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Enhancing rural students' science process skills through structured inquiry engagement in a non-immersive virtual reality chemistry laboratory

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ABSTRACT

Laboratory activities are essential for developing students' science process skills, yet many rural schools face limitations in conducting regular chemistry experiments due to inadequate laboratory resources. This study examined the effectiveness of structured inquiry engagement delivered through an Android-based, smartphone-delivered non-immersive virtual reality chemistry laboratory (VR-CL) in enhancing rural secondary students' science process skills. The intervention was grounded in structured inquiry learning principles and supported by multimedia and flexible learning design. A quasi-experimental pre-test–post-test design with non-equivalent groups was conducted with 129 students (experimental n = 64; control n = 65) over eight weeks. Science process skills were measured using a validated instrument, and post-test differences were analysed using two-way ANCOVA with pre-test scores as the covariate. Results showed that students in the structured inquiry-based VR-CL environment demonstrated significantly greater improvement in science process skills than those receiving conventional instruction. The findings suggest that the observed learning gains are associated with the structured inquiry engagement embedded within the VR-CL learning environment, rather than the use of virtual technology alone. The study highlights the potential of integrating structured inquiry pedagogies with accessible non-immersive virtual environments to support chemistry learning in resource-limited rural contexts.

Keywords: chemistry laboratory, non-immersive virtual reality, rural students, science process skills, chemistry education

INTRODUCTION

Science Process Skills and Inquiry Learning

Laboratory activities are a fundamental component of chemistry education because they enable students to engage directly with scientific inquiry, experimentation, and evidence-based reasoning (Agustian et al., 2022). Through laboratory work, students develop essential science process skills (SPS), which are critical for understanding chemical concepts and applying scientific reasoning in authentic contexts. SPS refer to the cognitive and procedural skills that enable students to observe phenomena systematically, classify information, make inferences, interpret data, design or conduct investigations, communicate findings, predict outcomes, and define variables operationally (Rezba et al., 2007; Roth & Roychoudhury, 1993). These skills are essential for developing scientific literacy and enabling students to engage in evidence-based reasoning and experimental problem solving (Bybee, 2013). In this study, SPS are conceptualised as an integrated construct comprising eight interrelated subskills: observing, classifying, inferring, experimenting, communicating, predicting, interpreting data, and operationally defining variables (Feyzioglu et al., 2012; Oktavianti & Aini, 2024). Meaningful science learning occurs when students actively engage with phenomena and interpret experimental evidence through inquiry-based processes (Andrews et al., 2023; Voon et al., 2020).

Existing research indicates that science process skills are most effectively developed through active engagement in structured inquiry-based learning environments. Studies have consistently shown that students acquire SPS when they are provided with repeated opportunities to observe phenomena, interpret data, and construct explanations based on evidence rather than passively receiving information (Lazonder & Harmsen, 2016; Roychoudhury & Roth, 1996). Instructional approaches that explicitly scaffold inquiry processes, such as guided experimentation and structured tasks, have been identified as particularly effective in supporting the development of these skills. These findings suggest that the design of learning activities, rather than exposure to experimental demonstrations alone, plays a central role in fostering science process skills.

However, science process skills are not developed effectively through passive observation or teacher explanation alone. Rather, students learn SPS through repeated opportunities to participate in structured inquiry, where they actively engage in observing experimental phenomena, recording evidence, interpreting patterns, and constructing explanations based on data (Constantinou et al., 2018; Harlen, 2014; Lazonder & Harmsen, 2016; Roychoudhury & Roth, 1996). Such inquiry-based engagement provides systematic practice in applying multiple science process skills during authentic laboratory problem solving (Kabapınar et al., 2025).

Challenges in Laboratory Learning in Rural Contexts

Despite their importance, effective laboratory experiences are not equally accessible across educational contexts. In many rural secondary schools, chemistry laboratory instruction is constrained by limited infrastructure, insufficient equipment, safety concerns, and shortages of consumable materials (Abrahams & Millar, 2008; Casado-Mansilla et al., 2023). As a result, practical activities are often reduced, replaced by demonstrations, or omitted altogether (Osborne et al., 2008). Such limitations restrict students' opportunities to practise science process skills systematically and may lead to weaker procedural understanding and reduced competence in conducting scientific investigations (Hofstein & Lunetta, 2003). When laboratory work is replaced by teacher-centred demonstrations, students may observe experimental outcomes but have limited opportunities to manipulate variables, generate evidence, or justify conclusions independently (Kaneza et al., 2023, 2024).

Virtual and Non-Immersive VR Laboratories

To address these challenges, educational technologies have increasingly been explored as alternative or supplementary approaches to laboratory instruction (Shambare et al., 2022). Virtual laboratories allow students to conduct simulated experiments in digital environments, enabling them to observe phenomena, manipulate variables, and practise experimental procedures without the constraints of physical laboratory resources (De Jong et al., 2013; Dyrberg et al., 2016). Prior studies indicate that well-designed virtual laboratories can support inquiry-based learning and skill development, particularly when they require active engagement rather than passive observation (Gunawan et al., 2019; Tatli & Ayas, 2013). However, some studies have reported limited or non-significant effects on cognitive outcomes when virtual environments lack sufficient pedagogical scaffolding, highlighting the importance of structured inquiry design. However, the effectiveness of virtual laboratories depends not only on visual simulation but also on how learning activities require students to sequentially observe, infer, interpret, and justify experimental outcomes (Meronda et al., 2025).Among technology-enhanced laboratory approaches, virtual reality (VR) has gained increasing attention for its potential to create interactive and visually rich learning environments. Educational VR applications are commonly categorised as immersive or non-immersive (Radianti et al., 2019). Immersive VR typically relies on head-mounted displays and specialised hardware, which may enhance presence and engagement but often involve high costs and technical complexity (Abadia et al., 2024; Buttussi & Chittaro, 2017). These constraints may limit the feasibility of immersive VR in many school environments, particularly in rural contexts where technological infrastructure is limited.

In contrast, non-immersive virtual reality is delivered through commonly available digital devices such as computers or smartphones, allowing users to interact with simulated environments without immersive head-mounted displays (Lee et al., 2019). Smartphone-based non-immersive VR applications therefore represent a more accessible and scalable alternative for schools with limited technological resources (Mora et al., 2016). From the perspective of the Cognitive Theory of Multimedia Learning (CTML), well-designed digital environments can support learning by directing students' attention toward relevant visual information while reducing unnecessary cognitive processing (Mayer, 2020; Sweller, 2019). Such design principles allow learners to focus cognitive resources on interpreting experimental evidence and reasoning about scientific phenomena.

