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Inquiry based experiments to enhance sustainability literacy: A systematic literature review and bibliometric analysis

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Abstract

This study aims to explore inquiry-based experiments' educational aspects, levels of inquiry, and contributions to sustainability literacy. In this study, a systematic literature review and bibliometric analysis were used. A systematic literature review in this study used a PRISMA flow diagram, and the bibliometric analysis was conducted using VOS Viewer. Using systematic literature review 79 articles were analyzed, focusing on three main aspects: pedagogy/education, levels of inquiry, and sustainability literacy. A bibliometric analysis was also used in this study. A RIS format of articles was compiled and then used for the bibliometric analysis using VOSviewer. The bibliometric analysis focused on network overlay, density visualization, and author and co-author relationships. The results of this study indicate that inquiry-based experiments significantly enhance students' understanding of scientific concepts, motivation, and essential scientific skills such as hypothesis formulation, experiment design, data collection, and analysis. This literature review also reveals a gap in integrating sustainability literacy into inquiry-based experiments. Although some studies have incorporated green chemistry principles and real-world applications, only a few explicitly promote sustainability literacy. This underscores an opportunity for future research to design inquiry-based experiments that more directly address sustainability literacy.

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1. Introduction

Textbooks for introductory chemistry courses rarely emphasize sustainability challenges. Chemistry educators also lack sufficient resources to help students make meaningful connections between chemistry and sustainability issues (Mahaffy et al., 2014). By presenting everyday problems that are relevant to students' lives, inquiry-based approach can motivate students and reinforce their understanding of sustainability principles. This approach helps students see the direct relevance of chemistry concepts to sustainability issues, such as acid-base reactions and energy conservation (Kovács et al., 2021). Inquiry-based approach emphasizes students' cognitive abilities and scientific reasoning to address experimental questions, which is crucial for understanding complex sustainability issues. This approach helps students develop the skills needed to tackle real-world problems related to sustainability (Paluri et al, 2015).

Inquiry-based teaching approaches are incredibly important in chemistry and science education because it helps students develop critical thinking, analytical reasoning, and a deeper understanding of concepts. Approaches like guided inquiry and hands-on activities have been shown to promote high-level thinking skills effectively (Mardoyo et al., 2017). When students are engaged in problem-solving tasks and encouraged to explore scientific concepts through experiments, they learn to think logically, systematically, and creatively. These skills are vital for the 21st century, where independent and critical thinking are highly valued (Mardoyo et al., 2017).

Inquiry-based instruction goes beyond traditional teaching by moving away from rote memorization and encouraging active student participation. When students are involved in brainstorming, planning investigations, and conducting experiments, they gain a deeper understanding of scientific principles and phenomena. This hands-on approach not only helps students remember information better but also enables them to apply their knowledge in real-world situations, making learning more meaningful (Huber & Moore, 2001; Mardoyo et al., 2017).

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Inquiry-based teaching promotes the development of scientific inquiry skills and a deeper understanding of the Nature of Science (NOS) (Eltanahy & Forawi, 2019). It encourages students to engage in problem-solving and investigation, which helps them to construct new knowledge scientifically(Eltanahy & Forawi, 2019). By integrating real-world contexts and hands-on experiences, inquiry-based teaching enables learners to apply scientific concepts in meaningful ways, bridging the gap between theory and practice. The approach fosters critical thinking and problem-solving skills by allowing students to explore and discuss their ideas in a collaborative environment (Kim, 2020).

Inquiry labs provide a structured framework where students can formulate hypotheses, design experiments, collect data, and make conclusions, offering a practical application of theoretical knowledge. This hands-on method not only reinforces what is taught in the classroom but also helps students develop crucial laboratory skills and scientific inquiry techniques. Engaging in inquiry-based experiments allows students to connect theory with practice, resulting in a more comprehensive understanding of scientific principles (Wenning, 2011).

In inquiry-based experiments, the locus of control gradually shifts from the teacher to the students. This empowers students to take ownership of their learning process, enhancing their engagement and motivation. Inquiry-based experiments require more intellectual effort than other level of inquiry like discovery learning. Students need to design experiments, control variables, and analyze data, which helps develop their critical thinking and problem-solving skills (Wenning, 2011).

