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Review

The impacts of open inquiry on students' learning in science: A systematic literature review

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ABSTRACT

Open inquiry is the fourth and highest level of an inquiry-based approach in science teaching and learning. Although previous research has highlighted several benefits of open inquiry, thus far, *no* studies have comprehensively reviewed its impacts using systematic and rigorous methodologies. Thus, the central aim of this review study was to develop a better understanding of the impacts of an open inquiry approach on students' learning in science. The search strategy was restricted to articles published in established scholarly databases (WOS, Scopus and ERIC), following the seven steps in conducting a systematic literature review process in educational research. As a result, 24 articles were extracted and qualified for inclusion in this review study. Finally, a thematic analysis was conducted to analyse the articles and five themes were generated: i) students' conceptual understanding, ii) students' motivation, iii) students' attitudes towards science, iv) students' scientific and thinking skills, and v) students' science literacy and other science-related skills. Although open inquiry positively impacted students' learning in science, the reviewed article also reported some challenges in its implementation, notably the need for classroom management, flexible teaching and learning, teacher-student interaction and teacher support. This review study provides a significant contribution to science education research, indicating that the highest level of an inquiry-based approach may *not* be the 'best' approach. However, this review offers a future opportunity for policymakers, teacher educators, science education academics, NGOs, science teachers, and other interested parties to promote inquiry pedagogy to improve students' learning in science.

1. The impacts of open inquiry on students' learning in science: A systematic literature review

Inquiry learning is a strategy for teaching science that enables students to study a subject that replicates scientific inquiry (Dmoshinskaia et al., 2021). In addition, inquiry-related curiosity may manifest itself in students' desire to explore and participate in various components of scientific research, which can help them improve their inquiry skills (Wu et al., 2018). Furthermore, inquiry-based activities must begin with a scientific question and include students in data analysis (Bell et al., 2005). While asking students questions, teachers adopt new and varied roles, which can increase student ownership of their learning and improve their

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cognitive performance (Chen et al., 2018). However, students' inquiry skills which include raising questions, developing investigations, and carrying out research, may be more closely connected to describing analytical and planning abilities (Pedaste et al., 2021).

In addition, students are able to construct their conceptual understanding and improve their learning by using the inquiry-based learning approach (Srisawasdi & Panjaburee, 2019). Active learning approaches such as inquiry learning are necessary to achieve deep-level understandings in science education, since subsequent learning frequently builds upon this knowledge (van Riesen et al., 2018). In inquiry classrooms, it is *not* uncommon for teachers to ask students questions, and this strategy is often recommended as best practice (Martin et al., 2019).

1.1. The four levels of inquiry

The study of scientific knowledge in the inquiry framework thoroughly examines what would otherwise be a cursory inquiry. There are many arguments for a transition toward inquiry-based learning in science education. Schwab (1958) was the first to explain the notion of several degrees of investigation which students learned through active participation in the inquiry process. Students discussed the details of research: problems, data, the role of technology, data interpretation, and conclusions reached by scientists (National Research Council, 2000). Herron (1971) later recognised three categories of receptivity to scientific research: i) exercises whereby the student was predicted to 'explore' specific principles or recognise patterns in chemical phenomena, ii) exercises requiring an inference or problem-solving behaviour with no predefined set of solutions, and iii) exercises intended to 'illustrate' or 'allow students to observe' a particular phenomenon, as well as tasks to give the student practice in developing experiments (Herron, 1971). Drawing on the studies of Schwab (1958) and Herron (1971), Rezba et al. (2007) established a four-level model of inquiry teaching comprising confirmation, structured, guided, and open inquiries (Bell et al., 2005). According to Bunterm et al. (2014), the four levels of the model are as follows: questions, procedures, and solutions are offered (confirmation inquiry); questions and processes are given to students (structured inquiry); questions are merely provided to students (guided inquiry); and students develop questions, procedures, and solutions (open inquiry).

1.2. Previous systematic reviews on inquiry-based approaches

A survey of relevant research found that 17 previous systematic reviews have discussed the core topic of this study: the implementation of inquiry-based approaches in science education. The majority of previous reviews have focused on the elements of inquiry learning, the integration of technology into inquiry learning, comparisons between conventional and inquiry-based approaches, challenges in practising inquiry learning, and the effects of 'general' inquiry approaches on students learning.

Studies have discussed the elements of inquiry that affect how inquiry activities are conducted, and a few are worthy of note in relation to the present study. Anuar et al. (2017) investigated the pattern of current inquiry-based learning research studies, while Baumfield (2006) discussed the thinking skills approach as an instrument for pedagogical inquiry, highlighting the need to reform inquiry-based teaching as a professional development strategy. Similarly, Alake-Tuenter et al. (2012) examined the skills and competencies that school teachers require to implement an inquiry-based science lesson. Herranen and Aksela's (2019) review focused on formulating students' questions in inquiry and their responsibilities during the lesson. Weiss et al. (2021) reviewed argument-based inquiry learning contexts in school-based education, and Rönnebeck et al. (2016) discussed the processes involved in evaluating students' skills. Beltrano et al.'s (2021) systematic review highlighted the relationship between risk and trust in students' early participation in inquiry-based lessons.

Previous reviews have also focused on the implementation of an inquiry-based approach that integrates technology. Kim and Gurvitch (2020) reviewed the community of inquiry framework in online education research, while Suárez et al. (2018) and Liu et al. (2021) reviewed various mobile activities in inquiry-based learning for student support. Some reviews have focused on specific technological interventions, notably that of Pedaste et al. (2020), which offered feedback on using augmented reality (AR) in inquiry-based learning. Previous systematic reviews on inquiry-based approaches have compared conventional and inquiry-based learning models and identified the limitations of traditional and inquiry-based learning (see Khalaf & Zin, 2018).

Previous systematic reviews have also discussed the challenges of practising inquiry learning in the science classroom. The teaching challenges identified and the ways in which they affect the clarification of teacher competencies were based on inquiry-based practical work findings (Akuma & Callaghan, 2019). Similarly, Marimuthoo and Nasri (2019) highlighted teachers' beliefs, the obstacles they face in applying inquiry-based learning in the classroom, and the reasons behind these challenges. Lastly, previous reviews on the 'general' inquiry-based approach have also aimed to explore its impact on students' learning (see Nugroho & Zulfiani, 2021; Santana-Vega et al., 2020; Zweers et al., 2019).