In addition, the present study draws on Cognitive Flexibility Theory (CFT), which emphasises the importance of flexible knowledge application across multiple contexts and representations (Spiro et al., 2013). In complex scientific domains such as chemistry, learners must interpret different forms of evidence and adapt their reasoning when experimental outcomes vary. During qualitative salt analysis tasks, students must examine reaction patterns, compare observations, and revise explanations based on emerging evidence. Learning environments that present multiple experimental scenarios therefore support the development of flexible reasoning and deeper procedural understanding (Baciu et al., 2024; Rogers & Price, 2004).

Beyond technological affordances, the effectiveness of digital laboratories depends on how they are pedagogically structured. Contemporary science education emphasises the integration of technology with inquiry-oriented pedagogies that engage students in authentic scientific practices (Gomez, 2025). Inquiry-based learning in this study was structured using the 5E instructional model, with additional task-based elements incorporated to support student engagement. (Hmelo-Silver et al., 2007; Van Uum et al., 2016).

Research Gap and Purpose of the Study

Although previous studies have reported positive outcomes associated with virtual laboratories and VR in science education, much of the existing research has focused on affective outcomes such as motivation, interest, or attitudes, or has been conducted primarily in higher education settings (Meronda et al., 2025; Patel, 2024). Consequently, relatively few empirical studies have examined science process skills as the primary learning outcome in non-immersive VR environments at the secondary school level (Boel et al., 2021; Xie et al., 2023). Moreover, recent empirical work has often emphasised immersive technologies or tertiary contexts, with limited attention given to smartphone-based non-immersive virtual reality laboratories in rural secondary schools (Cao et al., 2024; Hunegnaw et al., 2024; Ngema & Motlhabane, 2025).

Recent reviews and meta-analyses have highlighted the potential of virtual laboratories to support science learning while emphasising the need for context-sensitive effectiveness studies that examine cognitive and procedural learning outcomes in authentic classroom environments (Fadda et al., 2022; Ojetunde, 2025). However, existing research rarely examines how non-immersive virtual reality environments can systematically support the development of science process skills through structured pedagogical implementation in rural secondary school contexts (Ngema & Motlhabane, 2025; Norwine et al., 2025). In particular, limited empirical evidence is available regarding how smartphone-based non-immersive virtual laboratories, integrated with inquiry-oriented pedagogical approaches and instructional scaffolding, influence students' science process skills in real classroom settings (Nurlaini et al., 2025). This study contributes to science education research by providing empirical evidence that a smartphone-based non-immersive virtual reality laboratory, when integrated with structured inquiry activities, can effectively support the development of science process skills among rural secondary students.

To address these gaps, this study investigated the effectiveness of structured inquiry engagement delivered through an Android-based, smartphone-based non-immersive VR-CL designed to support inquiry-based learning in the Salts topic. The intervention integrated virtual experimentation with structured worksheets, AI-supported prompts, and inquiry-oriented learning activities to provide repeated opportunities for students to enact science process skills. Using a quasi-experimental design, the study examined whether students who learned through the VR-CL intervention demonstrated greater improvement in science process skills than those receiving conventional chemistry instruction in rural secondary school classrooms.

In addition to examining the effectiveness of the instructional intervention, this study also considers gender as a potential moderating variable. Previous research in science education has reported mixed findings regarding gender differences in science process skills, with some studies indicating comparable performance between male and female students when learning environments provide structured guidance and equal participation opportunities (Lazonder & Harmsen, 2016; OECD, 2019). In technology-enhanced learning environments, including virtual and digital laboratories, gender differences have also been reported inconsistently, with some studies suggesting differences in engagement or familiarity with digital tools, while others indicate no significant differences in learning outcomes when appropriate instructional scaffolding is provided. Therefore, including gender as a variable in this study allows for a more comprehensive understanding of whether structured inquiry engagement supports science process skills development consistently across different student groups.

Accordingly, the study addresses the following research question:

To what extent does participation in a structured inquiry-based non-immersive virtual reality chemistry laboratory improve rural secondary students' science process skills compared to conventional chemistry instruction?

CONCEPTUAL FRAMEWORK

Science process skills are not expected to develop simply through exposure to digital simulations; rather, they are cultivated through structured engagement in scientific inquiry where learners repeatedly observe phenomena, generate explanations, test ideas, and justify conclusions based on empirical evidence (Fitria et al., 2021; Rezba et al., 2007; Roth & Roychoudhury, 1993). This study is conceptually grounded in principles of active and inquiry-based learning, where students construct understanding through engagement with experimental tasks.

The instructional design of the VR-CL module was guided by Sidek's instructional design model, which emphasises systematic development of instructional modules through stages including needs analysis, design, development, implementation, and evaluation (Noah & Ahmad, 2005). This model ensured that the virtual laboratory activities, structured worksheets, and assessment tasks were aligned with the intended learning outcomes, particularly the development of science process skills.

The instructional design of the VR-CL module was structured using the 5E instructional model to guide students through inquiry-based learning activities. Among these, the 5E instructional model serves as the primary pedagogical structure guiding structured inquiry engagement within the VR-CL environment. Supporting elements such as contextual problem scenarios and digital tools were incorporated to enhance engagement and reasoning processes. The design also integrated multimedia representations and multiple experimental contexts to support cognitive processing and flexible reasoning.

Beyond pedagogical structuring, the integration of digital technology within the VR-CL environment can also be interpreted through the SAMR model, which conceptualises how technology can progressively transform learning activities from simple substitution to the redefinition of instructional tasks (Lyddon, 2019). Within the VR-CL environment, virtual simulations did not merely substitute unavailable laboratory activities but enabled modification of inquiry tasks by allowing students to manipulate virtual apparatus, repeat experimental procedures, and analyse reaction outcomes in multiple contexts.

In addition, AI-supported tools were integrated as part of the structured inquiry process, providing scaffolding during key phases of the 5E instructional model, particularly during exploration, explanation, and evaluation. These tools supported students in observing phenomena, interpreting data, and constructing evidence-based conclusions. AI-assisted prompts and online platforms were used to provide clarification, feedback, and opportunities for discussion as students engaged in inquiry-based reasoning (Anugrah & Suryani, 2025). Taken together, the conceptual framework integrates learning theories, instructional design principles, pedagogical approaches, and technology integration models to support the development of science process skills. Within this framework, the VR-CL environment functions as a scaffolded inquiry platform in which students repeatedly engage in observing, predicting, experimenting, interpreting data, and communicating conclusions during chemistry investigations. **Figure 1** illustrates the conceptual framework guiding the study.

As illustrated in **Figure 1**, the integration of learning theories, pedagogical approaches, instructional design principles, and digital learning tools creates structured opportunities for repeated procedural engagement. Through these learning processes, students practise multiple science process skills during inquiry-based chemistry tasks. This repeated procedural enactment is hypothesised to lead to measurable improvements in students' science process skills (Sutisnawati et al., 2025).