Laboratory experiments designed at higher levels of inquiry are characterised by a more exploratory and open-ended approach. Instead of merely following a fixed set of procedural instructions, students are encouraged to test different methods and strategies, fostering greater autonomy in the investigative process. This hands-on, flexible style of experimentation promotes deeper conceptual understanding and motivates learners to formulate their own hypotheses and examine multiple possible outcomes (Van Wyk et al, 2025). Inquiry-based laboratories promote collaborative learning, which is essential for social interaction. Students work together in groups, sharing ideas and solving problems collectively. This interaction helps build meaningful knowledge and enhances cognitive processing levels (Charles et al., 2022; Hamzah, Ahmad et al, 2023; Nagaraj et al, 2025; H. Xu & Talanquer, 2013).

Despite the many advantages and benefits of using inquiry-based experiments, many teachers have not yet implemented and applied inquiry-based experiments. Some teachers are hesitant to use inquiry-based experiments because they lack confidence in their ability to conduct them and believe these labs are not practical for their classes. Teachers often believe it is impractical for students to design experiments during regular chemistry lessons due to a range of logistical and pedagogical constraints. Traditional chemistry laboratory courses frequently operate under conditions that limit the feasibility of student-led inquiry, such as large class sizes, restricted instructional time, and limited access to laboratory resources (Farley et al, 2021).

These constraints make it challenging to shift from structured, protocol-driven experiments to open-ended investigations where students take the lead in formulating questions, designing procedures, and analysing outcomes. Furthermore, teachers may anticipate that students will face significant difficulties in both the conceptual understanding and procedural execution required for independent experimental design (Almeida et al, 2023). As a result, substantial scaffolding and continuous guidance would be necessary to support students through such processes, efforts that may be perceived as impractical within the confines of typical school schedules and curricula (Qi et al, 2024).

Another reason teachers hesitate to implement inquiry laboratories is that many students and teachers are accustomed to traditional lab teaching methods, which provide detailed procedures and minimize the need for independent planning and problem-solving (Cheung, 2011). The transition to inquiry-based instruction can be particularly challenging for teachers who are accustomed to conventional, teacher-centred approaches, often leaving them feeling as though they are starting over in their professional practice. Many educators struggle with the unfamiliar pedagogical demands of inquiry-based learning, which can temporarily undermine their confidence and perceived competence in the classroom (Makar, 2024; Nicol, 2021). Adapting to this instructional model requires a fundamental shift in teaching roles, from being the central source of knowledge to acting as facilitators who guide and support student-led exploration (Tawfik, 2025).

Addressing those challenges requires a thorough understanding of the current literature and trends in inquiry-based experiments. Therefore, this study aims to explore inquiry-based experiments' educational aspects, levels of inquiry, and contributions to sustainability literacy. A systematic literature review and bibliometric analysis in this study aims to bring together existing knowledge, identify trends, and find gaps in the research to guide future studies and improve professional development in chemistry education. To achieve these aims, the study is guided by the following research questions:

a. What is the overall publication landscape of articles related to inquiry-based experiments in science education?

b. How are the pedagogical aspects of inquiry-based experiments conceptualised and implemented in the existing literature?

c. What levels of inquiry are utilised in the design and implementation of inquiry-based experiments?

d. To what extent do existing studies integrate sustainability literacy within inquiry-based experimental teaching?

2. Method

In this study, a systematic literature review and bibliometric analysis were used. A systematic literature review in this study used a PRISMA flow diagram, and the bibliometric analysis was conducted using VOS Viewer.

2.1. Systematic Literature Review

Systematic reviews provide comprehensive summaries of the current knowledge in a field, which helps in setting priorities for future research. The author conducted systematic literature review utilizing PRISMA 2020 flow diagram and guideline (Page et al., 2021). The PRISMA flow diagram in this study is presented in Figure 1.