In conclusion, the utilisation of numerous search tactics across all academic and scholarly databases has revealed that thus far, *no* study has systematically reviewed the impacts of open inquiry-based teaching on students' learning in science.

1.3. Focus of the study

Since Bell et al. (2005) introduced the four levels of inquiry, an open inquiry learning approach has been viewed as a valid form of scientific investigation and the highest level of inquiry that students should aspire to, in contrast to the 'cook-book recipe' experiments that they often conduct at school. The fourth level of inquiry – the 'open' inquiry approach – is *not* a popular pedagogical practice in the science classroom, due to the challenges it presents in relation to time and resources (Ropika et al., 2021; Sadeh & Zion, 2012). For that reason, it has rarely been implemented (Yoon et al., 2012; Zion & Mendelovici, 2012). Yet, it is *not* impossible to do so. Thus, it is compelling to explore literature on open inquiry so that it becomes a guideline for science teachers and teacher educators. Despite the fact that there are millions of publications and resources on inquiry-based science (based on a Google search as of August 20, 2022, which yielded about 211,000,000 results), many science teachers and teacher educators have neglected this approach. Therefore, in this systematic literature review (SLR) of open inquiry-based learning in science classrooms, we have focused on the positive impacts of open inquiry on students' learning in science. The purpose of the study is to provide a comprehensive review of open inquiry using systematic and rigorous methodologies. Thus, the systematic review presented in this article focuses on answering the following research question: What are the impacts of open inquiry-based teaching on students' learning in science?

2. Methodology

This systematic literature review identified, selected and critically appraised studies in order to answer the proposed research question. The process of selecting articles to be reviewed was guided by the established guidelines for conducting Systematic Reviews in Educational Research (Zawacki-Richter et al., 2020) and the framework for Systematic Reviews and Meta-Analyses (PRISMA) (Page et al., 2021). These guidelines were designed specifically to investigate the impacts of the interventions used in previous studies. Aligned with the aim of this review, they were suitable for measuring the impacts of open inquiry on students' learning in science, as they provided comprehensive and detailed processes of conducting a systematic literature review in the context of educational research in order to inform policy and to support research and practice in education (Polanin et al., 2017). The SLR process has seven steps: i) formulate a research question and construct a conceptual design framework, ii) generate a set of selected criteria, iii) come up with a search strategy, iv) choose studies based on a set of criteria, v) quality appraisal, vi) coding research, and vii) data synthesis.

2.1. Phase 1: Formulate a research question and construct a conceptual design framework

This review aims to gain new insights into open inquiry science education, notably aspects such as identifying open inquiry settings and situations that have been studied before. The research question that led to the literature search was: What are the impacts of open inquiry-based teaching on students' learning in science? We were interested in how open inquiry in science teaching for K-12 students is implemented. Therefore, we reviewed previous studies that investigated the impacts of using an open inquiry-based approach in science education.

2.2. Phase 2: Generate a set of selected criteria

The generation of selection criteria for this study was based on PICo (Richardson et al., 1995), which consists of three essential elements: population or problem, interest, and context. Based on these concepts, we have included three main aspects in the review, namely K-12 students (population), open inquiry (interest), and science education (context). This population was selected because K-12 has a bigger sample to draw from than tertiary education and is mandatory in almost every country. We were interested in the open inquiry approach as our initial search showed that there is a need to explore how open inquiry is implemented in science classrooms and how it impacts students' learning in science. As for science education, it covers a larger knowledge area compared to subdisciplines of science, namely physics, chemistry and biology. For example, selection criteria for a review question on the impacts of open inquiry on science education would include who was impacted by open inquiry implementation, the features, and the results. Research participants, K-12 students, and the English language were also employed as selection factors.

2.3. Phase 3: Come up with a search strategy

We discovered two crucial keywords based on the research questions: open inquiry and science education. In addition, we looked back at previous keywords and sought expert advice to supplement these keywords. Several keywords related to open search were checked due to this procedure, including student-centered science education, student-question-based inquiry, self-directed learning, and student-centered instruction. Considering research field maturity, this review confined the screening procedure to publications published in the last ten years which is from 2011 to 2021 since research on inquiry-based approach was on trending during this period (Kraus et al., 2020). The quantity of published research was adequate for a representative study; hence, we selected this chronology. Because empirical research publications include primary data, we evaluated the relevant studies. To prevent any misunderstandings,

Table 1
Search string used in searching for articles from the database.

Database	String
Scopus	TITLE-ABS-KEY ("open inquiry") AND (LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017) OR LIMIT-TO (PUBYEAR, 2016) OR LIMIT-TO (PUBYEAR, 2015) OR LIMIT-TO (PUBYEAR, 2014) OR LIMIT-TO (PUBYEAR, 2013) OR LIMIT-TO (PUBYEAR, 2012) OR LIMIT-TO (PUBYEAR, 2011)) AND (LIMIT-TO (SUBJAREA, "SOCI")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (DOCTYPE, "ar"))
Web of Science	((TI=(open AND inquiry)) OR AB=(open AND inquiry)) OR KP=(open AND inquiry)
ERIC	TI ("open inquiry") OR AB ("open inquiry")

we considered only those written in English.

In July 2021, we started searching in three databases: the online sources Educational Resources Information Centre (ERIC), Scopus, and Web of Science. Combinations of these terms were analysed, utilising search functions such as field code functions, phrase searches, and Boolean operators. Furthermore, the investigation was conducted using a manual search approach. In databases such as Science Education Journals, 'handpicking' was utilised. The advanced search function and the following search terms were selected (see Table 1). The categories of sources chosen were academic journals.

2.4. Phase 4: Choose studies based on a set of criteria

The studies in this review were found through a process of identification, screening, and eligibility, and were subjected to a verification process to confirm that they fulfilled the selection criteria. The process of selecting articles followed the procedures outlined by PRISMA (Page et al., 2021), as shown in Fig. 1. In the identification process, a total of 290 possible articles were found from the specified databases, and 149 duplicated articles were removed before the screening procedure. In the screening process, titles and abstracts were evaluated to determine relevant studies. This method resulted in 141 articles and excluded 94 items that did *not* meet the inclusion criteria. We monitored the retrieved articles throughout the identification and screening process to guarantee that all remaining articles met the requirements. In total, 47 articles, consisting of qualitative, quantitative, and mixed methods studies, were chosen to be included in the quality assessment process in phase 5.

