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Exploring the effects of technology-supported collaborative inquiry and students' ICT competency on scientific literacy and subject knowledge in rural science classrooms

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Abstract

Technology-supported collaborative inquiry has notable potential to enhance students' scientific literacy and subject knowledge. However, most technological supports have been conducted in non-rural science classrooms, with their effectiveness in rural classrooms remaining underexplored. Rural students exhibit varying levels of Information and Communication Technology (ICT) competency, and the impact on technology-supported science classrooms warrants further exploration. To address these gaps, this study adopted a six-week experiment to conduct technology-supported collaborative inquiry activities in two eighth-grade classes, with a total of 101 students at a rural secondary school in China. Using a 2 × 2 quasi-experiment design, this study investigated the effects of different experimental interventions and levels of ICT competency on students' scientific literacy and subject knowledge. Students in the experiment class ($n=48$) used a structured collaborative inquiry platform, i.e., WeInquiry, to conduct, record, and share their learning progress, while the students in the comparison class ($n=53$) completed the same activities without the platform support. The results showed that technology-supported collaborative inquiry and students' ICT competency were both conducive to promoting rural students' scientific literacy. Further, the interactive effects of the experimental interventions and students' ICT competency significantly influenced their scientific literacy and subject knowledge. The findings suggest that considering different ICT competencies, technology-supported collaborative inquiry activities can positively impact students' science learning in rural classrooms. More studies are needed to explore how to integrate technological tools to better support science education in rural classrooms, with a particular focus on the influences of students' ICT competencies.

Extended author information available on the last page of the article

Keywords Technology-supported collaborative inquiry · ICT competency · Scientific literacy · Subject knowledge · Rural science classrooms

1 Introduction

Science education is an effective approach to equip learners with 21st-century skills, such as critical thinking, problem-solving, and collaborative work (Larson & Miller, 2011; National Research Council et al., 2012). Despite its importance, rural students often lag behind their non-rural peers in science achievement and engagement, with fewer pursuing science-related fields (Harris & Hodges, 2018; Saw & Agger, 2021). These disparities have raised concerns about educational equity and highlighted the need for strategies to support rural students' learning and development (Beeson & Strange, 2003; Kittleson & Morgan, 2012). While efforts to address these challenges have been tried, like curriculum reforms (Ministry of Education, 2022), technological resources and support (Di Pietro & Castaño Muñoz, 2025; Yang et al., 2019a, b), and improved pedagogical strategies (Moore et al., 2024; Yang et al., 2019a, b), the persistent gap between rural and non-rural science education underscores the need for further exploration of effective approaches tailored to rural contexts (Beeson & Strange, 2003; Cheng & Sun, 2015; Murphy, 2020).

In rural schools, developing students' scientific understanding during their early education is rather crucial, especially in China where nine-year compulsory education is a key period for fostering students' academic skills and personal development, which has a lasting impact on their future opportunities and lifelong learning (Ministry of Education, 2022). High dropout rates after secondary school in rural areas make it critical to maximize the impact of these years by engaging students in meaningful scientific practices that construct subject knowledge and practical skills (Yi et al., 2012). Secondary school marks a pivotal phase where students are introduced to science-specific disciplines (e.g. physics, chemistry, and biology) (Ministry of Education, 2022), with physics particularly relevant due to its strong connections to daily life. Early and meaningful engagement in science through hands-on exploration can spark students' interest and improve their learning outcomes (Abrams & Middleton, 2016; Larson & Miller, 2011), while traditional lecture-centered classrooms often position students as passive listeners, limiting their engagement and interaction with science content (de Jong et al., 2023; Eshuis et al., 2019). Interest, as both a cognitive and motivational factor, significantly influences students' learning experience, scientific identities, and future career aspirations (Fives et al., 2014; Vygotsky et al., 1978).

Engaging students in authentic scientific inquiry - such as asking questions, planning investigations, analyzing data, and drawing conclusions– has been shown to inspire scientific interest and deepen their understanding of the scientific process (Pedaste et al., 2015). However, scientific inquiry is a demanding process requiring critical thinking and active participation (National Research Council, 2012), which can be particularly challenging for rural students with limited prior exposure to such practices (Harris & Hodges, 2018). Collaborative strategies offer a promising solution by enabling students to leverage group efforts to overcome challenges they might struggle with individually (Vygotsky et al., 1978). Through collaborative inquiry, students engage in cycles of reflection and action to achieve shared goals (Bell et al., 2010), address gaps in prior knowledge through collective problem-solving (Eshuis et al., 2019), and make meaningful academic process while fostering a sense of belonging and identity as engaged learners (Abrams & Middleton, 2016). This approach is particularly important for rural students in China, many of whom face limited parental support for their education (Cheng & Sun, 2015; Yi et al., 2012). For these students, the classroom serves as a vital community where collaboration with peers and teachers fosters supportive group dynamics. Such positive interactions not only enhance academic progress (Chen et al., 2022), but also improve communication skills (Sun et al., 2022; Zhao & Chan, 2014), promote positive emotional engagement (Pietarinen et al., 2018), and encourage a greater willingness to participate in scientific inquiry (Simpson et al., 2017).

Scientific inquiry can take many forms, such as direct instructions, laboratory experiments, field trips, online explorations, and cultural and historical investigations (National Research Council, 2012), all of which have the potential to enhance students' scientific learning. Research shows that incorporating technology into inquiry-based learning significantly improves students' scientific performance compared to traditional teaching methods (de Jong et al., 2023; Eshuis et al., 2019). Tools, like the Web-based Inquiry Science Environment (WISE), wikis, and Physics Education Technology (PhET) simulations, provide structured guidelines and resources to support inquiry activities (Chen & Chen, 2024), making them particularly promising for rural classrooms. However, scientific inquiry is inherently contextual and exploratory, requiring explicit instruction and tailored support to address challenges like limited resources and students' prior knowledge (Chi et al., 2024; Cui et al., 2022; Fukuda et al., 2022; Sweller et al., 2023). When implemented thoughtfully, even basic technological tools can support inquiry activities, helping rural students bridge knowledge gaps and develop scientific understanding (Murphy, 2020).

This study focuses on practical scientific inquiry in junior high school physics, building on the prior learning experiences of rural students. By integrating technological tools, it seeks to support students in engaging in meaningful and structured inquiry activities as active learners. Specifically, the study examines the effects of technology-supported collaborative inquiry and students' ICT competency on two key outcomes: scientific literacy and subject knowledge. It provides empirical evidence on the impact of integrating technology into rural science classrooms and its roles in shaping student learning. This study makes two key contributions to science education in rural contexts. First, it offers practical evidence for implementing technology-supported inquiry in under-resourced schools, fostering collaboration and active participation among students. Second, it explores the relationship between students' ICT competency and the effectiveness of technological support, offering insights into how individual ICT skills influence learning outcomes. By addressing these factors, the study contributes to developing more effective and inclusive educational practices for rural classrooms.

2 Literature review

2.1 Collaborative scientific inquiry

Collaborative inquiry combines inquiry-based learning and collaborative learning (Kolloffel et al., 2011), drawing from the social constructivist theory (Vygotsky et al., 1978), which emphasizes learning as a social process where students actively construct and co-construct knowledge through interaction and collaboration (Bell et al., 2010). Inquiry-based learning takes many forms, like lecture-centered instructions, practical investigations in laboratories or outdoor settings, technology-supported online inquiries, cultural and historical investigations, and question-driven explorations. These methods have great potential to deepen students' scientific understanding and inquiry skills. For example, technology-supported environments like virtual labs in platforms such as WISE or PhET provide students with interactive tools to explore and visualize scientific phenomena (Blanchard et al., 2010; Wang & Yu, 2023). Similarly, collaborative tools, such as Knowledge Forums or wikis, support students in sharing and advancing ideas to build knowledge collaboratively (Zhao & Chan, 2014). As a distinct methodology, collaborative scientific inquiry is characterized by active student participation and practical experience to learn science content and science processes (National Research Council, 2007); for example, students engage in scientific inquiry processes where they collaboratively explore, construct, and refine knowledge structures (Bell et al., 2005; National Research Council, 2000). Through this process, students exchange ideas and share inquiry plans with their peers to foster broader exploration and achieve outcomes that might not be possible when working independently (Gijlers & de Jong, 2009). By integrating structured tools and collaborative platforms, collaborative scientific inquiry provides a multifaceted approach to enhancing students' scientific literacy and critical thinking skills.