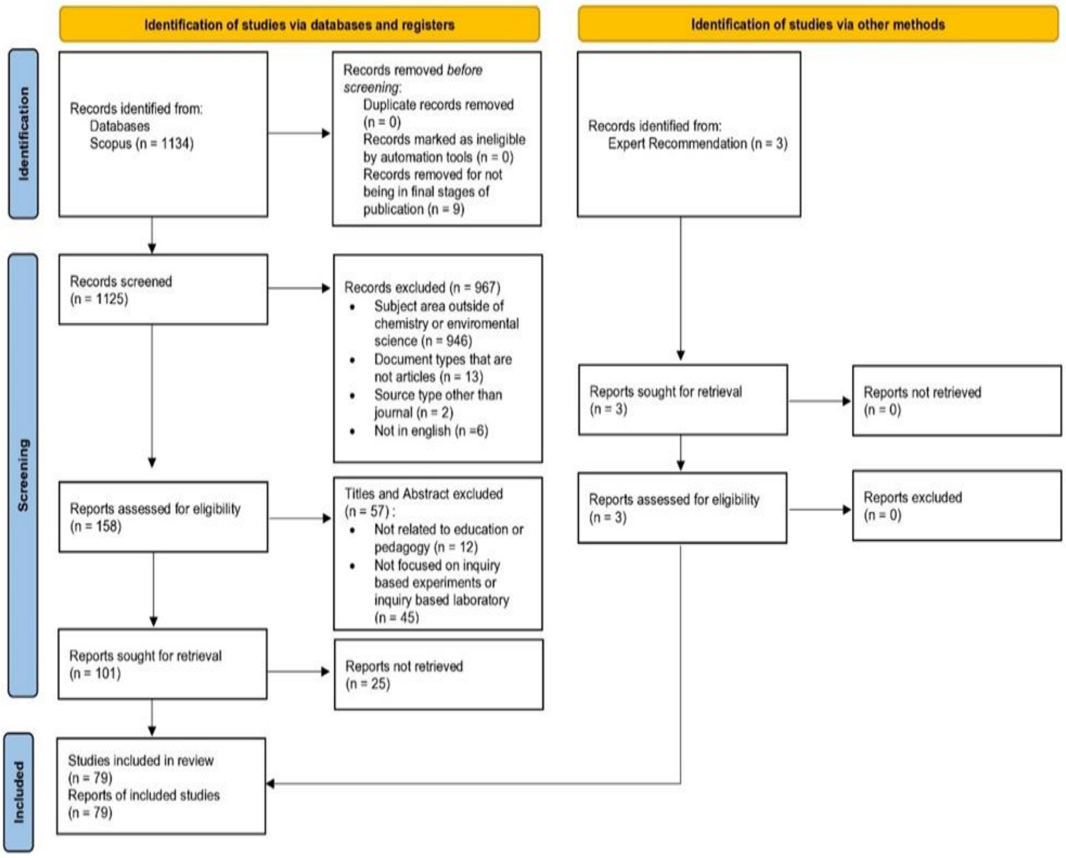

Figure 1. The PRISMA Flow Diagram

2.1.1. Article Selection Process

During the identification process via SCOPUS databases, the keywords were constructed with a boolean logic as follows: inquiry AND based AND experiments AND in AND education. The search results show 1134 documents related to the keywords. There were no duplicate documents marked as ineligible by automation tools. However, nine records were removed for not being in the final stages of publication. During the screening process, several exclusions were made. A total of 946 documents were removed because their subject areas were outside of chemistry or environmental science. Documents that are non articles (n = 13), non-journal sources (n = 2), and not written in English (n = 6) were also excluded.

2.1.2. Article Identification

For eligibility, 158 documents were read and assessed by their titles and abstracts. Documents that are not related to education or pedagogy (n = 12) were removed. Documents that are not focused on inquiry-based experiments or inquiry-based laboratories (n = 45) were removed.

Based on assessing the title and abstract, 101 documents related to inquiry-based laboratory/ inquiry-based experiments were sought for full-text retrieval. 25 documents were not available in full text. Finally, 79 articles were included for review including 3 articles that were specifically recommended by the experts

2.1.3. Analysis

To achieve the purpose of this study, 79 articles were analyzed, focusing on three main aspects: pedagogy/education, levels of inquiry, and sustainability literacy. These aspects were chosen because they are crucial for understanding how to effectively teach chemistry, engage students in inquiry-based experiments, and promote sustainability in education.

2.2. Bibliometric Analysis

A bibliometric analysis was also used in this study. All selected articles were gathered and utilized for bibliometric analysis. A RIS format of articles was compiled and then used for the bibliometric analysis using VOSviewer. This analysis focused on network overlay, density visualization, and author and co-author relationships.