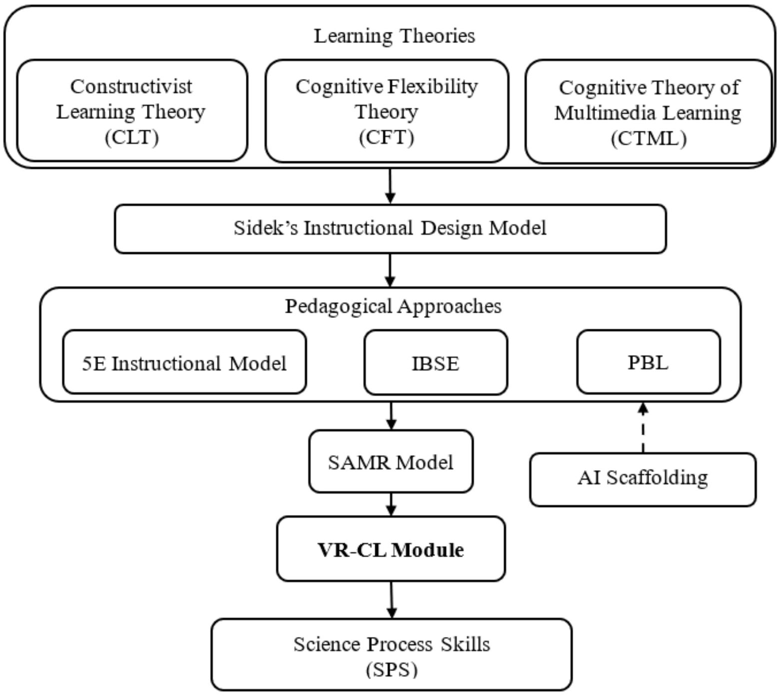


Figure 1. The VR-CL module operates within an integrated instructional framework. Consistent with prior research, virtual laboratory environments alone may yield limited or inconsistent cognitive outcomes when implemented without structured inquiry and pedagogical scaffolding (Source: Authors' own elaboration, adapted and synthesized by the authors based on relevant theoretical and pedagogical frameworks, which are cited in *Conceptual Framework* section)

While virtual laboratories provide opportunities for simulation-based learning, prior research has shown that such environments may yield limited or inconsistent cognitive outcomes when implemented without structured inquiry guidance. Therefore, in this study, the VR-CL environment is conceptualised not as the primary driver of learning, but as a platform through which structured inquiry engagement is enacted.

MATERIALS AND METHODS

This section describes the research design, participants and context, instructional intervention, instrumentation, procedures, data analysis, and ethical considerations employed to examine the effectiveness of structured inquiry engagement delivered through a non-immersive virtual reality chemistry laboratory on rural upper secondary students' science process skills.

Research Design

A quasi-experimental pre-test–post-test design with non-equivalent control and experimental groups was adopted, as random assignment was not feasible in the school setting (Creswell & Creswell, 2022; Shadish et al., 2002). The independent variable was the instructional approach (non-immersive virtual reality chemistry laboratory vs. conventional instruction), and the dependent variable was students' science process skills. Gender was included as a grouping factor to examine whether outcomes differed by gender across instructional conditions. The experimental group intervention was structured according to the 5E instructional model (Engage–Explore–Explain–Elaborate–Evaluate), which guided the pedagogical sequencing of the VR-CL lessons (Bybee et al., 2006). The 5E instructional model was applied exclusively to the experimental group as part of the virtual laboratory implementation. The control group received conventional teacher-centred instruction aligned with the national curriculum without explicit implementation of the 5E instructional sequence. The sequencing of pre-test administration, instructional implementation, and post-test assessment was consistent across both experimental and control groups.

Context and Participants

The study was conducted in rural upper secondary school settings characterised by limited access to fully equipped chemistry laboratories. Participants consisted of upper secondary students enrolled in chemistry courses. The instructional content focused on the Salts subtopic, a core component of the upper secondary chemistry curriculum that involves laboratory-based qualitative analysis and procedural experimentation. Participants were selected using purposive sampling, as the study focused specifically on rural secondary schools with limited laboratory facilities where access to chemistry laboratory resources is often constrained (Fraenkel et al., 2016).

A total of 129 students participated in the study, with 64 students assigned to the experimental group and 65 students to the control group. The experimental and control groups were based on intact classroom groups, as random reassignment of students was not feasible within the school timetable structure. The experimental group learned the Salts subtopic using the non-immersive virtual reality laboratory, while the control group received conventional chemistry instruction on the same subtopic. Both groups followed identical curriculum content, learning objectives, and instructional duration to ensure comparability of learning conditions (Fraenkel et al., 2016).

Instructional Intervention: Non-Immersive Virtual Reality Chemistry Laboratory

The instructional intervention comprised an Android-based, smartphone-delivered, non-immersive virtual reality chemistry laboratory developed specifically to support learning within the Salts subtopic. The virtual laboratory simulated key experimental procedures related to salt identification and qualitative analysis, allowing students to engage with laboratory activities that are typically constrained in rural school settings.

Students interacted with the mobile virtual laboratory environment using touch-based controls to manipulate apparatus, conduct qualitative tests, and observe reaction outcomes without the use of immersive head-mounted displays. Through the virtual environment, students were able to observe chemical reactions, manipulate virtual apparatus, follow step-by-step experimental procedures, and record observations relevant to salt analysis.

The VR-CL modules incorporated scenario-based inquiry contexts (e.g., agricultural soil contamination, water pollution, heavy metal detection, and forensic salt identification) to situate qualitative analysis tasks within authentic problem-solving environments. Students were required to plan experimental procedures, construct flow charts, identify variables, record observations in structured tables, write ionic equations, provide operational definitions, and formulate evidence-based conclusions. These tasks were aligned with IBSE principles (García-Carmona, 2020).

The intervention emphasised guided inquiry and procedural reasoning to support the development of science process skills, including observing, interpreting data, and drawing conclusions. In addition, AI-supported digital tools (e.g., ChatGPT, Telegram, and Google Classroom) were used as structured scaffolding under teacher guidance, with controlled frequency and purpose to support student discussion, clarification, and task completion. The non-immersive design was intentionally selected to enhance accessibility, usability, and classroom feasibility, particularly in rural contexts with limited laboratory resources (Lee et al., 2019; Norwine et al., 2025). **Figure 2** presents the interface of the non-immersive virtual reality chemistry laboratory used for the Salts subtopic in this study and an example of classroom implementation during the intervention.

As shown in **Figure 2**, the interface allowed students to manipulate reagents, observe reaction outcomes, and navigate sequential qualitative analysis steps within a guided virtual environment. The intervention design followed the conceptual framework presented in **Figure 1**, in which the VR-CL environment and worksheets functioned as scaffolds within a 5E instructional inquiry sequence to promote repeated enactment of SPS.