Pedaste et al. (2015) identified four key phases in the inquiry framework: orientation, conceptualization, investigation, and conclusion, building on earlier studies (Bell et al., 2010; Kim et al., 2015; Kuhn & Pease, 2008). The orientation phase focuses on introducing inquiry context and sparking students' interest in the inquiry topic (Kuhn & Pease, 2008). In the conceptualization phase, students develop a foundational understanding of key concepts and generate group hypotheses or questions (Pedaste et al., 2020). During the investigation phase, students plan and carry out activities, like doing experiments, phenomenon observations, data collection and analysis, to deepen their understanding and scientific interpretation (Kim et al., 2015). In the conclusion phase, students synthesize pieces of evidence to address the initial hypotheses (Kuhn & Pease, 2008), while teachers guide them in summarizing and reflecting on their inquiry processes. Effective collaborative work and discussions throughout all phases are critical for enhancing inquiry performance and learning outcomes (Pedaste et al., 2015). Past studies also highlighted the importance of teamwork in inquiry-based learning (Bell et al., 2010; Kuhn & Pease, 2008), showing that positive group dynamics facilitated productive learning behaviors and achievement through meaningful communication, emotional engagement, and group ideas advancements (Pietarinen et al., 2018; Sun et al., 2022; Zhao & Chan, 2014). Thus, the inquiry framework of Pedaste et al. (2015), combined with collaborative strategies, provides a foundation for designing classroom activities that support rural student engagement in the inquiry process.

The inquiry framework encompasses varying levels of inquiry based on the degree of student autonomy: structured inquiry (Level 1), guided inquiry (Level 2), and open inquiry (Level 3) (Bell et al., 2005; National Research Council, 2007). Structured inquiry, in particular, is well-suited for classroom environments, as it provides students with pre-defined driving questions and methods to support the student inquiry process while offering the room to allow them to interpret results independently (Blanchard et al., 2010). To support structured inquiry, platforms like WISE and PhET offer recourses such as driving questions, resource libraries, experiment stimulations, and argumentation templates to guide students through each stage of the inquiry process (Belland et al., 2019; Chen et al., 2017; Cui et al., 2022). Synchronous collaborative spaces have also been employed to facilitate student interaction and peer feedback during inquiry tasks (Cabiness et al., 2013; Chen et al., 2022). While these supportive tools significantly have been shown to improve student learning outcomes (Chen & Chen, 2024), they are often designed for non-rural classrooms where students typically have greater access to resources and prior exposure to scientific inquiry. Rural students, by contrast, face challenges such as resource constraints and limited support for inquiry-based activities (Harris & Hodges, 2018; Saw & Agger, 2021). These disparities have resulted in a lack of focus on rural students in research and practice, despite longstanding calls to improve rural science education (Beeson & Strange, 2003; Larson & Miller, 2011). Addressing these gaps requires designing strategies and tools that reflect the unique challenges of rural classrooms, ensuring that technology complements rather than disrupts their learning environment.

Scientific inquiry aims to achieve two key learning objectives: helping students understand scientific concepts ("learning through inquiry") and developing inquiry skills ("learning of inquiry") (Fukuda et al., 2022; Yang et al., 2019b). The former involves using inquiry as a means to develop a deeper understanding of scientific concepts through hands-on exploration, while the latter focuses on building the skills necessary to conduct scientific investigations. Although scientific inquiry offers significant potential, its effectiveness in rural classrooms remains certain (Chi et al., 2024). For example, Blanchard et al. (2010) reported positive effects of scientific inquiry activities on student learning outcomes, whereas Chi et al. (2024) reported a negative relationship between scientific inquiry activities and science achievement in certain contexts. These mixed findings highlight the need for further research, particularly in under-resourced settings, to evaluate the effectiveness of scientific inquiry strategies. This study aims to address these gaps by examining the impact of collaborative scientific inquiry in rural classrooms, with and without technology support, on students' subject knowledge and scientific literacy. Subject knowledge refers to the specific content knowledge gained through inquiry activities, such as experiments and hands-on exploration. Scientific literacy, on the other hand, reflects students' ability to understand scientific processes and engage meaningfully with scientific information (Fives et al., 2014). By focusing on these two outcomes, this study seeks to address the gaps in how collaborative scientific inquiry can be tailored to meet the needs of rural classrooms.

2.2 Technological support and ICT competency

ICT and relevant infrastructures have been widely integrated into educational settings to drive innovations and improve classroom practices. Research indicates that ICT-based support as an educational intervention effectively facilitates science education and positively impacts student achievement (de Jong et al., 2023; Eshuis et al., 2019; Hmelo-Silver et al., 2015). However, for ICT-based practices to be successful, students are required to be equipped with basic ICT competencies, including the ability to use computer technology to access learning resources, and the skills to investigate, create, and communicate within technology-supported activities (Fraillon et al., 2014; Heerwegh et al., 2016). Kalyuga (2011) pointed out that students who struggled with technological tools during limited class time might experience cognitive overload, which could hinder their learning performance; for instance, when managing technology consumed excessive mental effort, it reduced the time and focus available for core learning tasks, leading to lower academic performance (Kirschner, 2002). Therefore, the effectiveness of technological support in classrooms is closely tied to students' ICT competency.

Based on data from the Programme for International Student Assessment (PISA), research has highlighted links between student ICT-related factors and their scientific literacy (Guo et al., 2022; Hu et al., 2018). For example, Guo et al. (2022) found that students' ICT interest, autonomy in using ICT, and ICT availability at school positively impacted their scientific literacy. Huang et al. (2021) reported a positive relationship between students' ICT self-efficacy and their ICT use in learning, though they noted that ICT use in learning had a negative relationship with students' science proficiency. Hu et al. (2018) further revealed contrasting effects of ICT availability: school-based ICT use was positively linked to academic performance, while home-based ICT use had a negative association. Additionally, Porozovs and Āne (2017) found that students held positive attitudes toward ICT's role in their learning process, with ICT-based tools improving their understanding of subject knowledge and increasing their learning motivations. These studies indicated that students' ICT competency and the context in which ICT was used had varying impacts on scientific learning outcomes. However, most of these studies rely on existing datasets or surveys rather than empirical interventions, leaving the specific influence of students' ICT competency on the effectiveness of technology-supported collaborative inquiry activities underexplored.

Another key reason for focusing on the influences of students' ICT competency on learning outcomes in technology-supported scientific inquiry is the growing body of research on designing technological tools to enhance inquiry-based learning and their influences on students' learning achievements (Authors, 2024). For example, Chen et al. (2017) developed a structured inquiry platform that used driving questions and multimedia resources to guide students through learning about moon phases. Similarly, Cui et al. (2022) introduced WISE to help students explore thermal phenomena and principles. While these studies highlight the potential of technological tools in supporting inquiry activities, they rarely examine how students' ICT competency influences the effectiveness of these interventions. ICT competency is a critical factor that can shape students' inquiry processes and outcomes in technology-supported classroom activities (Guo et al., 2022), especially in rural classrooms where technological resources and pedagogical support are often limited (Ihrig et al., 2022; Yang et al., 2013). Students in these settings may have varying levels of ICT competency, which can affect their ability to engage effectively in collaborative scientific inquiry. Consequently, technological tools may yield different learning outcomes depending on students' ICT proficiency, influencing both their subject knowledge and scientific skills.