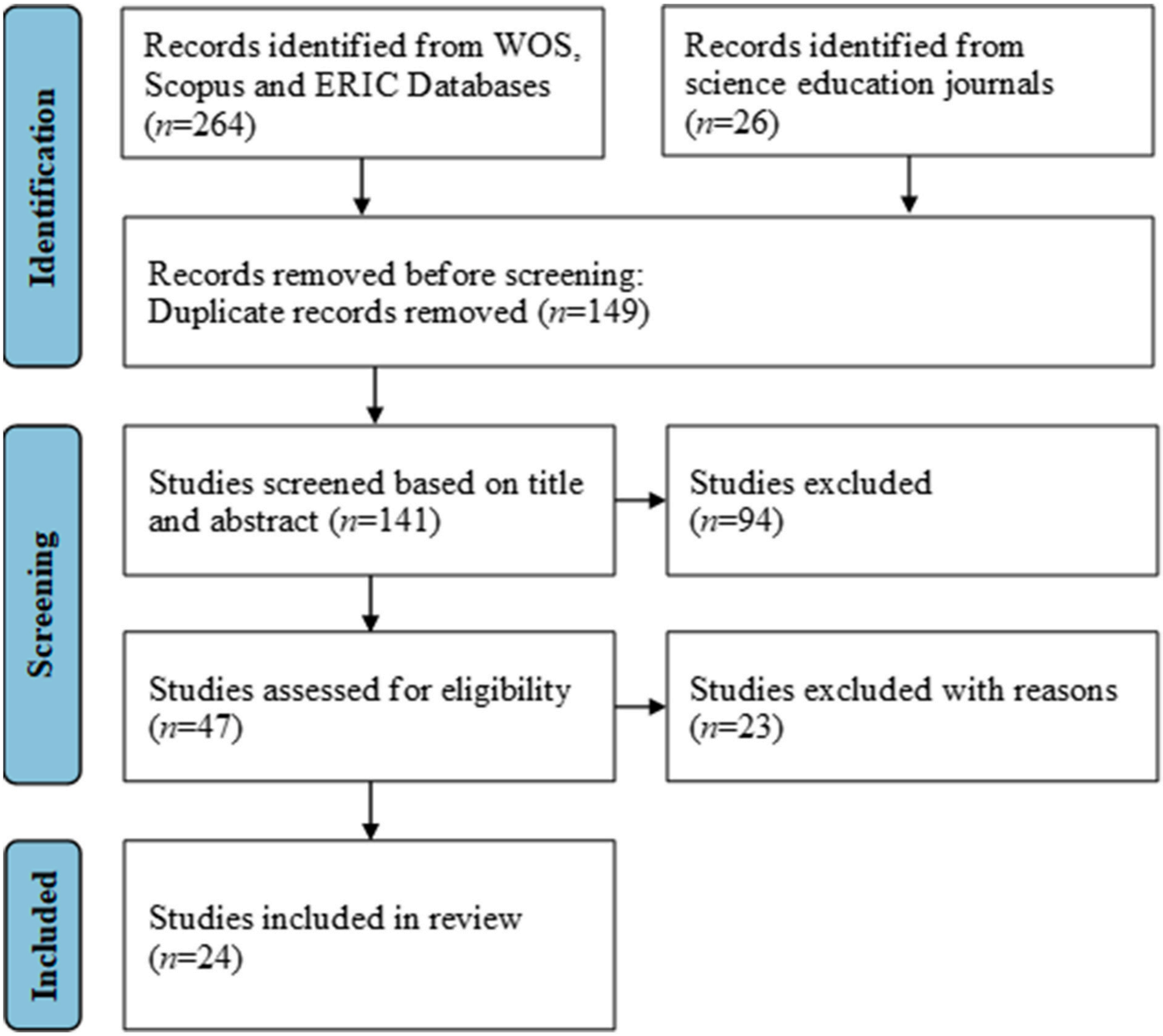

Fig. 1. The process of selecting articles to Be reviewed, following PRISMA (Page et al., 2021).

2.5. Phase 5: Quality appraisal

The 47 articles were sent to four experts within the research team for quality evaluation to ensure that the content of the articles was of sufficiently high quality. In the critical appraisal process, three factors were considered: the research design, research methods, and the study's relevance to the review topic (Gough, 2007). We used the Mixed Methods Appraisal Tool (MMAT) for the quality appraisal process (Hong et al., 2018, pp. 1–11). All reviewers reviewed each article and divided the articles into five categories of study designs and screening questions, with three choices for expressing their responses: 'yes', 'no', and 'don't know/can't tell'. The five categories of study designs are qualitative, quantitative randomised controlled trials, quantitative non-randomised, quantitative descriptive and mixed methods (Hong et al., 2018, pp. 1–11). The articles were only considered for the review if they related to at least one of the categories. As a result, all reviewers agreed that 24 articles fulfilled the minimum quality standard in terms of methodology and analysis, and 23 articles were removed from the procedure. They agreed on the evaluation judgments, and any disagreements were

Table 2
Five Themes and Sub-Themes were Generated from the 24 Selected Studies.

Authors	Students' conceptual understanding	Students' scientific and thinking skills	Students' attitudes towards science	Students' science literacy and other science-related skills	Students' motivation
Abaniel (2021)	Conceptual understanding		Learning attitudes	21st-century skills	
Adler et al. (2016)				Environmental literacy	
Adler et al. (2018)					Temporal motivation Motivational support
Buck et al. (2014)			Attitudes towards science	Instructional aspects	
Ellwood and Abrams (2018)	Student achievement			Student social interactions	State of flow
Katchevich et al. (2013)				Constructing argumentation skills	
Kock et al. (2013)	Conceptual understanding				
Kota et al. (2019)			Student engagement		
Mäeots and Pedaste (2014)		Students' general inquiry knowledge			
Moebius-Clune et al. (2011)	Student learning	Science inquiry skills	Students' attitudes Student engagement		
Pöntinen et al. (2019)		Contents of student-generated questions The way students pose questions in teams			
Puslednik and Brennan (2020)		Students' scientific skills			
Rahmat and Chanunan (2018)		Metacognitive skills			
Sadeh and Zion (2012)			Students' attitudes		
Schwartz et al. (2021)			Students' expressions of competence Students' expressions of autonomy		
Shaner et al. (2018)			Attitudes towards science		
Srisawasdi and Sornkhatha (2014)	Conceptual understanding				
Suryani (2017)			The collaborative attitude of students		
Tornee et al. (2017)		Science process skills Problem-solving competency	Scientific attitudes		
van Rens et al. (2014)	Students' understanding of inquiry peer reviews				
van Uum et al. (2017)	Students' understanding of the inquiry process				
Ward et al. (2016)		Science skills	Students' interest in science		
Yang et al. (2016)		Science inquiry performance Students' creative science thinking		Students' reflection	
Zion et al. (2011)				Environmental literacy	

immediately resolved through discussion.