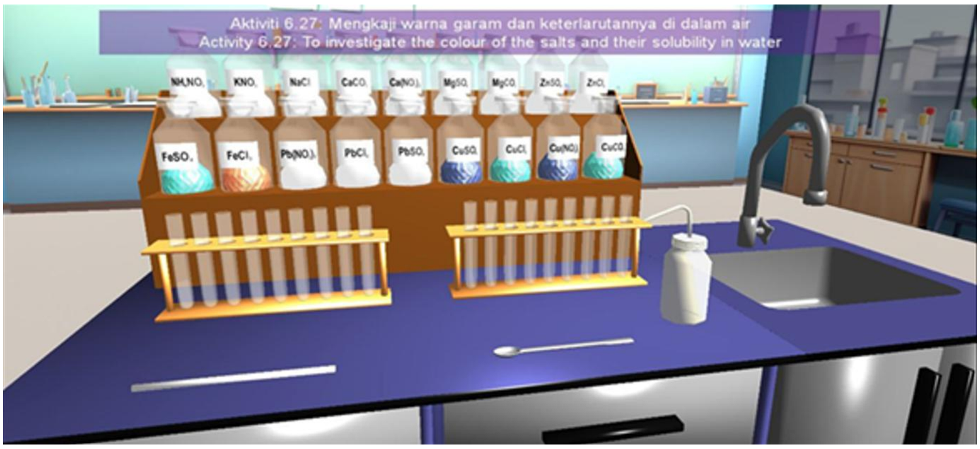
Operationalisation of Science Process Skills within the VR-CL

To ensure that SPS were explicitly developed rather than implicitly assumed, the VR-CL intervention was implemented together with structured experimental worksheets that guided students through qualitative analysis procedures. The worksheets were used alongside the virtual laboratory environment and required students to document procedural steps, observations, classifications, and justifications while interacting with the simulation.

The eight SPS conceptualised in this study, observing, classifying, inferring, experimenting, communicating, predicting, interpreting data, and operationally defining variables, were operationalised through specific task requirements embedded within both the VR environment and the accompanying worksheet activities.

Within the VR-CL environment, science process skills were enacted through structured inquiry activities that required students to observe experimental phenomena, analyse data, and construct evidence-based conclusions. These skills were not addressed in isolation but were integrated within inquiry tasks that involved planning procedures, interpreting results, and justifying conclusions. This approach ensured that students engaged in multiple interrelated science process skills simultaneously as part of authentic problem-solving processes.

Importantly, students were not passive observers of virtual demonstrations but were actively engaged in planning procedures, analysing experimental evidence, and justifying conclusions, thereby enacting structured inquiry engagement throughout the intervention.



(a)

(b)

Figure 2. (a) Screenshot of the VR-CL interface used for qualitative salt analysis tasks; (b) Students interacting with the VR-CL using smartphones during classroom inquiry activities (Source: Field study)

Assessing Science Process Skills

Students' science process skills were assessed using the Science Process Skills Test (SPST), a structured assessment instrument developed based on the upper secondary chemistry curriculum and established science process skills frameworks (Rezba et al., 2007). All SPST items were adapted from state-level and national Chemistry examination questions in Malaysia, which have been widely used and validated in authentic assessment contexts (Ebel & Frisbie, 1991). In this study, SPS were conceptualised as an integrated construct comprising eight interrelated subskills: observing, classifying, inferring, predicting, interpreting data, experimenting, communicating, and operationally defining variables. These subskills were assessed collectively rather than separately, as they are inherently interconnected and are typically enacted simultaneously during authentic chemistry laboratory inquiry and experimental problem-solving activities.

The SPST consisted of four structured items and one essay item, designed to assess students' ability to apply scientific procedures, interpret experimental data, and demonstrate inquiry-based reasoning within the context of the Salts subtopic. The structured items focused on procedural understanding, data interpretation, and evidence-based decision-making, while the essay item required students to articulate experimental reasoning, justify conclusions, and integrate multiple science process skills into a coherent explanation. An example of the essay item is provided in Appendix A. The items were designed such that each task required the integration of multiple science process skills simultaneously, ensuring alignment with the eight skills operationalised within the VR-CL intervention. The assessment tasks were contextually aligned with the instructional scenarios embedded within the VR-CL modules to ensure constructive alignment between learning activities and assessment outcomes (Isa et al., 2025). Importantly, the science process skills assessed in the SPST correspond directly to the eight skills operationalised within the VR-CL intervention (see **Table 1**), ensuring alignment between the instructional activities and the assessment of students' science process skills, a key principle of constructive alignment in educational design (Guerrero-Roldán & Noguera, 2018; Jaiswal, 2019).

Content validity of the SPST was established through expert review involving five experienced chemistry teachers and specialists in science education. The Content Validity Index (CVI) indicated that the instrument was appropriate in terms of relevance, clarity, and alignment with science process skills constructs (Lynn, 1986; Polit & Beck, 2006).The experts evaluated the alignment of the test items with curriculum objectives, targeted science process skills, and the intended cognitive demands of upper secondary chemistry laboratory tasks. Following this, face validity and linguistic equivalence were ensured through a back-to-back translation procedure (Caldana & Gabriel, 2017). The original English version of the instrument was translated into Malay by an experienced Malay language teacher and subsequently translated back into English by an experienced English language teacher. The translated versions were compared to verify semantic accuracy, clarity, and consistency of meaning across languages. Minor wording refinements were made where necessary to ensure that the Malay version accurately reflected the intended scientific and procedural meanings of the original items prior to pilot testing.

The reliability of the SPST was established through a pilot study Pfocusing on inter-rater consistency in scoring. Given that the instrument comprised structured and essay-based items requiring subjective judgement, reliability was addressed through independent scoring by two experienced assessors using a standardised marking scheme, followed by moderation and cross-checking procedures to ensure scoring consistency (Wu et al., 2024). This approach is widely recommended for performance-based assessments involving subjective evaluation (Jonsson & Svingby, 2007; Koo & Li, 2016). The high level of agreement observed during moderation indicates that the scoring process was consistent and reliable across assessors. To further ensure item quality, item-level analysis was conducted, including evaluation of item difficulty and discrimination indices, which are standard procedures in educational measurement for validating assessment items (Ebel & Frisbie, 1991). The item difficulty and discrimination indices were within acceptable ranges based on established benchmarks, indicating that all items were appropriate for assessing science process skills. Therefore, all items were retained for use in the main study.