In this study, students' ICT competency is defined as their access to ICT, attitudes toward technology, and confidence in using computer tools to perform basic ICT-based tasks and activities (OECD, 2018). The technological tools provided in this research are designed as learning aids to support students in hands-on inquiry tasks, requiring them to have basic ICT skills to effectively operate and utilize digital resources during collaborative inquiry activities. While previous studies have largely focused on the effects of ICT-based interventions or teachers' ICT competency on classroom practices (Eilks et al., 2017; Hmelo-Silver et al., 2015), there is limited research examining the interaction between students' ICT competency and technology-supported science learning, particularly in rural classrooms.

2.3 The current study

This study aimed to explore the influences of students' ICT competency and technology-supported collaborative inquiry on two core learning outcomes in rural science classrooms: scientific literacy and subject knowledge. The collaborative scientific inquiry activities in this study were designed using the framework of Pedaste et al. (2015), which included tasks such as inquiry orientation, hypothesis generation, hands-on exploration, data interpretation, and activity summary. These activities were implemented through a structured inquiry approach using the WeInquiry platform designed by this study. In this structured inquiry model, students were guided by driving questions and investigation methods but were free to interpret their data (Bell et al., 2005). Teachers provided predefined resources, such as driving questions and investigation guidelines, within the WeInquiry system to support collaborative inquiry and enhance learning performance.

Aligned with the two main objectives of scientific inquiry—learning through inquiry and learning of inquiry (Fukuda et al., 2022)—this study measured subject knowledge and scientific literacy to evaluate students' learning outcomes. Rural classrooms, characterized by limited technological resources and pedagogical support (Guo et al., 2022), often include students with varying levels of ICT competency, which may influence the effectiveness of technology-based interventions. Therefore, this study explored the interactive relationship between students' ICT competency and technological support and how these factors affected learning outcomes. This study was guided by the following research questions:

(1) what is the influence of technology-supported collaborative inquiry and students' ICT competency on scientific literacy?

(2) what is the influence of technology-supported collaborative inquiry and students' ICT competency on subject knowledge?

For the first research question, we hypothesize that technological support relates positively to the scientific literacy of students with high and low ICT competency, as prior studies have demonstrated the benefits of technological tools in enhancing inquiry skills (Chen et al., 2022; Delen & Krajcik, 2018; Fukuda et al., 2022). Similarly, for the second question, it is hypothesized that technology-supported inquiry improves subject knowledge for students with both high and low ICT competency. While previous studies have reported similar findings (Cui et al., 2022; Wang & Yu, 2023), these relationships have not been extensively explored in rural science classrooms.

3 Methodology

Using a 2 × 2 quasi-experimental design, the goal of the research was to investigate the effects of technology-supported collaborative inquiry of different experimental interventions and diverse levels of ICT competency on students' scientific literacy and subject knowledge.

3.1 Participants

This study was conducted in a rural secondary school in Chongqing, China, where ICT infrastructure supports only basic network connections. This school faces a shortage of science teachers and struggles to retain them. It serves approximately 800 students, over 80% of whom are left-behind children (Cheng & Sun, 2015). These students remain in rural areas with their grandparents while their parents migrate to urban centers for work to support their families. A total of 101 eighth-grade students from two classes participated in this study. One class, consisting of 48 students (24 girls, 24 boys, average age: 13.77), was designated as the experimental group (EG). The other class, comprising 53 students (26 girls, 27 boys, average age: 13.92), served as the comparison group (CG). The EG utilized the WeInquiry system to support their collaborative inquiry tasks, while the CG completed the same tasks without the support of WeInquiry. During the experiment, some students missed the classes or the tests due to illness or transfer, resulting in a total of 94 effective participants, with 46 students in the EG and 48 in the CG.

Both groups were taught by the same teacher, who holds a bachelor's degree in physics education, has over seven-year teaching experiences, and demonstrates high ICT competency and teaching enthusiasm. The teacher is experienced in practice-oriented pedagogies, such as project-based and inquiry-based learning. Before the experiment, this study design was disclosed to the school principal and the teacher, both of whom signed consent forms. Consent forms were also distributed to participating students, who took them home for their guardians to review and sign. During the experiment, all participants were informed of their rights to participate voluntarily and withdraw at any time. Confidentiality was maintained by anonymizing participants' identities.

3.2 Instruments

The instruments adopted in this study were pre- and post-tests about students' scientific literacy and subject knowledge and a questionnaire about their ICT competency.

The scientific literacy test aims to evaluate students' general understanding of science, including their abilities to think and act scientifically, recognize science roles in society, and understand its connections to media and mathematics (Fives et al., 2014). Adapted from Fives et al. (2014), the test consists of 26 items with a total score of 130. Example questions include: "A country has a high rate of tooth decay per person. Which of the following questions about tooth decay can only be answered through scientific experiments?" and "What percentage of people in the sample shown in the chart are over the age of 15?". To ensure the test's clarity and appropriateness, a pilot study was conducted with an eighth-grade class from the same rural school, which was not included in the main experiment. The pilot confirmed that students could comprehend the test content and complete the items within the allotted time. The reliability of the test was assessed using Cronbach's alpha, yielding a value of 0.772. This indicates good internal consistency, suggesting that the items reliably measure the construct of scientific literacy and are sufficiently cohesive to represent the intended domain.

The subject knowledge test assessed students' proficiency in the physics topics of pressure and buoyancy, using items selected from the Chinese High School Entrance Examination (CHSEE). Initially, 60 relevant items were chosen by the research team. These items were reviewed by five physics teachers from the school (excluding the participating teacher), who narrowed the selection to 45 items based on content relevance. After considering item difficulty and type, a final set of 20 items was chosen, with a maximum score of 80. The test consists of eight multiple-choice questions, nine fill-in-the-blank questions, and three comprehensive questions. Examples of test items included: "Pascal once used a sealed wooden barrel filled with water, inserted a thin tube into the lid of the barrel, and poured water into the thin tube. As a result, the barrel cracked after only a few cups of water. What physical principle can explain this experiment?" "Xiaoli was walking in the rain with an umbrella. When a strong wind blew, the umbrella surface was 'sucked' and severely deformed. Which of the following options correctly explains this phenomenon?" The subject knowledge test has been widely recognized for its reliability and validity in assessing students' mastery of physics. In this study, the test demonstrated good internal consistency, achieving a Cronbach's alpha of 0.886, meaning the test items are consistent in measuring the construct of physics knowledge.

An ICT competency questionnaire, adapted from the PISA 2018 assessment (OECD, 2018), was utilized in this study. Students' ICT competency refers to their access to ICT, as well as their attitudes and confidence in using computers for ICT-related tasks and activities (OECD, 2018). The questionnaire comprised 13 items measured on a five-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree). Sample items include: "The Internet is a great resource center for a lot of content that interests me" and "When I encounter problems with electronic devices, I believe I can solve them." The Cronbach's alpha of the questionnaire is 0.837, indicating good reliability.

3.3 WeInquiry system

The WeInquiry system is a structured collaborative inquiry platform developed to support three core inquiry tasks: hypothesis generation, scientific exploration, and interpretation, guided by the framework proposed by Pedaste et al. (2015). As shown in Fig. 1, the platform is designed for classroom inquiry environments, requiring only a basic school network connection and students' basic ICT competency, such as reading, typing, viewing, and recording pictures or short videos.

