project were A= Hardly related to our daily lives. B= Somewhat related to our daily lives. C= Closely connected to our daily lives.	A=1 B=2 C=3
Sustained inquiry	Regarding the sustained inquiry involved in the project, which of the following statements best reflects your actual experience? A = We only explored the problems during class time. B = We occasionally explored the problems outside of class. C = We frequently devoted time and effort outside class to explore the problems.	A=1 B=2 C=3
Autonomy in research questions	After the project topic was determined, how were the specific research questions formulated? A = The teacher formulated the research questions for us. B = With the teacher’s guidance, other group members formulated the research questions. C = With the teacher’s guidance, I actively participated in formulating the research questions.	A=1 B=2 C=3
Evaluation and feedback	How was your project outcome feedback provided? A = We did not receive any feedback. B = Feedback was provided only by the teacher. C = Feedback was provided by multiple sources, including the teacher and peers.	A=1 B=2 C=3
Project demonstration	Regarding the demonstration of project outcomes, which of the following statements best reflects your actual experience? A = The project did not produce any concrete outcomes. B = The project produced concrete outcomes, but they were not publicly presented. C = The project outcomes were presented within the class through speeches, posters, product creation, etc. D = In addition to classroom presentation, the project outcomes were also presented in broader settings, such as the school or community.	A=1 B=2 C=3 D=4
Group collaboration	Regarding group collaboration during the project, which of the following statements best reflects your actual experience? A = No group collaboration was involved so I completed the project independently. B = Group collaboration was involved, but I participated minimally. C = Group collaboration was involved, and I actively participated.	A=1 B=2 C=3



The development of the questionnaire involved multiple stages to ensure the questionnaire's quality. First, a framework was adapted from the GS to ensure a solid theoretical foundation. Second, think-aloud interviews with twelve seventh-grade students were conducted to confirm that the items developed on the basis of the framework were understandable to the target respondents. Third, a pilot test was conducted to assess the reliability and validity of the items. On the basis of the pilot test scores, schools with relatively high and low levels of student-reported QPBL were selected for classroom observations of science project-based learning lessons. Moreover, local education authorities were invited to assess the quality of the schools' implementation of science project-based learning. The analysis revealed a high level of consistency among the pilot test scores with respect to the questionnaire, classroom observations, and local education authorities' evaluations. The questionnaire used in the pilot test demonstrated good psychometric properties ($CFI = .986$, $TLI = .978$, $\alpha = .979$). Hence, the final version of the QPBL used in this study was identical to the pilot version.

Control Variables. The pretest of scientific problem-solving ability was developed using the same procedures that were employed for the posttest, following a parallel test design to ensure consistency in the assessment framework and equivalence in difficulty levels (Gross et al., 2012). The development process for both instruments was identical. The pretest instrument demonstrated acceptable psychometric properties ($CFI = .863$, $TLI = .823$, $\alpha = .602$). SES was measured on the basis of the PISA framework, using three indicators: household possessions, parents' highest educational attainment, and parents' occupations (OECD, 2009). The composite measure demonstrated acceptable reliability ($\alpha = .658$). Gender was measured using students' demographic information, with females coded as 1 and males coded as 0.

Data Analysis

Analysis Method. Given the nested structure of student performance on the dependent variable, hierarchical linear modeling (HLM) was employed in the data analysis. The student level was defined as Level 1, and the school level was defined as Level 2. In the analysis, the dependent variable was the posttest score for scientific problem-solving ability. The independent variables were divided into two categories: control variables, including SES, gender, and the pretest score of scientific problem-solving ability, and the key predictor, QPBL. Taking Research Question 1 as an example, the model can be specified as follows:

$$\begin{aligned}\text{Level-1: } f(t_{ij}, x_{ij}) &= \beta_{0j} + \alpha_1 ESCS_i + \alpha_2 Gender_i + \alpha_3 Pre_test_i + \alpha_4 QPBL_i \\ \text{Level-2: } \beta_{0j} &= \gamma_{00} + \mu_{0j}\end{aligned}$$

In the model specification, i denotes the individual student, and j denotes the school to which the student belongs. Data analyses were implemented in R 4.0.0, and all models were constructed using the "lme4" package.