2.6. Phase 6: Coding research

In phase 6 of the review, all four authors created the coding schema for assessing all found articles via discussions based on the topic of the studies. The extracted data contain information such as research design, research objectives, research questions/hypotheses, parameters, demographics of participants, country, subject, method of data collection, method of data analysis, intervention, and duration of intervention. We sought to detect patterns in the data obtained from all studies examined in the process. Charts were produced to illustrate key facts about all the 24 articles based on the countries where the studies were conducted, research design, publication years and students'/participants' age groups.

2.7. Phase 7: Data synthesis

The articles were analysed thematically following Braun and Clarke's (2019) reflexive thematic analysis. We employed a qualitative data analysis software, Atlas. ti to facilitate the process. Through this software, we identified, constructed and debated the codes and categories from the 24 studies to provide a comprehensive interpretation of the data. Leveraging our collaborative theoretical assumptions, analytical skills and the interpreted data (Braun & Clarke, 2021), we generate the emerging themes associated with the impacts of open inquiry on students' learning in science. As a result, five themes were identified: i) students' conceptual understanding, ii) motivation, iii) attitudes towards science, iv) scientific and thinking skills, and v) science literacy and other science-related skills (see Table 2). The validity of classification into categories was evaluated by utilising an interrater with whom the codes and types were discussed until agreement was attained.

3. Results

The results offer background information on the selected studies and the developed themes.

3.1. Background information on selected studies

Of the 24 selected articles, several countries were reported to have conducted studies on open inquiry (see Fig. 2). Six studies were conducted in Israel., five studies concentrated on the United States, two studies focused on Australia, two studies were conducted in the Netherlands, two studies in Indonesia and two in Thailand. Other than that, only one study from the Philippines, Estonia, Finland and Taiwan were also included in the review. Furthermore, only one study involved many countries: Brazil, Germany, Poland, and The Netherlands.

Open inquiry studies were conducted using qualitative, quantitative and mixed-method designs (see Fig. 3). It was recorded that eight articles focused on quantitative methods as a research design. Six articles utilised qualitative methods. Ten articles used a mixed-methods approach.

The findings show that from 2011 to 2021, only 2015 was *not* reported about open inquiry (see Fig. 4). Out of a total of 24 articles, two articles were published in 2011, one article was published in 2012, two articles were published in 2013, four articles were published in 2014, three articles were published in 2016, three articles were published in 2017, four articles were published in 2018, two articles were published in 2019, one article was published in 2020, and two articles were published in 2021.

An open inquiry approach was adopted for students across elementary, middle, and high school levels (see Fig. 5). Concerning the age distribution within the student population, open inquiry interventions were applied to elementary school students (ages 8–12 years) in four instances, middle school students (ages 12–15 years) in ten occurrences, and high school students (ages 15–19 years) in a total of 14 cases.

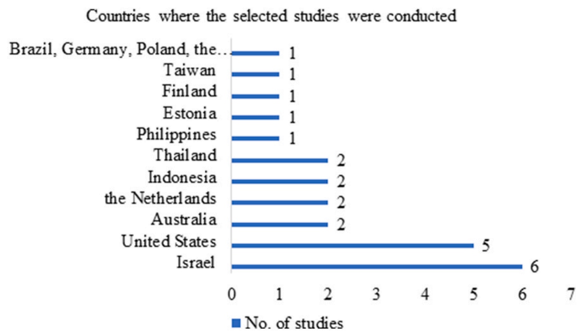

Fig. 2. Countries where the selected studies were conducted.

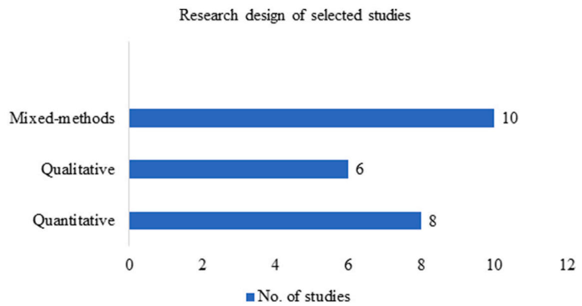

Fig. 3. Research design of selected studies.

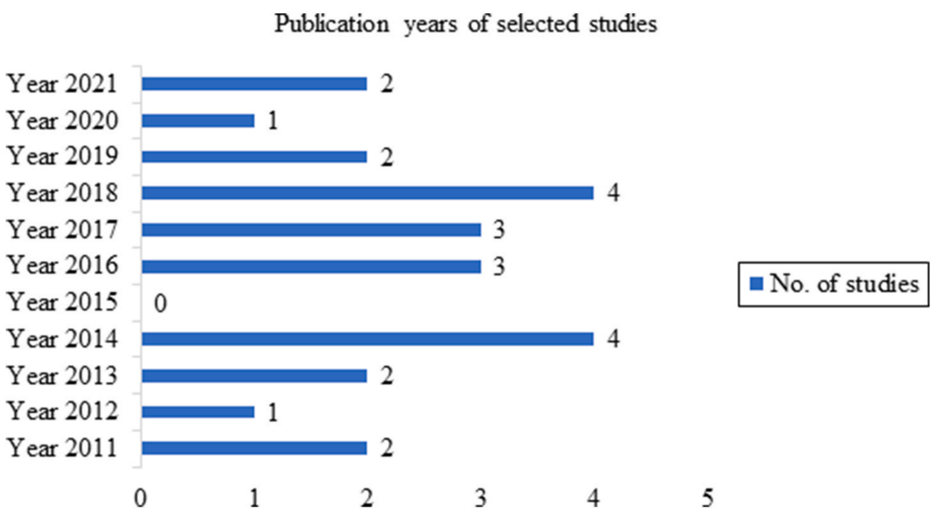

Fig. 4. Publication years of selected studies.