3. Results and Discussion

3.1. Overview of Inquiry Based Experiments Articles

Figure 2 shows the year of publication of articles research on inquiry-based experiments. Throughout the year, the frequency of publication shows fluctuating trends. Based on the search in the Scopus database, the terms "inquiry AND based AND experiments AND in AND education" show articles published between 2001 and 2024. However, no articles on inquiry-based experiments or laboratories were published in 2003, 2004, 2008, 2016, and 2022. The highest publication on inquiry-based experiments or inquiry-based laboratories was in 2019, with 12 articles.

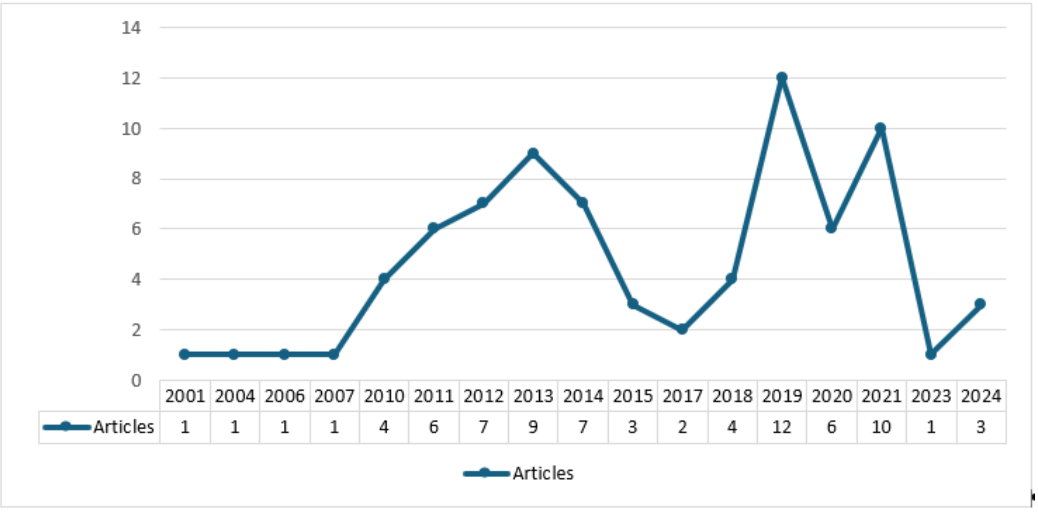

Figure 2. Year of Publications

Figure 3 illustrates the frequency of articles published in five academic journals on inquiry-based experiments. These journals are noted for having the highest number of inquiry based experiments/laboratories publications compared to other academic journals. The graph shows that Journal of Chemical Education has the most significant articles, with 56 publications. This suggests a strong emphasis on inquiry-based experiments within this journal, reflecting its focus on innovative teaching approaches and active learning strategies in chemical education.

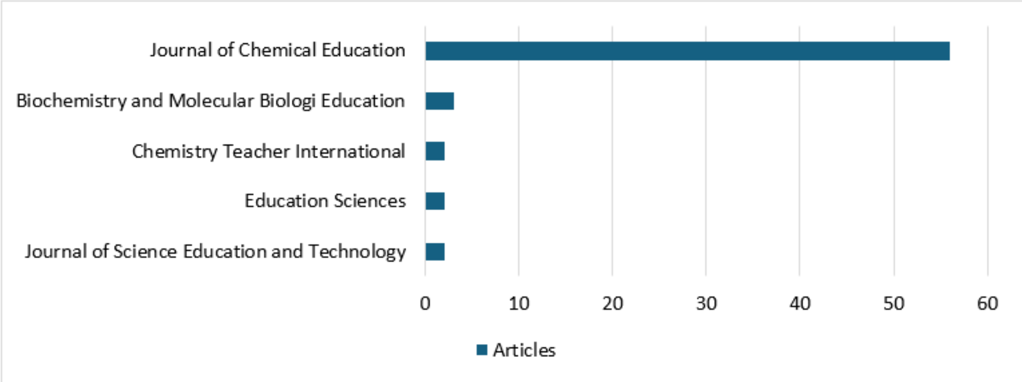

Figure 3. Frequency of Articles Published in Various Academic Journals

The other four journals Biochemistry and Molecular Biology Education, Chemistry Teacher International, Education Sciences, and Journal of Science Education and Technology have published only around two articles on inquiry-based experiments. This apparent difference highlights the dominant role of Journal of Chemical Education in promoting and discussing inquiry-based experiments or inquiry lab approaches. Figure 4 illustrates the top four countries contributing the most to research on inquiry-based experiments.