Analysis Steps. The data analysis conducted for this study featured three main steps. Step 1 involves variable processing. With the exception of gender, which was coded as a binary variable, all other variables were treated as continuous and entered into the model according to their raw scores. Owing to varying degrees of missing data across the 4,568 students, multiple imputation (MI) was employed to minimize the impact of missing values (Carpenter et al., 2023). To address Research Question 1, the seven indicators of project-based learning quality were averaged to create a composite variable, referred to as the QPBL. Similarly, the three subcomponents of scientific problem-solving ability were averaged to form a single composite variable, referred to as total ability.

Step 2 involves description and correlation analyses. The basic statistical characteristics, distribution patterns, and intercorrelations of the study variables were examined.

Step 3 is model construction. To answer Research Question 1, HLM was conducted with the posttest score of scientific problem-solving ability as the dependent variable and gender, SES, pretest scores, and QPBL as the independent variables. To address Research Question 2, three separate HLMs were constructed to examine the predictors of each subcomponent of scientific problem-solving ability. In these models, QPBL was further decomposed into seven indicators, whereas the other control variables remained the same as before.

Research Results

Table 2 presents the descriptive statistics for the variables in this study. Both the pretest and posttest scores for scientific problem-solving ability are transformed into proportion scores ranging from 0 to 1. The overall mean and item-level scores for QPBL are reported using raw scores.



Table 2
Descriptive Statistics Results

Variable	N	Min	M	Max	SD	ICC
Gender (Female = 1)	4568	0.00	0.48	1.00	0.50	-
SES	4568	0.50	4.54	7.00	1.16	0.33
Ability in Inquiry-pretest	4568	0.00	0.47	0.91	0.21	0.13
Ability in Reasoning-pretest	4568	0.00	0.81	1.00	0.15	0.05
Ability in Explanation-pretest	4568	0.00	0.47	1.00	0.35	0.09
Total Ability-pretest	4568	0.03	0.54	0.93	0.18	0.15
Ability in Inquiry-posttest	4568	0.00	0.51	1.00	0.22	0.09
Ability in Reasoning-posttest	4568	0.03	0.67	1.00	0.21	0.12
Ability in Explanation-posttest	4568	0.00	0.43	1.00	0.30	0.08
Total Ability-posttest	4568	0.01	0.54	1.00	0.19	0.14
Challenging Problems or Questions	4568	0.00	1.02	2.00	0.84	0.06
Authenticity	4568	0.00	1.44	3.00	1.15	0.07
Sustained Inquiry	4568	0.00	1.41	3.00	1.13	0.08
Autonomy in Research Questions	4568	0.00	1.45	3.00	1.14	0.07
Evaluation and Feedback	4568	0.00	1.67	3.00	1.30	0.08
Project Demonstration	4568	0.00	1.83	4.00	1.47	0.09
Group Collaboration	4568	0.00	1.65	3.00	1.29	0.07
QPBL	4568	0.00	10.47	21.00	7.94	0.07

Note. M = Mean; ICC = Intraclass Correlation Coefficient; SD = Standard Deviation.

Table 3 displays the Pearson correlation coefficients among the variables. Most of the variables are positively correlated to varying degrees, providing a foundation for model construction. First, pretest and posttest scores of Total Ability were significantly and positively correlated ($r = .318^{**}$), and significant positive correlations were also observed between the pretest and posttest scores of each sub-ability, with correlation coefficients ranging from $.132^{**}$ to $.217^{**}$. Second, the overall score of QPBL was significantly and positively correlated with the posttest score of Total Ability ($r = .187^{**}$), as well as with each sub-ability, with correlations ranging from $.145^{**}$ to $.159^{**}$. Third, all indicators of QPBL were significantly and positively associated with Total Ability, with correlations ranging from $.160^{**}$ to $.192^{**}$.