Table 1. Operationalisation of science process skills within the VR-CL learning activities

Science Process Skill	VR-CL Activity	Worksheet Task	Evidence in Student Output
Observing	Observe colour changes, precipitate formation, and reaction outcomes during qualitative analysis procedures.	Record visual observations of reactions and physical changes.	Observation notes in worksheets and laboratory reports.
Classifying	Students compared reaction results from different salts and reagents within the VR laboratory.	Students categorised salts based on solubility, reaction behaviour, and precipitate formation.	Classification tables completed in worksheets and included in laboratory reports.
Inferring	Students analysed reaction outcomes and patterns observed during simulated experiments.	Students inferred the possible identity of ions present based on observed reactions.	Written explanations and reasoning are provided in worksheets and reports.
Experimenting	Students followed procedural steps within the VR laboratory to perform qualitative salt analysis experiments.	Students planned and executed experimental procedures using the VR interface and documented procedural steps.	Step-by-step experimental procedures documented in lab reports.
Communicating	Students discussed experimental findings with peers and reported their experimental results.	Students prepared structured laboratory reports describing observations, interpretations, and conclusions.	Written laboratory reports submitted after each activity.
Predicting	Before performing certain reaction tests, students anticipated possible outcomes based on prior knowledge of chemical reactions.	Students predicted expected reaction outcomes before conducting VR-based experiments.	Prediction statements recorded in worksheets.
Interpreting Data	Students examined experimental results obtained from simulated tests and compared them across multiple trials.	Students interpreted patterns in reaction results to determine the presence of specific ions.	Interpretation sections included in laboratory reports.
Operationally Defining	Students used chemical terminology and experimental criteria to define reaction outcomes such as precipitate formation and solubility.	Students defined experimental observations using operational chemical definitions.	Definitions and explanations included in worksheet responses and reports.

*Note. The table illustrates how each science process skill was enacted through VR-CL activities, worksheet documentation, and laboratory reporting tasks during the intervention.

Procedure

Prior to the intervention, both groups completed a pre-test to assess baseline science process skills.

Experimental group

The experimental group participated in VR-CL-based lessons structured according to the 5E instructional model. Lessons began with scenario-based engagement activities designed to activate prior knowledge and introduce real-world problems related to qualitative salt analysis. Students then collaborated in planning experimental procedures and conducted simulated experiments using the non-immersive virtual reality chemistry laboratory. During the exploration phase, students interacted with the VR environment to perform qualitative tests, manipulate reagents, and observe reaction outcomes.

To support inquiry-based learning, students completed structured worksheets while interacting with the VR laboratory. Students engaged in structured inquiry processes including observation, experimentation, data interpretation, and evidence-based reasoning. These processes were facilitated through guided tasks within the VR-CL environment, supported by digital tools such as ChatGPT, Telegram, and Google Classroom as structured scaffolding for guided discussion and clarification. The use of these tools was standardised across instructional sessions, with teachers guiding students on when and how to use them for discussion and clarification. Their use was monitored during classroom activities to ensure consistency and to minimise potential confounding effects.

Table 1 summarises how the eight science process skills were operationalised through VR-CL activities, worksheet tasks, and laboratory reporting during the intervention.

Table 1 summarises how science process skills were enacted through structured inquiry activities within the VR-CL environment. These activities were designed to engage students in observing, analysing, and interpreting experimental evidence, as well as constructing and communicating conclusions through guided inquiry tasks. **Figure 3** provides an example of a student worksheet used during the VR-CL activities, illustrating how inquiry tasks supported students in recording observations, interpreting results, and constructing evidence-based explanations. The worksheet supported the enactment of science process skills during inquiry tasks.

Agriculture is a crucial sector in Malaysia, providing food and employment for many of the population. However, fertilisers and pesticides can accumulate various salts in the soil, potentially affecting crop growth and soil health as shown in Diagram 1. You have been asked to investigate the physical properties of a few salts in agricultural soils to understand their impact on soil quality and plant growth. The goal is to develop sustainable farming practices that minimize soil contamination.

Bahagian 1
Part 1:

Berdasarkan senario yang diberikan,
Based on the scenario given,

1. Klik VR-CL1 pada telefon pintar anda.
   Click VR-CL1 on your smartphone.
2. Perhatikan bahan dan radas diberikan.
   Observe the materials and apparatus given.

Bahagian 2: Inkuiri Pengesahan
Part 2: Confirmatory Inquiry

Dalam kalangan ahli kumpulan anda:
Among your team members:

1. rancang eksperimen. (Rujuk Buku Teks m/s 198-199 untuk prosedur)
   plan of the experiment. (Refer to Textbook page 198-199 for the procedures)
2. sediakan carta alir eksperimen.
   prepare the flow chart of the experiment.
3. semak dengan guru anda (guru anda mesti bersetuju dengan prosedur anda).
   check with your teacher (your teacher must agree with your procedures).
4. tuliskan
   write
   a) tujuan
      aim
   b) radas
      apparatus
   c) bahan
      material
   d) susunan radas (diperlukan untuk melukis di atas kertas, imbas, dan tampal dalam laporan praktikal iaitu dalam *Google Doc* anda)
      setup of apparatus (require you to draw on paper, scan, and paste in the practical report which is in your Google Doc)
   e) prosedur dalam ayat pasif
      procedures in a passive sentence
   f) sediakan jadual yang sesuai untuk pemerhatian dan keputusan. (Rujuk Jadual 6.11 dalam Buku Teks m/s 198)
      prepare a suitable table for the observation and results (Refer to Table 6.11 in Teks Book page 198)
5. kendalikan eksperimen
   conduct the experiment
6. rekodkan pemerhatian
   record the observations
7. tafsirkan data dengan mengambil kira soalan-soalan berikut.
   interpret the data by taking the following questions into account
   i) Nyatakan pepejal garam yang berwarna:
      Name solid salts that are coloured:
      (a) Hijau
          Green
      (b) Perang
          Brown
      (c) Biru
          Blue
      (d) Putih
          White
   ii) Nyatakan garam berwarna hijau yang:
      Name green salts that are:
      (a) tidak larut di dalam air
          Insoluble in water
      (b) larut di dalam air untuk menghasilkan larutan biru
          Soluble in water to form a blue solution
      (c) larut di dalam air untuk menghasilkan larutan hijau muda
          Soluble in water to form a light green solution

Figure 3. Example of a student worksheet used during VR-CL inquiry activities (Source: Student worksheet developed by the authors as part of the VR-CL module)

Control group

The control group received conventional classroom instruction aligned with the national chemistry curriculum. Instruction consisted of normal teacher-led sessions, including textbook-based explanations, class discussions, and physical laboratory experiments conducted using available school laboratory apparatus. Students in the control group performed actual qualitative analysis experiments using standard laboratory materials and reagents under teacher supervision. The control group did not use any virtual, simulated, or computer-based laboratory environments, and lessons did not explicitly follow the 5E instructional model.

Although both groups engaged with chemistry content and laboratory-related activities, the key distinction was in the nature of student engagement. The experimental group participated in structured inquiry-based learning guided by the 5E instructional model, with explicit scaffolding through worksheets and guided tasks that required students to actively observe, interpret data, and construct evidence-based explanations. In contrast, the control group followed conventional teacher-centred instruction without explicit inquiry sequencing or systematic scaffolding of science process skills.