The WeInquiry system includes three collaborative inquiry spaces tailored for different inquiry tasks: the joint problem space, the collaborative exploration space, and the shared knowledge space. These spaces are online, synchronous collaborative areas where students can implement, record, and share their inquiry tasks and achievements. The joint problem space includes driving questions and a group note-sharing area, which allows students to propose hypotheses and receive feedback from their peers. The collaborative exploration space features driving questions, exploratory scripts, and a group note-sharing area. The exploratory scripts contain multiple thinking questions and short experiment-related videos to guide students through executing and observing their group's experimental process. The group note-sharing area helps students document and share their exploration process. The shared knowledge space involves driving questions, interpretation templates, and group discussion areas, which guide students to propose and discuss their group's interpretations with peers using the CER (claim-evidence-reasoning) framework (McNeill et al., 2006). The WeInquiry system primarily facilitates the guiding, recording, and sharing of the group's collaborative exploration process in class. It helps students self-monitor and continuously adjust their group's exploration performance, thereby improving the quality and achievement of their group's exploration.

Fig. 1 Collaborative inquiry spaces within the WeInquiry system

3.4 Classroom hands-on inquiry activities

The classroom hands-on inquiry activities were conducted weekly during the experiment, lasting 40–60 min per session. These activities followed four stages based on the framework of Pedaste et al. (2015): orientation, conceptualization, investigation, and conclusion (see Fig. 2). The orientation and conclusion stages were teacher-guided, while the conceptualization and investigation stages were completed by students in groups, with teachers aiding as needed. Before the experiment, students in both EG and CG were introduced to the RIDE rules - Respect, Intelligent collaboration, Deciding together, and Encouraging - to promote effective collaboration, given their limited prior experience (Saab et al., 2007). Both groups participated in inquiry activities with similar structures and content, receiving comparable learning resources to complete the same tasks. The key difference was that EG students used the WeInquiry system (See Fig. 1) to support their inquiry, while CG students relied on their traditional inquiry methods.

The inquiry activities focused on physics-related topics such as flow rate and factors affecting buoyancy (Physics Course Materials Research and Development Center, 2012). For example, Fig. 2 depicts a group of students investigating the factors affecting buoyancy. Figure 2 shows the whole structure of classroom inquiry activities. The time allocated to each stage varied based on the complexity of the topic, but these adjustments were applied consistently across both groups. This structured approach ensured consistency between the groups while allowing the study to evaluate the impact of the WeInquiry system on the EG's inquiry process and learning outcomes. Each session followed this structure:

- Orientation stage: The teacher spent about five minutes reviewing previous

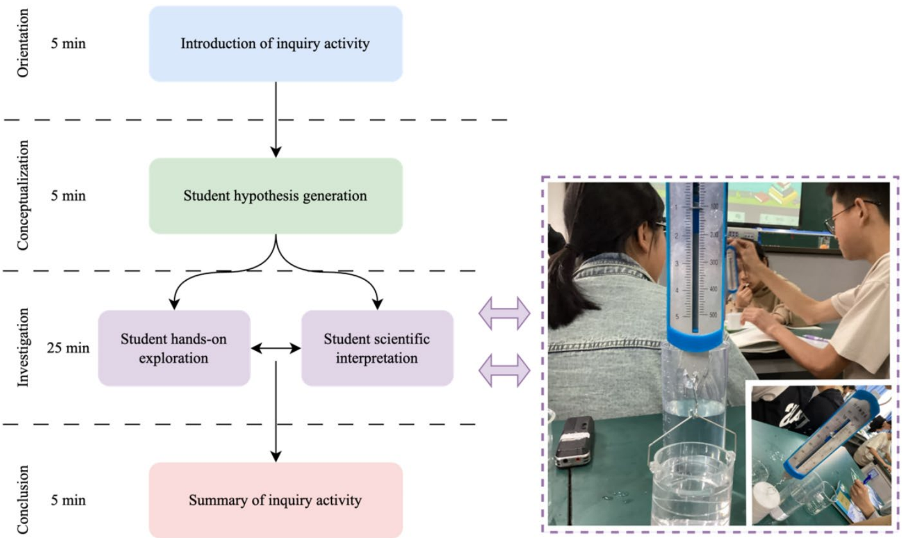

Fig. 2 The procedure of classroom collaborative inquiry through hands-on activities

knowledge, introducing new concepts, and stimulating interest in the inquiry topic.

- Conceptualization stage: Students worked in groups to discuss their ideas and propose inquiry hypotheses. All students could ask questions and share ideas with other groups. EG students recorded their hypotheses in the WeInquiry system (see left top in Fig. 1), where they could also view or browse hypotheses submitted by other groups. This feature allowed EG students to revise and resubmit their group's hypotheses based on peer input. In contrast, CG students recorded their group's hypotheses in their notebooks.
- Investigation stage: Students planned and conducted experiments based on their hypotheses. Both groups were encouraged to document their experimental processes in notebooks, including any information they deemed important. EG students were additionally required to record their data and observations in the WeInquiry system (see right top in Fig. 1), while CG students relied solely on their notebooks.
- Conclusion stage: Students organized their findings and developed scientific explanations using the CER framework (McNeill et al., 2006). EG students used a CER template integrated into the WeInquiry system (see bottom left of Fig. 1), which provided structured and technology-supported guidance for interpreting their data. CG students were also given the same CER template but were not required to use it. Instead, CG students followed their school's traditional practice of taking notes during data interpretation. This decision was made to reflect students' typical learning experience and maintain consistency with their prior practices. Pilot tests indicated that students struggled with CER-based interpretation without additional support, suggesting its mandatory use could introduce undue difficulty. To ensure fairness, all students received teacher guidance after completing their interpretations. During this time, the teacher facilitated reporting inquiry results using the CER framework, encouraged reflection on learning experiences, and addressed any remaining questions.

3.5 Experimental procedure

Before starting the experiment, we collaborated with the school's physics team to design classroom collaborative inquiry activities. The team consisted of six physics teachers with over seven years of teaching experience. We integrated scientific inquiry activities with subject knowledge learning to cultivate students' understanding and application of fundamental physical concepts as well as enhance their ability to analyze and solve physics-related scientific problems through hands-on activities (Physics Course Materials Research and Development Center, 2012). We worked closely with the participating teacher to ensure a comprehensive understanding of collaborative inquiry concepts, strategies, and implementation. During the preparation phase, the teacher practiced scientific inquiry activities in non-participating classes to refine and ensure the effectiveness of the subsequent classroom inquiry activities in EG and CG classes.

The experiment lasted six weeks. Figure 3 presents the experimental procedure. In the first week (Week 1), we introduced the project to the students and conducted a test