Table 3
Correlations among the Variables

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. Inquiry (pre)	1.00															
2. Reasoning (pre)	.315**	1.00														
3. Explanation (pre)	.341**	.080**	1.00													
4. Total ability (pre)	.875**	.415**	.728**	1.00												



Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
5. Inquiry (post)	.217**	.104**	.174**	.245**	1.00											
6. Reasoning (post)	.255**	.132**	.203**	.289**	.478**	1.00										
7. Explanation (post)	.228**	.091**	.183**	.254**	.554**	.485**	1.00									
8. Total ability (post)	.283**	.131**	.226**	.318**	.844**	.769**	.840**	1.00								
9. Challenging problems/questions	.097**	.041**	.097**	.118**	.135**	.124**	.133**	.160**	1.00							
10. Authenticity	.123**	.041**	.108**	.141**	.150**	.145**	.153**	.182**	.828**	1.00						
11. Sustained inquiry	.113**	.053**	.102**	.133**	.140**	.130**	.147**	.170**	.822**	.925**	1.00					
12. Autonomy in research questions	.104**	.040**	.097**	.123**	.138**	.121**	.148**	.166**	.823**	.920**	.916**	1.00				
13. Evaluation & feedback	.121**	.039**	.109**	.139**	.155**	.143**	.154**	.184**	.850**	.915**	.901**	.918**	1.00			
14. Project demonstration	.125**	.037*	.110**	.142**	.152**	.146**	.158**	.185**	.829**	.898**	.893**	.904**	.915**	1.00		
15. Group collaboration	.125**	.043**	.110**	.143**	.161**	.153**	.159**	.192**	.855**	.911**	.902**	.909**	.941**	.918**	1.00	
16. QPBL	.122**	.044**	.110**	.142**	.155**	.145**	.159**	.187**	.892**	.960**	.954**	.959**	.968**	.958**	.968**	1.00

Note. Values are Pearson correlations. N = 4,568. * indicates $p < .05$, and ** indicates $p < .01$.

Results of HLM for Question 1

To address Research Question 1, Table 4 presents the model estimation results. To ensure comparability of predictor coefficients across different model specifications, all reported results are standardized.

Table 4
Standardized Coefficients of HLM for Question 1

Parameter	Estimate	SE	95% CI
Intercept	-0.051	0.035	[-0.121,0.018]
Gender	0.069**	0.027	[0.016,0.122]
SES	0.086***	0.016	[0.055,0.116]
Total Ability-pretest	0.227***	0.014	[0.199,0.255]
QPBL	0.093***	0.014	[0.065,0.120]

Note. SE = Standard Error; CI = Confidence Interval. *** represents $p < .001$, ** represents $p < .01$, and * represents $p < .05$.

As indicated in Table 4, QPBL positively predicts performance on the dependent variable ($\beta = 0.093$, $p < .001$). Therefore, Research Question 1 has been verified as the QPBL significantly and positively predicts scientific problem-solving ability.

Results of HLM for Question 2

Table 5 presents the standardized predictor coefficients for each model, addressing Research Question 2.