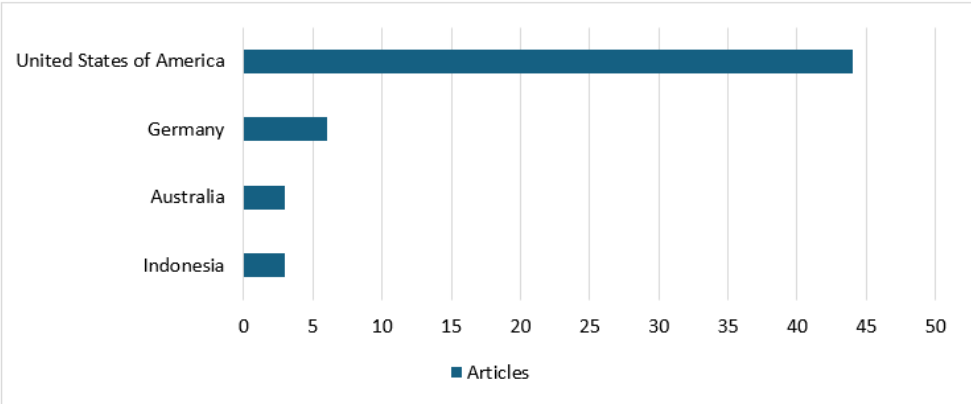

Figure 4. Frequency of Articles Published in Various Academic Journals

The United States leads significantly with 44 publications, reflecting its strong dedication to exploring and implementing inquiry-based experiments or inquiry labs as a pedagogical approach. This high volume of research indicates a substantial focus on fostering critical thinking and problem-solving skills through inquiry-based learning. Germany follows with six articles, showcasing its willingness to investigate and incorporate these innovative teaching methods. Both Australia and Indonesia have published three articles each, highlighting their emerging interest in the benefits and applications of inquiry-based experiments in education.

3.2. Pedagogical/Educational Aspect

Inquiry-based experiments in educational settings promote a deeper understanding of scientific concepts, enhance student engagement motivation, and develop essential scientific skills. One of the key benefits of inquiry-based experiments is the development of scientific process skills. These skills include formulating hypotheses, designing experiments, collecting and analyzing data, and drawing conclusions. Such hands-on experiences are crucial for students to understand the scientific method and to become proficient in laboratory techniques (Granger, 2004; McKee et al, 2007; Sieve, 2021). However, chemistry education faces challenges like lack of time, equipment requirements, safety concerns, and disposal issues, prompting inquiry-based experiments with everyday materials to address these challenges. Applying everyday chemicals and simple devices available at home, in the kitchen, garden, marketplace, and stores can help solve problems related to traditional chemistry experiments, potentially improving students' attitudes towards chemistry (Wada & Koga, 2013).

Inquiry teaching activities are designed to enhance the process of gaining scientific knowledge, making them valuable for science education and teacher preparation (Bicak et al, 2021). Craig & Hill (2012) propose experiment design in the general chemistry laboratory that incorporates a 'do-it-yourself' component for students, where they perform proven experiments and then apply the techniques to an experiment of their own design. Students engage in classifying inorganic reactions as acid-base, redox, complexation, and precipitation, gaining experience with techniques and taking chances with new ideas like working scientists (Craig & Hill, 2012).

Another study also propose inquiry-based laboratory design to determine the chemical composition of sodium percarbonate (SPC), a key component of domestic oxygen bleach, using students' knowledge of sodium carbonate (SC) and hydrogen peroxide (HPO) reactions. This inquiry-based laboratory design is intended for introductory chemistry courses in high school or college. It emphasizes hands-on learning and experimentation to determine the composition of SPC. The instructor plays a crucial role in leading students through experimental design and procedures while maintaining the benefits of student inquiry. This excercise is structured into four sections: introductory demonstrations, student discussions, laboratory exercises, and post-lab exercises, taking approximately three hours to complete (Wada & Koga, 2013).