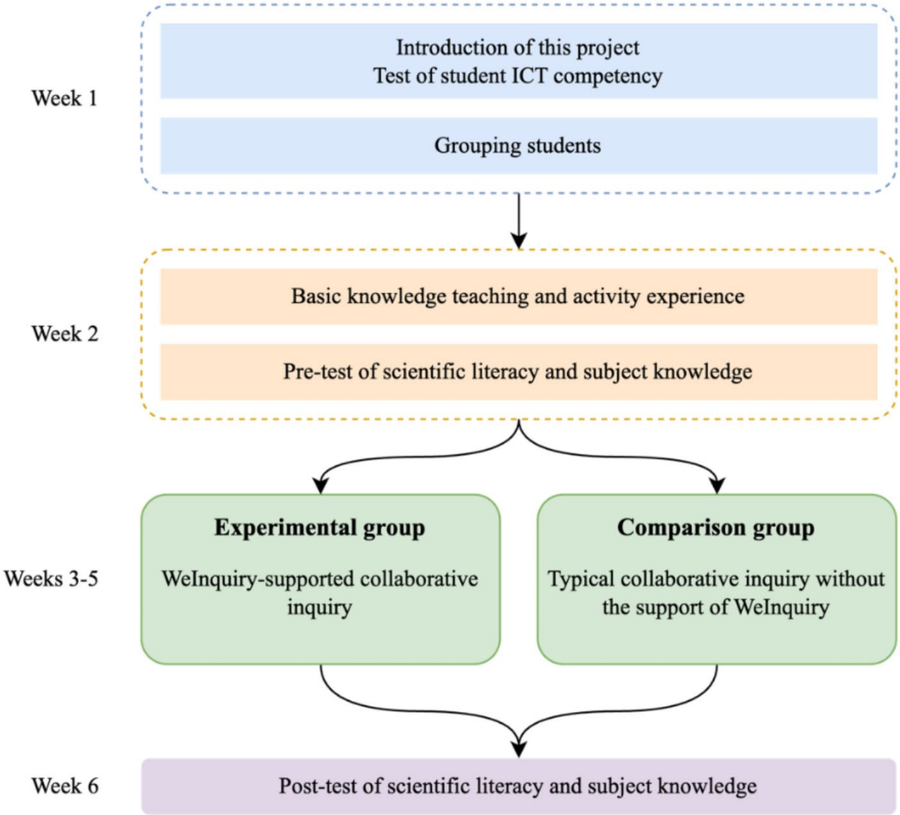

Fig. 3 Overview of the experimental procedure

to assess their ICT competency. Then, we grouped the students based on their academic performance in physics, classroom participation, ICT competency, and gender. Each group consisted of 5 to 6 students, with one tablet shared among them. In the second week (Week 2), we introduced the concepts of collaborative inquiry to prepare students for classroom activities. The content included the inquiry framework (Pedaste et al., 2015), learning goals (Physics Course Materials Research and Development Center, 2012), and collaborative strategies such as RIDE rules (Saab et al., 2007). We also provided collaborative inquiry learning experience activities to help students understand how to participate effectively in these activities. For students in EG, we introduced the WeInquiry system and provided sufficient time for them to familiarize themselves with the platform. After ensuring that students in both EG and CG classes had no further questions about collaborative inquiry and no questions about the platform for EG students, we conducted the 40-minute scientific literacy pretest and the 60-minute subject knowledge pretest. Students were required to complete all the items using a paper-and-pencil format for the two tests.

After that, we conducted three consecutive weeks (Weeks 3–5) of technology-supported classroom collaborative hands-on inquiry activities. During this period, both classes engaged in 40- to 60-minute inquiry sessions each week. The EG students used the WeInquiry system to complete their inquiry tasks, while the CG students did not use the WeInquiry system and followed their traditional inquiry strategies. After completing three weeks of classroom activities, students in both EG and CG were required to complete a 40-minute scientific literacy posttest and a 60-minute subject knowledge posttest using the paper-and-pencil format (Week 6). Following the tests, we facilitated a session for students and the teacher to summarize and reflect on the classroom inquiry activities.

4 Results

This study developed the WeInquiry system to support rural secondary students for collaborative inquiry in science classrooms. We conducted a six-week quasi-experimental study to investigate the effects of different interventions (i.e., CG and EG) and levels of ICT competencies (i.e., high and low) on students' scientific literacy and subject knowledge. Based on the mean scores collected from the ICT competency questionnaire collected during the first week of the experiment, we divided students into low-ICT and high-ICT groups. In the CG, there were 25 high-ICT students (53%) and 22 low-ICT students (47%). In the EG, there were 30 high-ICT students (65%) and 16 low-ICT students (35%). A total of 94 out of 101 students (93%) completed the technology-supported collaborative inquiry activities and the tests of scientific literacy and subject knowledge. One student's post-test score was identified as an outlier and was excluded from the subsequent analysis. Therefore, data from 93 students, with 46 in the EG and 47 in the CG, were analyzed in the following sections.

4.1 Analysis of student scientific literacy

To examine the impact of different experimental interventions and levels of ICT competency on student scientific literacy, we employed a two-way analysis of covariance (ANCOVA) using the pre-test scores of students' scientific literacy (Pre-SL) as the covariate to investigate the effectiveness. The dependent variable was the student's scientific literacy as measured by the post-test results (Post-SL), while the independent variables were two experimental interventions (i.e., CG and EG) and two levels of ICT competencies (i.e., high and low). We used partial eta square (η^2) to represent the measure of effect size, categorized as follows: (1) 0.01 for a small effect size, (2) 0.06 for a medium effect size, and (3) 0.14 for a large effect size (Cohen, 2013). Levene's test for the assumption of homogeneity was not violated ($F[3, 89]=2.626$, $p=0.055>0.05$), suggesting that a common regression coefficient was appropriate for a two-way ANCOVA. The descriptive data of students' scientific literacy for the two experimental intervention groups with both high and low ICT competency appear in Table 1.

As presented in Table 2, the ANCOVA results showed that the experimental interventions had a statistically significant effect on students' scientific literacy ($F[1, 88]=12.215$, $p<0.001$), with a medium effect size of 0.122. Likewise, students' ICT competency had a significant effect on their scientific literacy ($F[1, 88]=10.619$, $p=0.002<0.01$) with a medium effect size of 0.108. Furthermore, the results showed

Table 1 Descriptive data of students' pre-and post-test scores in scientific literacy

Group	ICT	*n*	Pre-SL[1] (*max* = 130)		Post-SL[2] (*max* = 130)	
			M	*SD*	*M (adjusted)*	*SD (adjusted)*
CG[3]	Low-ICT	22	51.818	19.673	44.604	17.416
	High-ICT	25	60.000	20.716	65.99	17.66
EG[4]	Low-ICT	16	51.250	17.654	66.911	17.42
	High-ICT	30	50.667	19.902	69.779	17.461
Total	Low-ICT	38	51.579	18.603	55.758	17.661
	High-ICT	55	54.909	20.627	67.885	17.517

[1] Pre-SL, Pre-test Scientific Literacy

[2] Post-SL, Post-test Scientific Literacy

[3] CG, Comparison Group

[4] EG, Experimental Group

Table 2 The two-way ANCOVA results of scientific literacy

	SS	df	MS	F	η^2
Pre-SL[1] (covariate)	10829.074	1	10829.074	35.766***	0.289
Intervention	3698.506	1	3698.506	12.215***	0.122
ICT	3215.187	1	3215.187	10.619**	0.108
ICT * Intervention	1868.574	1	1868.574	6.172*	0.066
Error	26643.934	88	302.772		

* $p<0.05$, ** $p<0.01$, *** $p<0.001$

[1] Pre-SL, Pre-test Scientific Literacy

Table 3 Simple main-effect analysis results of different experimental interventions on students' scientific literacy

Variables		SS	df	MS	F	η2
Low-ICT	Between groups	4608.785	1	4608.785	15.222***	0.147
	Within groups	26643.934	88	302.772		
High-ICT	Between groups	189.27	1	189.27	0.625	0.007
	Within groups	26643.934	88	302.772		

*** $p<0.001$

a significant interaction effect between the experimental interventions and students' ICT competencies ($F[1, 88]=6.172$, $p=0.015<0.05$). The interaction effect (η^2) was 0.066, representing a relatively medium effect size (Cohen, 2013).