Table 5*Standardized Coefficients of HLM for Question 2*

	Total Ability		Ability in Inquiry		Ability in Reasoning		Ability in Explanation	
	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
Intercept	-0.065	[-0.136,0.005]	-0.079	[-0.143,-0.015]	-0.060	[-0.135,0.015]	-0.038	[-0.103,0.026]
Gender	0.102***	[0.049,0.154]	0.147	[0.092,0.202]	0.067	[0.013,0.122]	0.055	[0.000,0.111]
SES	0.087***	[0.056,0.117]	0.099	[0.068,0.131]	0.081	[0.049,0.113]	0.077	[0.045,0.108]
Total Ability-pretest	0.226***	[0.199,0.254]	0.110	[0.081,0.139]	0.122	[0.094,0.149]	0.153	[0.124,0.181]
Challenging problems or questions	-0.032	[-0.084,0.021]	-0.032	[-0.087,0.024]	-0.023	[-0.078,0.031]	-0.03	[-0.085,0.025]
Authenticity	0.135**	[0.054,0.217]	0.090*	[0.004,0.176]	0.172***	[0.087,0.257]	0.098*	[0.013,0.184]
Sustained inquiry	-0.025	[-0.102,0.053]	-0.008	[-0.090,0.073]	-0.055	[-0.136,0.026]	0.004	[-0.078,0.085]
Autonomy in research questions	-0.146***	[-0.227,-0.066]	-0.091*	[-0.176,-0.006]	-0.162***	[-0.246,-0.078]	-0.125**	[-0.210,-0.041]
Evaluation and feedback	-0.021	[-0.111,0.069]	-0.041	[-0.135,0.054]	0.017	[-0.076,0.111]	-0.029	[-0.123,0.066]
Project demonstration	0.067	[-0.007,0.141]	0.028	[-0.049,0.106]	0.058	[-0.020,0.135]	0.092**	[0.015,0.170]
Group collaboration	0.129**	[0.040,0.218]	0.147**	[0.054,0.241]	0.086	[-0.007,0.179]	0.095*	[0.001,0.188]

Note. *** represents $p < .001$, ** represents $p < .01$, and * represents $p < .05$.

As shown in Table 5, when total ability was used as the dependent variable, two indicators of QPBL, authenticity ($\beta = 0.135, p < .01$) and group collaboration ($\beta = 0.129, p < .01$), significantly and positively predicted students' ability scores. In contrast, autonomy in research questions exhibited a significant negative association with scientific problem-solving ability ($\beta = -0.146, p < .001$).

When the prediction of different subcomponents of scientific problem-solving ability was examined, the effects of the QPBL indicators varied. With respect to the ability to design scientific inquiry, autonomy in research questions exhibited a significant negative effect ($\beta = -0.091, p < .05$), whereas authenticity ($\beta = 0.090, p < .05$) and group collaboration ($\beta = 0.147, p < .01$) had significant positive effects. With respect to scientific reasoning ability, autonomy in research questions was a significant negative predictor ($\beta = -0.162, p < .001$), whereas authenticity was a significant positive predictor ($\beta = 0.172, p < .001$). With respect to scientific explanation ability, autonomy in research questions had a significant negative effect ($\beta = -0.125, p < .01$), whereas authenticity ($\beta = 0.098, p < .05$), project demonstration ($\beta = 0.092, p < .01$), and group collaboration ($\beta = 0.095, p < .05$) positively predicted performance.

Discussion

Authenticity is the Focal Point for Efforts to Enhance Students' Scientific Problem-Solving Ability

Authenticity means that the problems to be solved in a project can actually occur in society, have practical significance, and must be solved by citizens (Markham, 2003). The item related to "authenticity" in the QPBL questionnaire focused on whether the problems to be solved are closely linked to students' lives. Students who perceived the problems to be solved in their experienced projects as more relevant to life exhibited better overall scientific problem-solving ability ($\beta = 0.135^{***}$) and better performance in each dimension of the posttest (β ranged from 0.090^* to 0.172^{***}). "Authenticity" is the only indicator that exhibited a positive predictive effect on all three subdimensions of scientific problem-solving ability.