The intervention was implemented over a period of eight weeks during regular class sessions. At the conclusion of the intervention, both groups completed a post-test using the same science process skills instrument. All instructional activities were conducted during regular class sessions following the planned instructional sequence.

Data Analysis

Data were analysed using descriptive and inferential statistical techniques. Descriptive statistics were computed to summarise pre-test and post-test performance. To examine the effect of the instructional approach on post-test science process skills while controlling for pre-test differences, a two-way Analysis of Covariance (ANCOVA) was conducted with instructional group and gender as fixed factors, post-test science process skills as the dependent variable, and pre-test scores as the covariate (Field, 2017). Prior to conducting ANCOVA, all underlying assumptions were examined for the KPS data. Normality was assessed using the Shapiro–Wilk test and was considered acceptable based on supporting skewness and kurtosis indices. Homogeneity of variance was evaluated using Levene's test, which indicated a significant result for SPS ($F = 6.118$, $p < .001$). However, this violation was considered acceptable as ANCOVA is robust to such deviations when group sizes are approximately equal (Tabachnick et al., 2018). Linearity between the covariate (pre-test scores) and dependent variable (post-test scores) was confirmed through scatterplot

Table 2. Mean and standard deviation of science process skills scores by group at pre-test and post-test

Group	Pre-test		Post-test		N
	M	SD	M	SD	
Control	46.49	11.32	52.06	10.49	65
Experimental	44.91	11.49	60.84	12.31	64

inspection. Homogeneity of regression slopes was verified through non-significant interaction effects between the covariate and independent variables ($F(1,124) = 1.020$, $p = .315$). Overall, the assumptions for ANCOVA were considered sufficiently met.

Ethical Considerations

Ethical approval for this study was obtained from the Educational Planning and Research Division (EPRD), Ministry of Education Malaysia, as well as the relevant State Education Departments. Permission to conduct the study was also secured from school administrators prior to data collection. Participation in the study was voluntary. Informed consent was obtained from all participating students and their parents or legal guardians before the commencement of the study. To ensure confidentiality and anonymity, all student data were coded and analysed in aggregate form, and no identifying information was disclosed in any reports or publications. The instructional activities implemented in both the experimental and control groups followed the prescribed curriculum to ensure that no group was academically disadvantaged. All procedures were conducted in accordance with established ethical guidelines for educational research (Cohen et al., 2002).

RESULTS

This section presents the findings regarding the effectiveness of the non-immersive virtual reality chemistry laboratory on rural upper secondary students' science process skills. Descriptive statistics are reported first, followed by inferential results addressing the research question. **Table 2** presents the pre-test and post-test science process skills scores for the experimental and control groups. At pre-test, both groups demonstrated comparable baseline performance. Following the intervention, both groups improved; however, the increase was greater for the experimental group ($M = 60.84$, $SD = 12.31$) than for the control group ($M = 52.06$, $SD = 10.49$).

At pre-test, both groups demonstrated comparable baseline performance. Following the intervention, both groups improved; however, the increase was greater for the experimental group. Paired-sample comparisons indicated that both groups demonstrated significant improvement from pre-test to post-test. The experimental group showed a statistically significant increase in science process skills scores, as did the control group, although the magnitude of improvement was greater for the experimental group. These findings indicate that while both instructional approaches supported learning gains, the structured inquiry-based VR-CL intervention resulted in a stronger improvement in science process skills. To examine whether the observed post-test difference remained significant after controlling for pre-test scores, a two-way ANCOVA was conducted. These descriptive results indicate that both groups improved from pre-test to post-test; however, the increase was substantially greater for students in the VR-CL group. This improvement is consistent with the structured inquiry activities described in **Table 1**, where students repeatedly enacted key science process skills such as observing, predicting, interpreting experimental results, and communicating conclusions while interacting with the VR-CL environment. These findings indicate that students in the VR-CL group demonstrated greater improvement in science process skills following the structured inquiry activities described in **Table 1**.

To examine the effect of the instructional approach on students' science process skills while controlling for pre-test differences, a two-way ANCOVA was conducted. Post-test science process skills scores served as the dependent variable, instructional group (experimental vs. control) and gender were treated as independent variables, and pre-test scores were included as the covariate. Preliminary analyses confirmed that assumptions of normality, homogeneity of variance, linearity, and homogeneity of regression slopes were satisfied.

The ANCOVA results revealed a statistically significant main effect of instructional group on post-test science process skills scores after controlling for pre-test performance, $F(1, 124) = 20.802$, $p < .001$, partial $\eta^2 = 0.144$. This effect size indicates a moderate practical impact of the VR-CL intervention on students' science process skills development, suggesting that students who learned using the virtual laboratory achieved meaningfully higher post-test performance than those receiving conventional instruction (Cohen, 1988; Hittleman & Simon, 2006). The covariate, pre-test science process skills score, was also a significant predictor of post-test performance, $F(1, 124) = 21.177$, $p < .001$, partial $\eta^2 = 0.146$, indicating that students' initial science process skills contributed to post-intervention outcomes.

In contrast, no significant main effect of gender ($F = 0.120$, $p = .730$) and no significant interaction effect between instructional group and gender ($F = 1.020$, $p = .315$) were observed. Descriptively, male ($M = 51.75$) and female ($M = 50.97$) students demonstrated comparable adjusted post-test science process skills scores, indicating similar patterns of improvement across genders.

Overall, the results indicate that students who learned using the non-immersive virtual reality chemistry laboratory achieved significantly greater improvements in science process skills than those who received conventional chemistry instruction, thereby supporting the research hypothesis that the VR-CL intervention enhances students' science process skills.

Table 3. Summary of two-way ANCOVA results for post-test science process skills scores

Source	F	p	Partial η^2	Interpretation
Group (VR-CL vs. Control)	20.802	<0.001	0.144	Significant main effect of intervention
Pre-Test (Covariate)	21.177	<0.001	0.146	Pre-existing SPS influenced the post-test
Gender	0.120	0.730	0.001	No main effect of gender
Group × Gender	1.020	0.315	0.008	No interaction between group and gender

Note. Significance level, $p < 0.05$

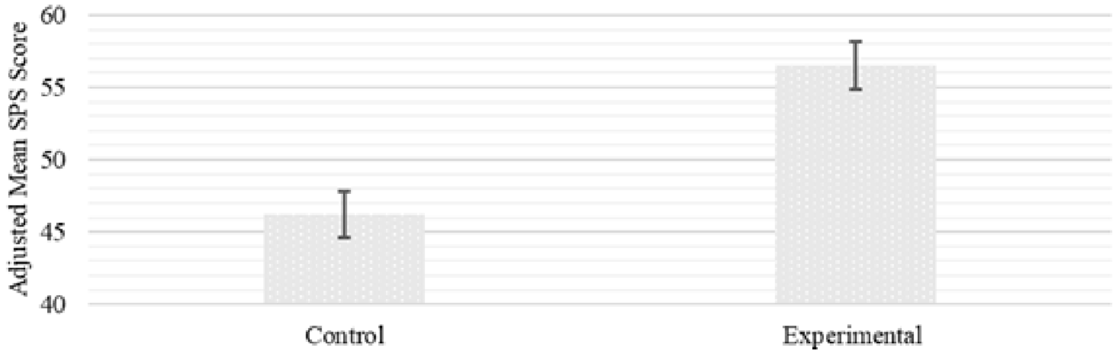


Figure 4. Adjusted mean SPS scores (±SE) for experimental and control groups after controlling for pre-test differences (Source: Authors' data analysis)