To further investigate the simple main effects analysis of experimental interventions, the study examined students' scientific literacy at different levels of ICT competency, using Bonferroni adjustments for multiple comparisons. As shown in Table 3, there was a significant difference in scientific literacy among low-ICT students of different experimental interventions ($F[1, 88]=15.222$, $p<0.001$, $\eta^2=0.147$). Specifically, low-ICT students in the EG (M_{adj} = 66.911) demonstrated significantly higher adjusted mean scientific literacy compared to their peers in the CG (M_{adj} = 44.604). On the other hand, the results showed no significant difference in scientific literacy among high-ICT students in both EG and CG interventions ($F[1, 88]=0.625$, $p=0.431>0.05$). These results show that the EG intervention, which included the

Table 4 Simple main-effect analysis results of different ICT competency levels on students' scientific literacy

Variables		SS	df	MS	F	η2
CG	Between groups	5233.384	1	5233.384	17.285***	0.164
	Within groups	26643.934	88	302.772		
EG	Between groups	85.825	1	85.825	0.283	0.003
	Within groups	26643.934	88	302.772		

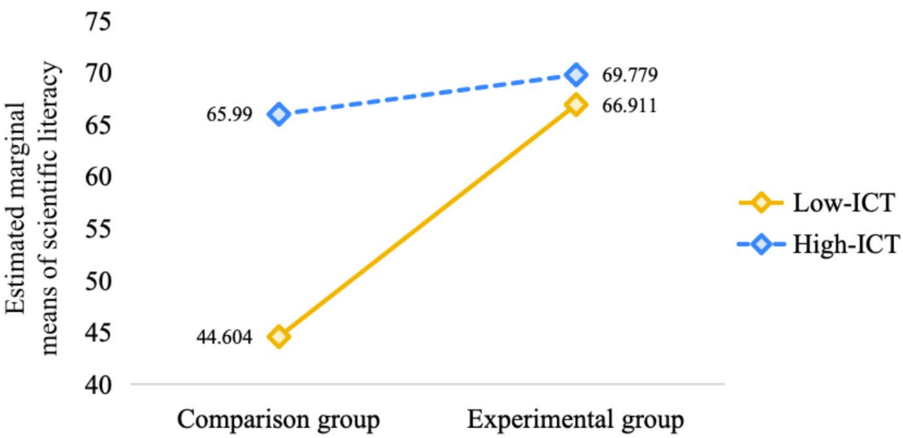

Fig. 4 Interaction between different experimental interventions and ICT competency levels on students' scientific literacy

support of WeInquiry, was more beneficial for low-ICT students than high-ICT students.

Table 4 shows the results of the simple main effects analysis on the influence of ICT competency levels on students' scientific literacy across different experimental interventions. The results revealed a significant difference in scientific literacy among students in CG of different ICT competency levels (F[1, 88] = 17.285, p < 0.001, η^2 = 0.164). Specifically, students with high ICT competency (M_{adj} = 65.99) exhibited higher scientific literacy than those with low ICT competency (M_{adj} = 44.604). In contrast, within the EG, where students engaged in WeInquiry-supported collaborative inquiry, there was no significant difference in scientific literacy between students with high and low ICT competency (F[1, 88] = 0.283, p = 0.596 > 0.05). These results indicate that, in the CG intervention without the support of WeInquiry, students with high ICT competencies achieved greater gains in scientific literacy compared to those with low ICT competencies.

Figure 4 depicts the interaction between the two experimental interventions and ICT competency levels on students' scientific literacy. The data show that students with low ICT competencies in the EG outperformed their peers in the CG in terms of post-test scores. In contrast, no significant differences were observed between students with high ICT competencies in both the EG and CG. Additionally, within the CG intervention, students with high ICT competencies demonstrated higher scientific literacy compared to those with low ICT competencies. Nevertheless, in the EG inter-

Table 5 Descriptive data of students' pre- and post-test scores in subject knowledge

Group	ICT	*n*	Pre-SK[1] (*max* = 80)		Post-SK[2] (*max* = 80)	
			M	*SD*	*M (adjusted)*	*SD (adjusted)*
CG[3]	Low-ICT	22	36.045	14.311	42.953	10.385
	High-ICT	25	43.160	17.119	50.290	10.325
EG[4]	Low-ICT	16	44.688	19.168	46.519	10.348
	High-ICT	30	39.567	16.666	44.816	10.297
Total	Low-ICT	38	39.684	16.849	44.736	10.424
	High-ICT	55	41.200	16.813	47.553	10.338

[1] Pre-SK, Pre-test Subject Knowledge

[2] Post-SK, Post-test Subject Knowledge

[3] CG, Comparison Group

[4] EG, Experimental Group

Table 6 The two-way ANCOVA results of subject knowledge

	SS	df	MS	F	η^2
Pre-SK[1] (covariate)	14820.036	1	14820.036	139.949***	0.614
Intervention	19.981	1	19.981	0.189	0.002
ICT	174.888	1	174.888	1.652	0.018
ICT * Intervention	436.360	1	436.360	4.121*	0.045
Error	9318.862	88	105.896		

* $p < 0.05$, *** $p < 0.001$

[1] Pre-SK, Pre-test Subject Knowledge

vention, there were no significant differences in scientific literacy between students with high and low ICT competencies. These results indicate that WeInquiry-based support was particularly beneficial for enhancing scientific literacy among low-ICT students.

4.2 Analysis of student subject knowledge

Table 5 presents the descriptive data of students' subject knowledge across the two experimental interventions, categorized by high and low ICT competencies. We employed a two-way analysis of covariance (ANCOVA) using students' pre-test scores of subject knowledge (Pre-SK) as the covariate to examine the effectiveness of the interventions. The dependent variable was the student's subject knowledge as measured by the post-test results (Post-SK), while the independent variables were two experimental interventions (i.e., CG and EG) and the two levels of ICT competencies (i.e., high and low). Levene's test confirmed the assumption of homogeneity was not violated ($F[3, 89] = 0.967$, $p = 0.412 > 0.05$), suggesting that a common regression coefficient was appropriate for conducting the two-way ANCOVA.

As presented in Table 6, the ANCOVA findings revealed a significant interaction effect between the experimental interventions and students' ICT competencies ($F[1, 88] = 4.121, p = 0.045 < 0.05, \eta^2 = 0.045$), indicating a small effect size (Cohen, 2013). These results suggest that the interaction of different experimental interventions and varying levels of ICT competencies could impact students' subject knowledge.

Table 7 Simple main-effect analysis results of different experimental interventions on students' subject knowledge

Variables		SS	df	MS	F
Low-ICT	Between groups	114.605	1	114.605	1.082
	Within groups	9318.862	88	105.896	
High-ICT	Between groups	405.821	1	405.821	3.832
	Within groups	9318.862	88	105.896	

Table 8 Simple main-effect analysis results of different ICT competency levels on students' subject knowledge

Variables		SS	df	MS	F	η2
CG	Between groups	615.281	1	615.281	5.81*	0.062
	Within groups	9318.862	88	105.896		
EG	Between groups	29.956	1	29.965	0.283	0.003
	Within groups	9318.862	88	105.896		

* $p<0.05$

To further investigate the results of the simple main effects analysis of experimental interventions, the study examined students' subject knowledge across different ICT competency levels using Bonferroni adjustments. As shown in Table 7, there was no significant difference in students' subject knowledge among low-ICT students of different experimental interventions ($F[1, 88]=1.082$, $p=0.301>0.05$). Similarly, the analysis showed no significant difference in subject knowledge among high-ICT students between EG and CG interventions ($F[1, 88]=3.832$, $p=0.053>0.05$).

Table 8 shows the results of the simple main effects analysis on the influence of ICT competency levels on students' subject knowledge across different experimental interventions. The results revealed a significant difference in subject knowledge among students in CG of different ICT levels ($F[1, 88]=5.81$, $p=0.018<0.05$, $\eta^2=0.062$). Specifically, in the CG, students with high ICT competency (M_{adj} = 50.29) had higher adjusted mean subject knowledge than those with low ICT competency (M_{adj} = 42.953). Conversely, in the EG, where students were supported by WeInquiry, there was no significant difference in subject knowledge between students with high and low ICT competency levels ($F[1, 88]=0.283$, $p=0.596>0.05$). These results indicate that, in the CG without the support of the WeInquiry system, students with high ICT competency gained more subject knowledge than those with low ICT competency.