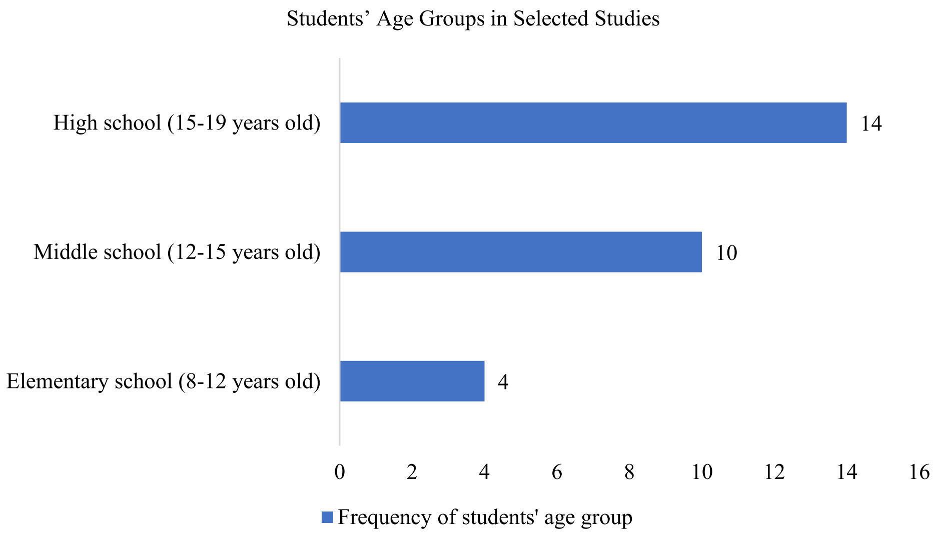

Fig. 5. Students' age groups in selected studies.

3.2. The developed themes

We critically discuss the themes that have been generated from the studies reviewed: i) students' conceptual understanding, ii) students' scientific and thinking skills, iii) students' attitudes towards science, iv) students' science literacy and other science-related skills, and v) students' motivation. These themes are interconnected yet distinct, each one highlighting a unique aspect of the impact that open inquiry has on students. Student conceptual understanding in open inquiry involves engaging with core ideas and principles, thereby enhancing their grasp of scientific concepts. Students' scientific and thinking skills are developed through hands-on open inquiry, fostering independent learning, creativity and critical thinking. Students' attitudes towards science, which include their feelings and values, will be positively influenced by their future engagement in science as a result of participating in open inquiry. Students' science literacy and other science-related skills—such as environmental literacy, 21st-century skills like information literacy and effective communication, as well as abilities in social interaction, argumentation, autonomy, and reflection—are all enhanced through open inquiry learning. Lastly, students' motivation in open inquiry is driven by personal interest, real-world relevance, and autonomy, encouraging them to actively engage in and investigate scientific problems.

3.2.1. Students' conceptual understanding

Students' conceptual understanding involves connecting scientific concepts to real-world situations, expressing them in their own words, creating visual models, or using relevant metaphors (Koniceck-Moran & Keeley, 2015). Instead of focusing solely on studying facts, students engage in quality learning experiences centered on core concepts and essential ideas through the application of conceptual understanding. Seven articles have discussed concept understanding and learning (see Abaniel, 2021; Ellwood & Abrams, 2018; Kock et al., 2013; Moebius-Clune et al., 2011; Srisawasdi & Sornkhatha, 2014; van Rens et al., 2014; van Uum et al., 2016). Abaniel (2021) reported that open inquiry learning has been shown to help students gain knowledge by creating, performing, evaluating, and presenting research. Overall, the findings of this research suggest that open inquiry learning can improve students' grasp of scientific ideas.

Many tools have been used in open learning inquiry to help students construct their knowledge. Computer technology was an example tool in this learning strategy. The research conducted by Srisawasdi and Sornkhatha (2014) highlighted that a significant majority of students demonstrated improvements in their conceptual understanding. Notably, the students exhibited a proficient scientific comprehension of Newton's first and second laws of motion. However, it was observed that a substantial portion of the students still maintained only a rudimentary understanding of Newton's third law of motion. The study emphasized the implementation of simulation-based open-inquiry activities embedded within the framework of the Dual-Situated Learning Model which provided students with visualizations of force, action and reaction. This pedagogical approach was strategically employed to facilitate an enhanced inquiry learning process among the students and to encourage a more thorough comprehension of the fundamental principles governing Newton's laws of motion.

Discussion techniques are a set of platforms for the open-ended, collaborative discussion of ideas between a teacher and students or between students to improve students' thought, knowledge, problem-solving, comprehension, or literary appreciation. As Ellwood and Abrams (2018) described, students' meaningful verbal exchanges on lesson material positively influenced their progress. In addition, students behaved like scientists when they communicated with one other, debated ideas, and offered critical reviews.

Furthermore, the results are reinforced by van Rens et al. (2014), who claim that peer reviews may help build critical thinking and shared knowledge. In another piece of research, van Uum et al. (2017) found that questioning encourages the inquiry process to continue. Many tools also have been used in open learning inquiry to help students construct their knowledge such as computer technology (Srisawasdi & Sornkhatha, 2014). As a result, open inquiry learning domains, tools, and strategies have significantly improved conceptual understanding.

3.2.2. Students' scientific and thinking skills

Scientific skills denote proficiency in the process of inquiry, involving tasks such as identifying problems, formulating hypotheses, designing experiments, and identifying and defining variables (Feyzioglu et al., 2012). Meanwhile, thinking skills encompass the cognitive abilities and processes utilised in the practice of scientific inquiry, including critical thinking, problem-solving, logical reasoning, and the use of scientific methods to analyse and interpret information (Miri et al., 2007). Inquiry-based learning incorporates fundamental scientific skills, including observation, communication, classification, inference, measurement, and prediction. Several studies have shown that the environment of open inquiry learning is suitable for improving scientific skills (see Mäeots & Pedaste, 2014; Moebius-Clune et al., 2011; Puslednik & Brennan, 2020; Rahmat & Chanunan, 2018; Tornee et al., 2017). For example, according to research by Tornee et al. (2017), open inquiry learning enhanced problem-solving competence, science process skills and scientific attitudes by performing experiments.