DISCUSSION

The present study examined whether a smartphone-based non-immersive virtual reality chemistry laboratory could enhance rural secondary students' science process skills compared with conventional instruction. The findings demonstrate that students who participated in the VR-CL intervention achieved significantly higher post-test science process skills scores than those in the control group, as indicated by the ANCOVA results reported in **Table 3** and the adjusted mean comparison presented in **Figure 4**. These findings therefore answer the research question by demonstrating that participation in the VR-CL learning environment resulted in greater improvement in science process skills than conventional instruction. It is important to acknowledge that the observed effects cannot be attributed solely to the VR-CL technology. The experimental group was exposed to a combination of instructional elements, including structured inquiry activities, guided worksheets, and AI-supported scaffolding within a 5E instructional sequence. In contrast, the control group followed conventional teacher-centred instruction without structured inquiry sequencing or equivalent scaffolding support. Therefore, the findings should be interpreted as reflecting the combined influence of an integrated instructional design rather than the independent effect of virtual laboratory use alone. These pedagogical differences may have contributed to the observed improvements in science process skills. This distinction is important because it indicates that the pedagogical design of the learning environment, rather than the technology itself, played a central role in supporting the development of science process skills. The results further suggest that the observed learning gains cannot be attributed solely to the presence of digital technology, but rather to the structured inquiry engagement embedded within the VR-CL learning activities, indicating that instructional design played a more critical role than the technological component alone. These findings can be interpreted in relation to the conceptual framework presented in **Figure 1**, which proposes that the integration of constructivist learning principles, multimedia-supported representations, and structured inquiry activities within the VR-CL environment creates repeated opportunities for students to enact science process skills during laboratory investigations.

Structured Inquiry Mechanisms Supporting Science Process Skills

The significant improvement in science process skills among students in the experimental group suggests that non-immersive virtual reality can function as an effective instructional medium for supporting procedural and inquiry-based learning in chemistry. Science process skills require coordinated cognitive actions such as observing experimental phenomena, interpreting evidence, identifying patterns, and drawing conclusions through systematic procedures (Hunegnaw & Melesse, 2023). The VR-CL environment enabled students to repeatedly practise these processes while engaging with simulated qualitative analysis tasks. Such repeated procedural engagement likely strengthened students' ability to coordinate multiple science process skills simultaneously, which is a key characteristic of authentic scientific inquiry. This repeated enactment of inquiry processes may have contributed to the stronger learning gains observed in the experimental group.

One possible explanation for the observed improvement lies in the structured alignment between virtual experimentation, worksheet activities, and inquiry-based reasoning tasks. Students were required to repeatedly observe simulated reactions, record experimental observations, interpret reaction patterns, and justify conclusions during the VR-CL activities. This repeated enactment of inquiry processes likely strengthened students' ability to coordinate multiple science process skills simultaneously, which is essential for authentic laboratory investigation (Wiseman et al., 2020).

This finding can be further interpreted through established learning theories. The observed improvement in science process skills can be explained through the integrated influence of structured inquiry pedagogy and supportive learning design principles. The VR-CL environment enabled students to actively engage in key inquiry processes such as observing, experimenting, interpreting data, and constructing evidence-based conclusions, consistent with constructivist learning principles (Lai et al., 2021). At the same time, the structured sequencing of tasks aligned with the 5E instructional model and IBSE framework provided guided support for students to progressively develop procedural understanding (Sypsas et al., 2020). From a cognitive perspective, the design of the VR-CL environment supported meaningful learning by directing attention to relevant representations and reducing unnecessary cognitive load (Mayer, 2020), while exposure to multiple experimental contexts facilitated flexible reasoning across problem situations (Walker et al., 2019). Collectively, these elements contributed to the development of science process skills t through structured and guided inquiry engagement.

These findings are consistent with previous research indicating that virtual laboratory environments can support meaningful learning when students actively interact with experimental procedures rather than passively observing outcomes (Puntambekar et al., 2020; Tatli & Ayas, 2013). In the present study, the virtual laboratory simulated key qualitative analysis procedures related to salt identification, allowing students to rehearse procedural steps and interpret reaction outcomes in a controlled environment. Such opportunities for repeated procedural engagement are particularly important for the development of science process skills, which typically require iterative practice and feedback rather than isolated laboratory experiences (Aljuhani et al., 2018; Van Den Beemt et al., 2022).

Beyond the technological affordances of virtual laboratories, the effectiveness of the intervention appears closely linked to the pedagogical structure through which the VR-CL environment was implemented. The learning activities were organised according to the 5E instructional model, which provides a structured sequence for engaging students in scientific inquiry. The Engage phase introduced contextualised problems related to salt analysis, while the Explore phase required students to conduct simulated experiments using the VR laboratory. During the Explain and Elaborate phases, students interpreted experimental results and applied their reasoning to solve inquiry tasks. The Evaluate phase enabled students to consolidate their understanding through laboratory reporting and reflection. This structured inquiry progression likely facilitated systematic practice of science process skills throughout the intervention.

Elements of PBL were also incorporated through contextualised scenarios embedded in the VR-CL modules. Students engaged with problems related to environmental contamination, water quality, and forensic salt identification, which required them to apply qualitative analysis procedures to interpret experimental evidence and formulate conclusions (Melesse et al., 2025). Such problem-centred contexts may have encouraged deeper engagement with scientific reasoning and promoted the application of science process skills in authentic situations (Hicks & Bevsek, 2011).

The systematic design of the VR-CL module may also have contributed to the effectiveness of the intervention. The learning activities were developed following Sidek's instructional design model, which emphasises alignment between learning objectives, instructional activities, and assessment tasks. This alignment ensured that the virtual laboratory simulations, worksheets, and assessment instruments consistently targeted the development of science process skills. As a result, students were repeatedly required to enact science process skills through structured inquiry tasks rather than encountering them incidentally during laboratory activities.

Furthermore, the integration of digital technology within the learning environment can be interpreted through the SAMR model of technology integration. According to SAMR, technology can transform learning tasks by enabling modification or redefinition of instructional activities rather than merely substituting traditional methods. In the present study, the VR-CL environment did not simply replace physical laboratory experiments but enabled students to repeat experimental procedures, manipulate virtual apparatus, and analyse reaction outcomes across multiple contexts. These affordances allowed students to engage more extensively with experimental reasoning processes than might be possible during limited physical laboratory sessions in resource-constrained school settings (Mphafudi & Ramaila, 2020).