Figure 5 depicts how two experimental interventions and ICT competency levels interacted to affect students' subject knowledge. The data shows that, in the CG, students with high ICT competencies outperformed their peers with low ICT competencies in post-test scores. In contrast, students in the EG demonstrated no significant differences in their subject knowledge scores regarding their ICT competency levels. Furthermore, there was no significant difference in subject knowledge scores between CG and EG students, regardless of their ICT competency levels. These results suggest that while the WeInquiry-supported experimental intervention did not impact students' subject performance, ICT competency itself played a significant role. Specifically, students with high ICT competency benefited more from classroom

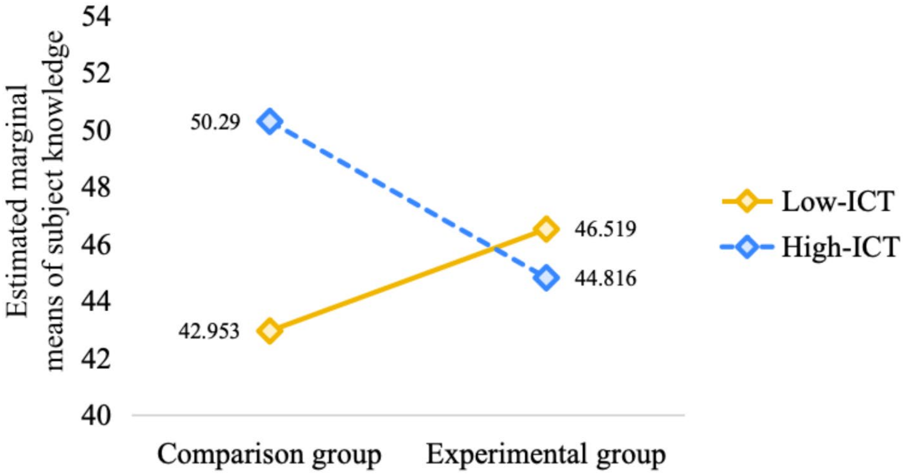

Fig. 5 Interaction between different experimental interventions and ICT competency levels on students' subject knowledge

activities, showing greater growth in subject knowledge compared to their low-ICT competency peers.

5 Discussion

This study conducted a six-week quasi-experiment in rural science classrooms to examine the influence of technology-supported collaborative inquiry and students' ICT competency on two learning outcomes: scientific literacy and subject knowledge. The findings confirmed both hypotheses. The results showed that, on the one hand, both the experimental interventions and students' ICT competency were significantly conducive to promoting students' scientific literacy. On the other hand, the experimental interventions and students' ICT competency had interactive effects both on students' scientific literacy and subject knowledge.

5.1 Practices of technology-supported collaborative inquiry in rural science classrooms

The findings confirm that technology-supported collaborative inquiry positively impacts students' scientific outcomes: subject knowledge and scientific literacy. However, only scientific literacy showed a significant difference between CG and EG groups, which suggests that engaging students in practical inquiry activities fosters learning through inquiry (developing subject knowledge) and learning of inquiry (building scientific skills) (Fukuda et al., 2022; Yang et al., 2019b). This aligns with prior research showing that hands-on exploration and action-oriented activities support the development of scientific knowledge and skills (Chen & Chen, 2024).

In this study, practical inquiry activities and group collaboration provided meaningful support for students in both groups. Rural students– who often have fewer opportunities for scientific learning and limited ICT competencies (Di Pietro & Castaño Muñoz, 2025; Saw & Agger, 2021)– benefited from inquiry activities tailored to their constraints. The activities were designed around everyday physics topics (Physics Course Materials Research and Development Center, 2012), enabling students to explore real-world phenomena through collaborative and hands-on exploration, which potentially enhanced students' interest in science, boosted their motivation to learn, and contributed to their cognitive development (Larson & Miller, 2011). Working in groups allowed students to construct knowledge through peer interaction, fostering positive emotional engagement, improved communication skills, and continuous social interaction (Pietarinen et al., 2018; Simpson et al., 2017). These collaborative experiences helped students develop a stronger sense of belonging and identity within the science classroom (Abrams & Middleton, 2016), ultimately supporting productive scientific exploration. By shifting away from rote memorization to meaningful, collaborative tasks, students deepened their connection to science. Consequently, both groups showed improvements in scientific literacy and subject knowledge.

The WeInquiry system supported EG significantly, particularly for students with higher ICT competency, resulting in better post-test performance. This finding aligns with prior research showing that structured technological interventions enhance students' inquiry processes and outcomes (Belland et al., 2019; Blanchard et al., 2010; Cui et al., 2022). The WeInquiry system offered both generic and content-specific support by guiding students through staged inquiry tasks, enabling them to document experimental processes (e.g., taking photos, describing observation), and facilitating their understanding and construction of topic-related explanations. These structured supports acted as explicit scaffolds to reduce their potential competence frustration and help them adopt effective learning behaviors, then improve their learning achievements (Delen & Krajcik, 2018; Pedaste et al., 2015). Besides, real-time shared areas in the WeInquiry system, which displayed the progress of other groups, encouraged students to reflect on and refine their group's exploratory outcomes. These collaborative activities fostered a positive and interactive group atmosphere, promoting constructive emotions and behaviors that supported productive learning (Bell et al., 2010). Through these cooperative problem-solving experiences, students likely developed essential skills such as experimental design, problem-solving, group argumentation, and collaborative communication (Blanchard et al., 2010; Chen et al., 2017). However, further research with more detailed data on the learning process is needed to validate the long-term impacts of these potential benefits.

However, students with limited ICT competency faced challenges in effectively utilizing these resources. For these students, technological barriers may impede their ability to access and benefit fully from the WeInquiry system's support (Fraillon et al., 2014). Similarly, CG students, who lacked the structured support of the system, had to rely on traditional methods to monitor and regulate their group's inquiry process. This proved difficult for rural students with limited prior experience in inquiry learning. Without explicit instruction or technological support, students often struggle to develop foundational inquiry skills (Abrams & Middleton, 2016; Chi et al., 2024). Previous studies indicate that when students lack the ability to effectively use support strategies, they experience greater competence frustration (Raes & Schellens, 2016), which undermine their confidence and negatively impact task performance and learning outcomes (Pietarinen et al., 2018). Moreover, it is challenging for teachers to provide individualized guidance to every group in large-size classrooms, as shown in this study. The WeInquiry system helped address this limitation by offering structured, consistent support to EG students, enabling teachers to better facilitate the inquiry process and promote student learning outcomes. However, further exploration is needed to explore how technology can provide more adaptive support in rural classroom settings, where these designs require careful account for factors like diverse student needs, teacher teaching preferences, and environmental resource limitations.

5.2 The main effects of technology-supported collaborative inquiry and ICT competency

The findings indicated that the experimental interventions significantly impacted students' scientific literacy, particularly among EG groups supported by the WeInquiry system. This finding aligns with previous studies showing the effectiveness of structured collaborative inquiry platforms in enhancing students' inquiry performance and skills (Belland et al., 2019; Cabiness et al., 2013). These structured supports aim to help students monitor and regulate their inquiry performance and achievements while working collaboratively with their peers (Authors, 2024). This collaborative process benefits students by helping them develop and strengthen their scientific skills through practical activities. ICT competency also emerges as a significant factor influencing scientific literacy. High-ICT students were more effective in using technology-supported inquiry to achieve better inquiry outcomes in post-tests, aligning with previous research that showed the relationship between students with basic ICT competency and their science literacy (Guo et al., 2022). In technology-supported science classrooms, students with basic ICT skills are better equipped to utilize digital tools to enhance their learning (Fraillon et al., 2014; Heerwegh et al., 2016). Conversely, students with limited ICT skills may struggle to use these tools effectively, potentially hindering their learning.