Metacognitive skills may help students improve their thinking and learning abilities. The aspect of monitoring in metacognitive skills involves investigating, observing, collecting, and interpreting data. According to Rahmat and Chanunan (2018), through open inquiry students gained higher metacognitive skills than through conventional models. As part of empowering their metacognitive skills, students had to define the problem observed and analyse what they had done independently (Rahmat & Chanunan, 2018). Furthermore, according to Puslednik and Brennan (2020), high-achieving students encounter essential scientific skills and subsequently understand changes. In open inquiry, students learn independently and actively plan, monitor, and evaluate their learning with control from the teacher.

Hands-on projects and experiments are the best way to teach science skills. Students' scientific skills, such as problem-solving, communicating, planning, designing, and conducting, improve more by analysing the multimedia science assessment, according to

Puslednik and Brennan (2020). These findings are confirmed by the study of Moebius-Clune et al. (2011), which highlights that open inquiry-based learning is an effective pedagogical strategy for engaging and challenging a classroom of students with a wide variety of material knowledge and skill levels. Students who concentrate on acquiring scientific skills will regularly remember and practise the scientific method.

Using an open inquiry approach in science learning helps students think more creatively. For example, in Yang et al.'s (2016) study, students significantly progressed in the performances of science inquiry, and divergent and convergent thinking due to open inquiry learning. The students are capable of making scientific conclusion and reviewing and commenting on group presentation (Yang et al., 2016). These findings provide empirical evidence to support the effectiveness and feasibility of encouraging students' creative thinking through open inquiry-based learning environment. Furthermore, these findings support Rahmat and Chanunan's (2018) assertion that the capacity to think creatively is essential in developing strategies, conducting experiments, addressing problems, and impacting intellectual growth. As a result, open inquiry may lead to the tangible use of critical and creative thinking skills.

3.2.3. Students' attitudes towards science

Students' attitudes towards science develop considerably via open inquiry-based learning. Attitudes towards science encompass the feelings, beliefs and values held about an object, which could be the enterprise of science, school science, the impact of science on society, or scientists themselves (Osborne et al., 2003). Many studies have mentioned the positive impact of open inquiry on scientific perspectives (see Buck et al., 2014; Moebius-Clune et al., 2011; Sadeh & Zion, 2012; Shaner et al., 2018; Tornee et al., 2017). According to Sadeh and Zion (2012), open inquiry students were more satisfied and thought they had obtained advantages from conducting the project. Furthermore, students take more initiative and collaborate with their project partners (students, teachers, lab assistants) at a more advanced level (Sadeh & Zion, 2012). Therefore, although students experienced perceived difficulty conducting the project, it was successfully handled with the community's help.

Open inquiry promotes collaboration and teamwork, as the studies reviewed demonstrated statistically significant differences in student attitudes. According to Shaner et al. (2018), students can cooperate and convey their discoveries to peers and professional scientists via open inquiry. These findings are supported by Moebius-Clune et al. (2011), who highlight that cooperation and the communication of scientific ideas in open inquiry, both verbally and in writing, are the basis of science. However, some practical collaboration qualities, such as productivity, flexibility, and organisation, are unlikely directly related to working with others.

Making a presentation is an essential element of presenting your findings. Furthermore, communication is good when you are open-minded, tolerant, and prepared to receive criticism. The results of Moebius-Clune et al.'s (2011) study indicate that discussion and feedback could have assisted all students in gaining a more substantial capacity to comprehend and communicate their findings and to enable them to better present projects that matched the requirements. Furthermore, these data support Abaniel's (2021) claim that effective communication improved when implemented with open inquiry. Thus, students' capacity to correctly express their thoughts with their groupmates is a form of adequate communication. Therefore, communication is *not* merely a group conversation, but it also entails presenting results clearly and openly.

Self-confidence is an attitude towards talents and abilities. According to Buck et al. (2014), hands-on activities can boost students' self-confidence in science. These findings are also confirmed by Moebius-Clune et al. (2011), who highlighted that when students were given authentic tasks, they took ownership of their learning and were substantively engaged. As a result, open inquiry has slowly improved the experiences of students with low self-esteem.

3.2.4. Students' science literacy and other science-related skills

Science literacy involves knowing, understanding, and critically engaging with science content, applications, and the nature of science, including problem-solving skills, awareness of risks and benefits and the ability to think critically about scientific expertise (Mat Noor, 2021). Eight research studies have explored the impacts of open inquiry on students' science literacy and meanwhile, other science-related skills, including environmental literacy, student interrelationships, and student skills (See Abaniel, 2021; Adler et al., 2016; Buck et al., 2014; Ellwood & Abrams, 2018; Katchevich et al., 2013; Schwartz et al., 2021; Yang et al., 2016; Zion et al., 2011). The interventions in an open inquiry activity positively affect students in the environmental literacy category. Roth (1992, p. 10) defines environmental literacy as the capacity to perceive and interpret the relative health of environmental systems and to take appropriate action to maintain, restore, or improve the health of those systems. Based on this conceptual definition, Adler et al. (2016) developed an intervention of metacognition in an open inquiry activity. They found that the treatment group showed more positive values related to the environment than the control groups. Similarly, Zion et al. (2011) revealed that the students expressed positive attitudes towards the environment due to participating in an open inquiry project.

Six research studies have focused on the impact of open inquiry on students' skills, notably 21st-century skills, social interaction, constructing argumentation skills, students' expression of competence, students' expression of autonomy, and students' reflection. Abaniel (2021) use an open inquiry learning model intervention that significantly focuses on students' 21st-century skills. Their information literacy, inventive thinking, effective communication, high productivity, and leadership skills increased after being exposed to open inquiry. In Ellwood and Abrams' (2018) study, social interactions occur, as open inquiry promotes students to enter a state of flow, which encourages increased participation, perseverance and motivation as they experience positive emotions (Ellwood & Abrams, 2018). Thus, students that utilise open inquiry in science education foster a feedback loop between states of flow and acting like scientists.