The real-world problems encountered in students' lives are often ill structured, complex, and open ended, thereby requiring students to comprehensively apply the concepts, principles, and skills they have learned to find solutions (Adikayanti & Retnawati, 2022). Accordingly, research indicates that individuals with a systematic and scientific conceptual knowledge structure are often better able to solve problems (Friege & Lind, 2006; Zajchowski & Martin, 1993). Existing research has also shown that compared with traditional teaching, authentic projects deepen students' grasp of scientific concepts and boost their scientific problem-solving skills (Chen et al., 2019; Harris et al., 2015). Moreover, from the perspective of self-determination theory, authentic problems closely related to life can stimulate students' intrinsic motivation to learn. When students realize that the knowledge they have learned can solve real-world challenges and that their learning has practical significance, they tend to more proactively engage rather than passively complete tasks (Barron et al., 1998; Krajcik & Shin, 2014; Ryan & Deci, 2000). When students actively engage in completing tasks, it promotes the development of their problem-solving abilities (Jonassen, 2000; Zimmerman, 2002). Additionally, from the perspective of situated learning theory, learning is not an isolated acquisition of knowledge but rather occurs in real-world social contexts involving interactive learning in communities of practice (Herrington & Oliver, 2000; Greeno et al., 1998). In an authentic problem situation, which is precisely one of the embodiments of situated learning theory, students go through the process of applying knowledge to collaboratively solve complex tasks, thereby developing problem-solving abilities.

Dialogues in Peer Collaboration Increase Students' Level of Thinking

Group collaboration refers to a social learning approach in which individuals work together in groups to solve real-world problems and achieve knowledge construction and skill development through the division of labor, communication, resource sharing, and collective decision-making (Kokotsaki et al., 2016; Krajcik et al., 1994). In this study, the students who engaged in group collaboration and actively participated in experiential projects demonstrated better overall scientific problem-solving ability ($\beta = 0.129^{**}$), the ability to design scientific inquiry ($\beta = 0.147^{**}$), and scientific explanation ability ($\beta = 0.095^{*}$).

Existing studies have shown that collaboration can simulate real scientific problem-solving scenarios and enhance students' scientific inquiry and problem-solving abilities through peer dialogs (Fischer et al., 2013; Roschelle & Teasley, 1995). When students collaborate around the same project goal, they communicate with each other through various means, such as brainstorming, discussion, and debate, which promotes clearer expression and interpretation of ideas and helps improve scientific explanation skills (Baram-Tsabari & Osborne, 2015; Brownell et al., 2013). In essence, from the perspective of social constructivist learning theory, peer dialogs trigger the collision of different viewpoints and mutual questioning among students and then expose logical flaws to promote students' revision of their own understanding, which is conducive to enhancing students' level of thinking (Howe & Mercer, 2007; Mercer, 1995). For example, when the schemes for scientific inquiry in disciplinary practices are designed, collisions of different perspectives often give rise to breakthrough hypotheses, thereby improving the quality and efficiency of inquiry (Ford & Forman, 2006; Wells, 1999). When peers debate the explanation of a certain phenomenon, it prompts students to use more scientific and clearer explanatory language with strong logic and enhances students' ability to explain phenomena scientifically (Chen et al., 2016; Osborne, 2010).

Presentation of Project Outcomes is Conducive to Conceptual Understanding and Personal Reflection

The display of project products involves students presenting their project problem-solving solutions and research results to audiences through diversified approaches, and it is also a systematic combination and integration of the entire learning process (Evans, 2019). In the QPBL questionnaire, the item for the "project presentation" focused on the project products being displayed not only in the class through speeches, posters, product making, and other approaches, but also in schools, communities, and other places. It is believed that the students whose project products are widely displayed have better scientific explanation ability in the posttest ($\beta = 0.092^{**}$).

Existing studies have shown that students who participate in project presentation during their project-based learning course possess a deeper understanding of conceptual knowledge (Barron et al., 1998; Harris et al., 2015). When students have a more accurate understanding of scientific concepts and principles, their ability to apply those concepts to explain phenomena is stronger (Braaten & Windschitl, 2011; Liu et al., 2011). Additionally, to clearly and effectively display project products, based on connecting the learned concepts and principles, students must repeatedly consider and practice the expressions in their explanation of results, which naturally improves students' explanatory ability (Harris et al., 2015; Larmer et al., 2015). Moreover, from the perspective of social learning theory,

individuals can actively receive external stimuli; select, organize, and transform those stimuli; and adjust their behaviors accordingly (Bandura, 2001). Accordingly, when students present project outcomes publicly and receive feedback from the audience, they are strongly inclined to reflect on whether the application of scientific principles is appropriate and whether the solutions for driving questions are reasonable. This reflection undoubtedly lays a foundation for encouraging students to continuously improve their explanatory ability.