However, both experimental intervention and ICT competency showed no significant impact on students' subject knowledge. It is inferred that the short duration of the experiment may have limited impacts on students' subject knowledge. For example, Sung et al. (2016) highlighted a direct relationship between the duration of technology-supported interventions and their influence on participants, demonstrating that longer-term use of technological tools leads to more substantial learning gains compared to short-term interventions. Similarly, Bernacki et al. (2020) found that significant educational benefits are more likely to be observed when students are provided with extended periods to engage in learning with the support of mobile learning technology. Therefore, to examine the influence of longer duration, WeInquiry-based interventions, our future research plans to extend the duration of the experiment, allowing us to further explore the impact of long-term interventions and students' ICT competency on subject knowledge gains.

5.3 The interaction effects of technology-supported collaborative inquiry and ICT competency

The interaction effects of experimental interventions (i.e., EG and CG) and ICT competency (i.e., high and low) on both scientific literacy and subject knowledge showed a similar trend: in the comparison group (CG), high-ICT students scored notably higher on the post-tests of scientific literacy and subject knowledge compared to low-ICT students. A possible explanation is that high-ICT students, encountering fewer barriers to technological usage, could focus more effectively on technology-supported inquiry activities (Scherer et al., 2019). In contrast, low-ICT students, due to their limited ICT competency, may experience a higher cognitive load when participating in these activities (Kirschner, 2002; Paas & Van Merriënboer, 1994). The increased cognitive load could cause them to expend more mental effort on navigating the technology rather than on the core inquiry activities. Consequently, low-ICT students may be hindered by technology in classroom inquiry activities, making it difficult for them to efficiently participate in and complete tasks within limited class time, resulting in lower test scores compared to high-ICT students. Similar findings have been reported in previous studies, indicating that technological support does not always promote learning for all students (Cheung & Slavin, 2013).

Additionally, for low-ICT students, the EG intervention was shown to be more beneficial to their scientific literacy compared to those in the CG. This improvement may be attributed to the WeInquiry platform, which provides more structured inquiry support for students with similar technological difficulties. This structured support can alleviate technology-related confusion to some extent, allowing EG students to focus more on core inquiry tasks. This inference is also supported by the cognitive load theory (Kirschner, 2002). According to this theory, reducing extraneous cognitive load allows students to allocate more mental resources to essential learning activities. Consequently, within the same inquiry time, students with structured support can concentrate more on core tasks and can invest greater mental effort in learning content (Wang & Yu, 2023), thus leading to better outcomes. Nevertheless, this should be interpreted with caution as no process data were included in this study to further substantiate the inference. Multimodal data regarding the learning process in subsequent studies can be collected to examine how technological supports affect students with relatively low ICT competency.

5.4 Implications and future directions

This study demonstrated the benefits of technology-supported collaborative inquiry activities in rural science classrooms, highlighting their potential to enhance students' scientific skills and knowledge. It also revealed the critical role of students' ICT competency in maximizing these benefits. These findings suggest the need for refined theoretical frameworks that account for individual differences and the interactive effects of technological interventions on learning outcomes. By incorporating rural-specific considerations, this study underscores that platforms like WeInquiry can be effective beyond urban contexts. The results also highlight the importance of integrating ICT competency into educational technology models, as students with higher ICT skills engage more effectively and benefit more from such interventions. This dynamic interaction calls for nuanced frameworks to better predict and support learning outcomes.

The observed improvement in students' scientific learning outcomes indicates that active participation and hands-on practice in inquiry-based classrooms contribute to cognitive development and increased interest in science. Despite the constraints of limited resources and technological infrastructure in rural schools, effectively using resources and offering adaptable support can foster the development of critical scientific skills, including problem-solving and critical thinking. Prior research supports this view, showing that, even with resource limitations, rural science education can be improved (Ihrig et al., 2022; Murphy, 2020). The physics topics in this study, closely tied to students' everyday lives, provided opportunities for students to connect scientific principles with real-world phenomena. Researchers and practitioners should leverage the rural environment and available resources to design exploratory activities that help students consolidate scientific knowledge and abilities (Harris & Hodges, 2018).

Appropriate technological support has the potential to transform rural science classrooms, provided it is tailored to the unique needs and limitations of these settings. This study highlighted that structured technological support could engage students more effectively in science activities and improve their learning performance. However, implementing such interventions in rural areas requires careful consideration of challenges in local contexts, including shortages of educational resources, limited network infrastructure (Harris & Hodges, 2018; Kittleson & Morgan, 2012), students' lower scientific and technological competency (Yang et al., 2013), and teachers' limited experience with inquiry-based teaching (Beeson & Strange, 2003). Simply transferring advanced technology to rural schools without modifications is unlikely to yield favorable outcomes (Livingstone, 2015). Instead, technological interventions should align with the school's needs, teachers' abilities, and pedagogical strategies to ensure effectiveness.

Future research might explore how practical activities in rural science classrooms can be better supported and how these supports influence student engagement and achievement. Although many studies have demonstrated the positive effects of technological tools in science education (Belland et al., 2019; Chen et al., 2017; Cui et al., 2022), more work is needed to determine whether these tools yield similar benefits in rural classrooms or how they can be adapted to meet the specific needs of these environments. This is particularly important because science education in rural areas has historically received less attention, resulting in lower student performance and engagement in science-related learning and careers (Murphy, 2020; Saw & Agger, 2021). Addressing these disparities is critical to preventing educational polarization, which can exclude rural students from science-related careers and hinder their long-term development. Future research could aim to bridge the gaps in science education by ensuring all students, regardless of geographic location, have equitable opportunities to succeed in science learning and related fields. Achieving this goal will not only promote educational equity but also contribute to the broader goal of sustainable development for rural communities.

5.5 Limitations

This study has several limitations that should be acknowledged. First, CG students, lacking prior experiences with the CER framework, relied on traditional methods to record their data interpretations in notebooks. In contrast, EG students, supported by the WeInquiry system, were able to conduct CER-based data interpretations with ease. This difference may have introduced potential confounding effects, making it difficult to isolate the impacts of technological support on students' learning outcomes. Second, the relatively short duration of the experiment may not have been sufficient to significantly impact students' subject knowledge, although it successfully enhanced their scientific literacy within the limited timeframe. Third, the study relied solely on summative assessment scores collected before and after the experiment. The lack of process data limits our understanding of how the technological intervention and its interaction with students' ICT competencies influenced their learning behaviors. Lastly, the study was conducted in two physics classrooms in a rural area. Given the variability in resource availability and student characteristics across rural environments, caution should be exercised when generalizing these findings to other rural contexts. As this study is part of an ongoing project, future research will address these limitations by expanding the scale and duration, collecting richer multimodal process data, and further exploring the impact of supportive strategies on rural science classrooms. These efforts will collectively provide deeper insights into how technological interventions influence rural students with varying ICT competencies and lead to more robust and generalizable conclusions.

Author contributions Fan CHEN and Gaowei CHEN collaboratively conceptualized and planned the study. Fan CHEN and Ying ZHANG discussed and performed the data analysis. Fan CHEN executed the experimental implementation and drafted the initial manuscript. Ying ZHANG contributed to revising and enhancing the manuscript. Gaowei CHEN provided guidance and further revisions to improve the manuscript. All authors have thoroughly reviewed and approved the final manuscript for submission.

Data availability The data that support the findings of this study are available from the first author, Fan CHEN, upon reasonable request.

Declaration

Ethics approval statement This project received approval from the Human Research Ethics Committee (HREC) of the University of Hong Kong. The HREC reference number for this project is EA240122.

Competing interest No potential conflict of interest was reported by the authors.

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