Schwartz et al. (2021) investigate the effect of open inquiry on students' expression of competence and autonomy. Their research suggests that when the inquiry process moves into the conducting stage, it shows a significant difference, as the percentage of notes linked to competence was higher when students were engaged in an open inquiry process (Schwartz et al., 2021). Meanwhile, in terms of students' expression of autonomy, as the inquiry process moved to the conducting stage, open inquiry activity persuaded students to demonstrate increasing levels of independence (Schwartz et al., 2021). This statement indicates that students' competence and autonomy increased as the open inquiry progressed. Buck et al. (2014) found that the science lab and lab teacher provide opportunities to explore and perform inquiry-based, hands-on experiments, which allows students to experience a feeling of freedom, thus contributing to the surge of self-confidence in science. Students mentioned that when they were involved in science by doing inquiry-based science lab activities with the aid of the lab teacher, they became more attracted to science.

Open inquiry experiments also support students to improve their argumentation skills. Katchevich et al. (2013) stated that when open-ended inquiry experiments are conducted, this places the students at the centre of the process, thus promoting the construction of arguments. However, written statements in students' written reports show that *no* significant difference existed between average levels of opinion and levels of inquiry. Yang et al. (2016) investigated open inquiry in promoting students' reflection. Based on this research, effective open inquiry strategies that encourage students to work like scientists will support students' reflection on divergent and convergent thinking. As a result, students will develop creative scientific thinking.

3.2.5. Students' motivation

Students' motivation, defined as the energy propelling and sustaining behavior, encompasses goal-driven activities, requiring persistence, effort, and interconnected beliefs, perceptions, values, information and actions (Yilmaz et al., 2017). Four research studies have explored the impacts of open inquiry on students' motivation (see Abaniel, 2021; Adler et al., 2018; Ellwood & Abrams, 2018; Suryani, 2017). First, Abaniel (2021) explored students' motivation as changes in learning attitudes such as personal interest, real-world connection, general problem-solving, problem-solving confidence, and sense-making or effort. These changes were influenced by the nature of open inquiry, which encourages students to choose how to conduct the investigation and connect it to real-life situations. Motivation can also be seen in students' social interactions and collaborative attitudes. Ellwood and Abrams (2018) discovered that students who experienced any inquiry process had increased motivation because they got the opportunity to have an authentic reflection and open discourse with their peers. On the other hand, Suryani (2017) found *no* significant difference in the test result concerning students' collaborative attitudes due to open inquiry learning. Adler et al. (2018) suggested that contextual factors, namely autonomy and competence, affect student motivation during open inquiry. They found that changes in students' temporal motivation from the beginning to the end of the inquiry process showed a significant difference in the analysis of students' notes regarding positive autonomy and positive competence.

4. Discussions

Conceptual learning allows students to apply their acquired knowledge in comprehending new ideas or concepts. Moreover, integrating the inquiry phase can stimulate students' epistemic knowledge (Van Uum et al., 2017), consequently enhancing their understanding of the subject matter (Moebius-Clune et al., 2011). In addition, the students not only demonstrated ownership of their scientific learning but also effectively applied these concepts to real-world issues, exhibiting behaviours akin to those of scientists (Ellwood & Abrams, 2018; Moebius-Clune et al., 2011). As noted by Ellwood and Abrams (2018), the students engage in the development of research questions, the design and execution of experiments, the collection and analysis of data, and the communication of their findings to others. However, the open-inquiry process presents additional challenges as students grapple with complex situations to achieve a deeper understanding (Adler et al., 2019) and students require higher cognitive skills and more complex manipulations of materials (Ellwood & Abrams, 2018). Consequently, science teachers need to adequately prepare before initiating open inquiry to ensure effective inquiry-based learning for students (Muhamad Dah, 2021a; 2021b). Moreover, students can successfully tackle inquiry or problem-solving tasks with various forms of support or guidance, including motivation, task structure, prompts, and suggestions (Chen et al., 2018). Successful implementation of open inquiry may be facilitated by teachers who can effectively manage and regulate the learning environment (Kang, 2022; Mentzer et al., 2019), especially considering that students often conduct experiments or projects in small groups (Fauth et al., 2019). Additionally, teachers frequently rely on high-achieving students during open inquiry learning (Kang, 2022). Van Rens et al. (2010) proposed that open inquiry seems suitable and preferable for upper secondary school students, considering the challenges teachers face when handling a class with heterogeneous abilities (Chadwick et al., 2021).

Science process skills involve observing, measuring, using numbers, classifying, understanding space, communicating, inferring, predicting, controlling variables, hypothesizing, experimenting, and interpreting data and conclusions (Tornee et al., 2017). Thinking skills involve metacognition, which is the ability to reflect on one's thinking process. Students were encouraged to enhance their metacognitive skills by independently identifying problems, evaluating their work and expressing and testing their ideas. They were motivated to intensify critical thinking, find information, analyse arguments, synthesize new ideas, apply insights to problem-solving, and draw conclusions from data (Rahmat & Chanunan, 2018). Enabling students to engage in scientific inquiry through an open inquiry approach can be significantly enhanced their scientific and 21st-century skills (Pusednik & Brennan, 2020). These skills cannot be polished in an environment where students simply follow 'cookbook recipes' for scientific experiments rather than engaging in conceptually guided hands-on activities. Furthermore, implementing open inquiry as a direct application of student-centered learning proved to be particularly challenging for students with lower abilities (Rahmat & Chanunan, 2018). Therefore, for low-ability students, open inquiry was not an ideal method for directly applying high student-centered learning (Rahmat & Chanunan, 2018). To support these students, adaptation and modification are necessary. For example, providing general procedures during the initial learning period or allowing students to watch examples and attempt activities before classroom instruction could be beneficial. Unfortunately, a teacher preparation programme is insufficient and cannot include all of the necessary information and abilities necessary for science education (Wang & Sneed, 2019). Consequently, teachers often lack the necessary experience to effectively implement inquiry-based learning (Mat Noor, 2022; Musengimana et al., 2021). Therefore, science teachers require extensive professional development and practical experience, such as conducting field trips (Zulfiani & Herlanti, 2018) to improve students' scientific and critical thinking skills (Murphy et al., 2021).