Autonomy in Research Questions is Not Predictive under a Specific Cultural-Educational Context

Students' control of the right to choose and make decisions in the learning process of PBL is crucial and encouraged (Capraro et al., 2016; Larmer et al., 2015). The item for "autonomy in research questions" in this study focused on whether the research questions were actively put forward by students or directly proposed by teachers. The results indicated that students who believed that the driving questions in their experienced projects were proposed by teachers exhibited better overall scientific problem-solving ability and better performance in each dimension of the posttest. Contrary to the results of this study, some research has concluded that when students proactively motivate themselves to think and pose research questions, they are more likely to develop the ability to solve complex problems (Condliffe et al., 2017; Krajcik & Shin, 2014). Faced with these different results, it is necessary to analyze them by combining the educational and cultural systems of the Chinese student sample.

First, the teaching system in China's basic education stage is attempting to achieve a balance between teacher-centered and learner-centered approaches. Before the introduction of PBL, China had long been influenced by the Confucian classical educational paradigm, which values examinations and modern Soviet educational theories that emphasize the systematization of knowledge and influence China's curriculum development, thereby resulting in a focus on the teaching of basic knowledge (Li, 2004). Accordingly, Chinese students have advantages in terms of the logicity and standardization of knowledge structure (OECD, 2019). While influenced by theories such as constructivism and Dewey's "learning by doing", PBL holds that the acquisition of knowledge is a process of sustained exploration for students, and it has been implemented mainly on the basis of the original Western theoretical framework after being introduced in China. That being said, Chinese students may become aimless in applying it and lack experience in mastering essential skills, such as autonomously proposing good thought-provoking questions (Hu, 2024; Kokotsaki et al., 2016). Rather, students' proposed driving questions may fall outside the teaching objectives and fail to achieve curricular effects, whereas teachers are generally better able to formulate driving questions that align with the curricular goal. Therefore, driving questions directly provided by teachers are likely to be more valuable for sustained inquiry. Second, influenced by thousands of years of Confucian culture, China attaches great importance to the concept of "respecting teachers and valuing morality" and pays close attention to the task of fostering a harmonious teacher-student relationship (Li, 2012). At present, although the Chinese basic education community emphasizes student subjectivity, owing to factors such as cultural inertia, institutional design (e.g., the head teacher system), and parental support for teacher authority, the authority of teachers in many regions remains prominent in classrooms. As a result, students are reluctant to proactively espouse highly challenging views in class, and students' autonomy often remains at a superficial level, resulting in the ineffectiveness of autonomy in posing research questions (Biggs, 1996; Cortazzi & Jin, 1996; Li, 2012). Third, having teachers directly pose research questions may be the most efficient approach given the current Chinese educational situation, which is driven by two practical dilemmas. One dilemma is that under the pressure of high-stakes examinations, classroom time is precious. Thus, efficiently securing high exam scores is the crucial task for teachers and the central demand of students (Hu, 2024). However, as the autonomous question-posing link in PBL requires considerable time for thinking and discussion (Larmer et al., 2015), many teachers directly provide research questions because they dare not waste students' time, given the pressure they are under to pass their exams. The second dilemma is that, owing to China's large population, many regions adopt large-class teaching programs. Hence, teachers' energy is easily excessively disseminated to monitor all classes, thereby making it difficult for them to pay in-depth attention to the progress of each group and the individual needs of each student. This obviously resulted in limited opportunities for teachers to effectively guide students in the art of developing good thought-provoking questions (Blumenfeld, 1991; Thomas, 2000).