In addition, AI-supported digital tools functioned as scaffolding mechanisms that supported students' reasoning processes during inquiry tasks. AI-assisted prompts and online platforms provided opportunities for clarification, discussion, and feedback as students interpreted experimental observations and constructed explanations (Hamedi et al., 2025). Such scaffolding may have facilitated deeper engagement with inquiry processes and supported students in coordinating multiple science process skills during laboratory activities.

Implications for Rural Chemistry Learning

Another important implication of this study is that immersive technologies are not necessarily required to achieve meaningful learning gains in chemistry education. Although immersive virtual reality has been associated with increased engagement and presence, its implementation in school settings is often constrained by cost, technical complexity, and infrastructure requirements (Enoiu & Sabou, 2023; Rizvan et al., 2023). These challenges are particularly pronounced in rural contexts where schools may lack the resources necessary to support immersive technologies.

The findings of this study demonstrate that a non-immersive smartphone-based virtual laboratory can produce significant educational benefits without reliance on specialised hardware. This observation is consistent with research highlighting the potential of mobile learning technologies to improve equitable access to high-quality educational experiences (Zhao, 2025). By leveraging widely available smartphones, the VR-CL intervention enabled students to participate in laboratory-based inquiry activities despite structural resource limitations.

These findings contribute to broader discussions on technology-enabled equity in science education. Mobile and low-cost digital technologies have been increasingly recognised as practical solutions for addressing disparities in laboratory access across rural and resource-limited educational contexts (Neupane, 2015; Patel et al., 2024). In this respect, the present study provides empirical evidence that non-immersive virtual laboratories can serve as viable instructional alternatives for supporting inquiry-based science learning when access to physical laboratory facilities is limited.

Consistency Across Gender

The absence of a significant gender effect or interaction between instructional group and gender suggests that the effectiveness of the VR-CL intervention was consistent across male and female students. This finding is consistent with prior research indicating that well-designed inquiry-based learning environments can reduce or minimise gender differences in science learning outcomes (Nunaki et al., 2019).

Previous research has indicated that gender differences in science achievement are often influenced by contextual factors such as instructional practices and classroom environments (Pande & Jepsen, 2024). The present findings support this perspective by suggesting that well-designed inquiry-based learning environments can create inclusive opportunities for students to engage in scientific reasoning and laboratory investigation.

By foregrounding science process skills as the primary learning outcome, this study extends existing research on virtual laboratories and virtual reality in science education, which has frequently focused on affective outcomes such as motivation, engagement, or attitudes (Alnaser & Forawi, 2024). While such outcomes are valuable, science process skills represent a fundamental component of scientific literacy and are essential for students' ability to participate meaningfully in scientific inquiry.

Recent empirical studies and systematic reviews have increasingly highlighted the potential of virtual laboratory environments to support cognitive and procedural learning outcomes, while emphasising the need for context-sensitive research conducted in authentic classroom environments (Lailiyah et al., 2024). The present study contributes to this growing body of literature by demonstrating that non-immersive virtual reality environments can support the development of science process skills among secondary school students.

Furthermore, by situating the study within a rural educational context and focusing on a procedurally demanding chemistry topic, the research addresses an underrepresented population and learning outcome in the virtual laboratory literature. The findings demonstrate that effective development of science process skills does not depend on immersive technologies or sophisticated hardware. Instead, carefully designed non-immersive virtual learning environments can provide sufficient affordances for inquiry-oriented learning when they are aligned with pedagogical frameworks and curricular objectives (Chan et al., 2021; Lynn, 2020).

Overall, the study provides evidence-based insights for educators and researchers seeking scalable and resource-sensitive alternatives to traditional laboratory instruction. By demonstrating that meaningful improvements in science process skills can be achieved through accessible smartphone-based virtual laboratories, this research contributes to bridging the gap between technological innovation and practical classroom implementation in rural and resource-limited educational contexts. These findings therefore extend previous research on virtual laboratories by demonstrating that non-immersive, smartphone-based VR environments can support the development of science process skills at the secondary school level, particularly in rural educational contexts where access to laboratory facilities is limited.

CONCLUSION

This study examined the effectiveness of an Android-based, smartphone-delivered non-immersive virtual reality chemistry laboratory in enhancing rural upper secondary students' science process skills. The results showed that students who participated in the VR-CL intervention achieved significantly greater improvements in science process skills than those receiving conventional instruction, even after controlling for pre-test differences. These findings indicate that the structured integration of virtual laboratory activities, worksheets, and inquiry-oriented learning tasks can provide meaningful opportunities for students to practise key scientific processes such as observing, interpreting experimental evidence, and drawing conclusions. The findings extend existing research on virtual laboratories by demonstrating that non-immersive virtual reality environments can support procedural and inquiry-related learning outcomes, rather than only affective variables such as motivation or engagement. Importantly, the results suggest that accessible smartphone-based virtual laboratories can function as practical instructional complements to traditional laboratory learning, particularly in rural educational contexts where access to fully equipped laboratories may be limited. Overall, the study highlights the potential of pedagogically structured virtual laboratory environments to support science process skills development in secondary chemistry education (Kusmawan, 2024; Siddiqi, 2024)

LIMITATIONS AND FUTURE RESEARCH

Several limitations should be considered when interpreting the findings of this study. First, the use of a quasi-experimental design with non-equivalent groups limits the strength of causal inference, although analysis of covariance was employed to control for baseline differences. Future studies using randomised experimental designs could provide stronger evidence regarding the causal effects of structured inquiry-based virtual laboratory interventions. Second, science process skills were assessed as an integrated construct rather than as separate subskills. While this approach reflects the interconnected nature of scientific inquiry, future research could examine the effects of non-immersive virtual laboratories on specific science process skills (e.g., observing, inferring, and data interpretation) to provide more detailed insights into learning processes. Third, the intervention was implemented within a single chemistry subtopic over an eight-week period. Future research could investigate the effectiveness of structured inquiry-based virtual laboratory environments across different chemistry topics beyond qualitative salt analysis, as well as over extended instructional durations, to enhance generalisability. In addition, future studies could systematically isolate the individual contributions of instructional components, such as structured inquiry sequencing, scaffolding strategies, and virtual simulation features, to better understand their relative impact on learning outcomes. Further research incorporating qualitative approaches, such as classroom observations or student interviews, may also provide deeper insights into how students engage with inquiry processes within virtual laboratory environments and how these experiences support the development of science process skills over time.

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AI statement: The authors stated that they used generative AI tools (ChatGPT) solely for language refinement and proofreading. All scientific content, analysis, interpretation, and conclusions were developed and verified by the authors.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

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