Concerning students' attitudes towards science, these include their feelings, opinions, and beliefs about learning science within school setting (Musalamani et al., 2021). Additionally, Ma (2023) has suggested students' attitudes towards science from dimensions science interest, self-efficacy and instrumental value. They connect with personal and contextual issues such as gender, family background and school, and can be expressed through cognitive and affective mechanisms, and behaviours. Furthermore, they play an essential role in engagement while learning science. However, classroom management deals with interruptions and misconduct that adversely impact the maximisation of learning time (Kang, 2022). Open inquiry-based learning may need a more flexible learning environment (Variacion et al., 2021). Therefore, classroom management is critical since this student-centered approach needs more time and engagement (Fauth et al., 2019). According to Kousa et al. (2018), when the teaching method used is liked by the students, they exhibit optimistic attitudes that may result in improved academic performance. Furthermore, attitudes also influence the choice of a potential career in the future. Thus, how and what students feel are crucial to learning science.

Scientific literacy, as defined by the OECD (2017), is the competency to actively engage in discussions about science-related matters and comprehend scientific concepts. This fosters a reflective approach essential for responsible citizenship. Furthermore, the OECD (2017) highlighted three competencies in science literacy: students should be adept at explaining phenomena scientifically, evaluating and designing scientific inquiry, and interpreting data and evidence scientifically. These competencies are nurtured through an open inquiry approach—a student-centered method that begins with student-generated questions. Subsequently, students or groups immerse themselves in designing, conducting investigations or experiments, and communicating the results. In the broader context, science literacy encompasses students' levels of argumentation, interest, engagement, attitudes, and the development of 21st-century skills (Mat Noor, 2021). According to Abaniel (2021), information literacy is a component of 21st-century skills, pertains to students' ability to find information using digital technology. Notably, science literacy propels students towards developing critical thinking skills, enabling them to articulate arguments and promoting their scientific reasoning skills, as highlighted by the Mat Noor, 2021.

Motivation, a pivotal aspect of the learning process, can be categorised into intrinsic motivation and extrinsic motivation. Students exhibit intrinsic motivation when they actively engage with and explore the issues inherent in an investigation. Conversely, extrinsic motivation comes into play when students receive rewards, such as high marks, upon completing open-inquiry tasks. The utilisation of an open inquiry approach in the learning process has the potential to stimulate long-term motivation among students. From the perspective of the expectancy-value theory, teachers play a crucial role in enhancing students' expectations of success and the perceived value of academic tasks (Green, 2002). Aligning the curriculum with students' interests and abilities is instrumental in fostering an environment where students enjoy learning. This alignment is significant because motivation has a profound impact on human behaviour (Kılıç et al., 2021) and ultimately influences the effectiveness of learning outcomes (Ahmad et al., 2021). Moreover, motivation serves as a key driver in shaping student behaviour, promoting engagement, and facilitating knowledge acquisition in the realm of science teaching and learning (Hagger & Hamilton, 2018; Kılıç et al., 2021). Consequently, a teacher's approach and attitudes within the science classroom can exert a significant influence on students (Dávila-Acedo et al., 2021). Students who perceive greater teacher support may be more inclined to view challenges or setbacks in scientific investigation as integral to their beneficial progress (Lin et al., 2020).

5. Limitations, recommendations and implications

Nonetheless, this research has several limitations. It only drew on: i) articles on open inquiry written in English, ii) articles that applied this methodology to qualifications from the social sciences and in a school setting with students as participants, iii) publications almost exclusively drawn from research-oriented journals, and iv) articles found in academic databases (WOS, Scopus, and ERIC). Nevertheless, overall, we feel the findings of this study helped further our knowledge of open inquiry since, unlike earlier findings, they enabled us to gain insight into a variety of different operationalisations of inquiry-based activities in the context of empirical research.

However, this review offers a future opportunity for policymakers, teacher educators, science education academics, NGOs, science teachers, and other interested parties to promote inquiry pedagogy to improve students' learning in science. Assessment is a key aspect of policymakers' strategic planning for educational change (Shepard, 2000). Teacher educators need to actively facilitate teacher training as they require a gradual orientation in the process of developing lessons relevant to science contents (Kamarudin, Mat Noor, & Omar, 2022). The literature further recommends that the same organisation should create the curriculum and carry out the evaluation so that inspirational goals can be manifested efficaciously (Darling-Hammond, 2000). This review offers science education practitioners valuable insights, highlighting that there is a need to further research the relationship between curriculum, pedagogy and assessment using an open inquiry approach (Mat Noor, 2014).

Accordingly, several research gaps were identified based on a systematic literature review. First, there is a need to understand in-depth analyses of the effects of the open inquiry learning model on students' learning. Second, there is a need to understand the students' learning environment, self-esteem and beliefs. These themes, while important, were less discussed in previous studies. Third, the existing gap can be narrowed if future scholars focus on action research approaches and develop more publication standards.

6. Conclusions

Although prior research has identified several advantages of open inquiry, *no* studies have offered an in-depth exploration of its effects using systematic and rigorous approaches. As a result, the primary goal of this evaluation was to gain a better understanding of the effects and benefits of open inquiry-based learning on students' science learning. A critical evaluation makes it possible to identify gaps and open up possibilities for future research. A systematic literature review technique was used to assess the quality of 24 publications in this research. In addition, because the review was based on a range of research designs, thematic analysis was performed on the 24 articles chosen, yielding five main themes.

The review concluded that most studies are focused on attitudes towards science. In addition, open inquiry affects conceptual understanding and enhances students' motivation to learn science. The open inquiry approach provides opportunities for students to build scientific and thinking skills when they go through the inquiry process itself. Finally, this approach enhances students' science literacy and other science-related skills because students will be able to gain scientific knowledge such as explaining phenomena scientifically, evaluating and designing scientific inquiry, and interpreting data and evidence scientifically.

Open inquiry is considered the highest level of inquiry. However, this review study significantly contributes to science education research, indicating that the highest level of an inquiry-based approach may *not* be the 'best' approach. As the most complicated type of inquiry, open inquiry begins with students' questions, and they then design their research or experiment based on their own interests. As a result, this strategy is most likely to follow the work of actual scientists. Therefore, teachers need to consider all instructional quality aspects when implementing an open inquiry approach, including classroom management, flexible teaching, teacher-student interaction, and teacher support (Kang, 2022).

Credit author statement

Norsyazwani Muhamad Dah: Conceptualisation, Methodology, Validation, Formal Analysis, Writing - Original Draft, Visualization. Mohd Syafiq Aiman Mat Noor: Validation, Formal analysis, Writing - Review & Editing, Supervision. Muhammad Zulfadhli Kamarudin: Validation, Formal analysis, Writing - & Editing. Saripah Salbiah Syed Abdul Azziz: Review, Supervision.

Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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