Notably, first, the situation wherein "autonomy in research questions" has not yet become a factor in enhancing scientific problem-solving ability may not be unique to China because it might be observed in the broader Confucian cultural circle. Second, the fact that "autonomy in research questions" does not currently promote students' scientific problem-solving ability under China's existing educational culture does not mean that it will never do so, as China's educational ecosystem is constantly improving. Third, "autonomy in research questions", as one of



the core characteristics of PBL, remains important because this study focused only on scientific problem-solving ability and did not discuss other dependent variables (e.g., scientific interest and attitude).

Conclusions and Implications

The results of this study reveal that (1) the QPBL significantly and positively predicts students' scientific problem-solving ability; (2) in terms of the effects of each indicator of the QPBL on total ability, "authenticity" and "group collaboration" positively predict students' scientific problem-solving ability, whereas "autonomy in research questions" exhibits negative effects; and (3) different indicators of QPBL have varying predictive effects on subcomponents of scientific problem-solving ability. Specifically, "authenticity" positively predicts the ability to design scientific inquiry, scientific reasoning ability, and scientific explanation ability; "autonomy in research questions" negatively predicts all three subcomponents; and "group collaboration" and "project demonstration" positively predict some of the subcomponents.

The findings of this study provide valuable implications for how to apply PBL more effectively in educational practice to enhance students' scientific problem-solving ability. First, from the perspective of a powerful combination, by emphasizing the knowledge structure, as long as the authenticity of research questions in PBL is firmly grasped, PBL not only ensures the standardization and logic of the knowledge structure but also permits the application of knowledge in practice and transforms knowledge into capabilities. In this way, the purpose of learning is elevated from "passing exams" to "solving authentic problems," thus enhancing students' scientific problem-solving ability. Second, on the basis of ensuring the authenticity of research questions, students should be encouraged to actively participate in peer collaboration activities and be guided to transform fragmented knowledge into comprehensive abilities in a rigorous and engaging manner during the presentation of project products. This extends learning from the classroom to the real world, which enhances students' scientific problem-solving ability. Third, for future research on PBL, on the basis of emphasizing the advantage of a systematic knowledge structure, China's basic education community can further expand students' autonomous space, perfect the ecological relationship between teachers and students, and organically integrate the traditional wisdom of respecting teachers with the modern concept of valuing learning. Additionally, localizing the theory of PBL in conjunction with China's educational context is necessary to meet the needs of individuals experiencing examination pressure and large-class teaching more effectively. This study is particularly valuable as a reference in PBL research in some countries and regions of the East Asian Confucian cultural circle.

This study has certain limitations with respect to both the instrument and the sampling. First, the QPBL was measured solely through a self-report questionnaire. Although the measurement instrument used in this study was highly correlated with previous classroom observations and local education authorities' evaluations, potential bias may still exist. For instance, students with greater ability might be more willing to participate in PBL and thus perceive the quality of such learning as higher. Consequently, rather than high-quality project-based learning leading to stronger scientific problem-solving ability, it may be that students with greater ability are more likely to report experiencing high-quality project learning. Future research should incorporate more measurement methods, such as classroom observations and analyses of teachers' lesson plan materials, to assess the implementation status of PBL. Second, this study focused on students' autonomy in posing research questions, which is only one aspect of the broader concept of autonomy within the PBL process. Hence, additional questionnaire items should be developed to more comprehensively investigate the effect of autonomy on students' scientific problem-solving ability. Third, at the sample level, this study focused exclusively on students from China through a convenience sampling technique, which limits the generalizability of the findings. Accordingly, further research should be conducted to determine how the QPBL predicts students' scientific problem-solving ability in the broader Confucian cultural circle (Japan, South Korea, Singapore, etc.), and in countries and regions outside of that circle.

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Conflict of Interest Statement

The authors declare no competing interest.

Consent Statement

The authors declare that there was no violation of informed consent.

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