Moreover, the inquiry-driven approach allows students to connect theoretical knowledge to practical problems, enhancing their ability to plan and conduct experiments effectively. By incorporating contemporary biochemistry and molecular biology concepts and techniques, inquiry-driven laboratory experiments provide students with course-based undergraduate research experiences (CUREs) that have defined learning objectives. The use of inquiry-driven laboratory methods helps students develop proficiency in standard biochemistry and molecular biology techniques, fostering collaborative communication and goal achievement. Inquiry-based experiments also enable students to revisit theoretical backgrounds, assess learning objectives, and increase confidence levels in achieving set goals (Periyannan, 2019).

The primary pedagogical purpose of inquiry-based experiments is to establish empirical laws based on the measurement of variables. Inquiry-based experiments are often associated with integrated skills such as measuring metrically, establishing empirical laws based on evidence and logic, designing and conducting scientific investigations, and using technology and math during investigations (Wenning, 2011). 79 articles were analyzed and classified based on the associated skills that students possessed during the experiments. The analysis and classification are presented in Table 1.

Table 1. Associated skills that students possessed during the experiment

No	Associated Skills	Number of Articles	References
1	measuring metrically	8	Students measured the density of water using different glassware and balances (Prilliman, 2012). This task allowed students not only to explore the concept of density but also to critically evaluate the precision and accuracy of different measuring instruments The quantitative analysis of acetaminophen, acetylsalicylic acid, and caffeine in commercial analgesic tablets using LC-MS (Fenk et al., 2010). In this more advanced inquiry-based experiment, students were responsible for designing the analytical approach, preparing samples, operating complex instrumentation, and interpreting the resulting chromatographic and mass spectral data.
2	establishing empirical laws on the basis of evidence and logic	14	Students' critical evaluation of the analytical performances of potentiometric electrodes, aiming to determine their potential use as universal detectors for anions in ion chromatography (Cuartero & Crespo, 2018). This activity required students to interpret complex experimental data and apply logical reasoning to identify patterns, relationships, and deviations in electrode responses thus reinforcing the skill of constructing evidence-based generalisations rooted in scientific reasoning. Students designed experiments to test mechanochemical polymer properties using principles from chemistry, physics, calculus, and software programming courses (Greer et al., 2021). Their investigations required identifying trends, establishing cause-effect relationships, and applying logic to correlate experimental outcomes with theoretical models, thereby cultivating the skill of developing empirical laws based on evidence.
3	designing and conducting scientific investigations	79	Students demonstrated excellent laboratory practices and applied green chemistry principles in the synthesis methods, showcasing their ability to conduct scientific investigations (Paluri et al., 2015). Students' ability to design their synthetic routes, make procedural decisions, and carry out experiments from start to finish provided clear evidence of their capacity to conduct structured scientific investigations in a research-like environment. Students engaged in activities like investigating chromatographic column packing materials, performing solvent selection processes, and using preparative-LC systems for larger-scale separations, which align with the skill of designing and conducting scientific investigations (Xie et al., 2020). These tasks mimicked industrial-scale analytical chemistry work, requiring students to make design choices, troubleshoot processes, and reflect on outcomes. The complexity and autonomy involved in these tasks align directly with the skill of designing and conducting comprehensive scientific investigations.

No	Associated Skills	Number of Articles	References
4	using technology and math during investigations	36	Students observed and analyzed various thermal processes using IR imaging technology (Xu et al., 2019). This integration of digital tools and data analysis reinforces students' ability to use technology and mathematics to conduct and interpret scientific investigations. The FluSpec educational software package serves as a tutorial and simulator for fluorescence spectroscopy experiments, providing theoretical discussions and practical exercises for students (Bigger et al, 2014). This approach supports the development of both technological fluency and quantitative reasoning skills essential for modern scientific inquiry.

Measuring metrically is a fundamental skill in scientific experiments, ensuring precision and consistency in data collection. This skill involves using the metric system for various measurements, such as volume, mass, and density, which are critical for achieving accurate and reproducible results in scientific research. Mastery of this skill allows students to perform precise measurements and understand the significance of measurement accuracy in experimental outcomes.

For instance, students measured the density of water using different glassware and balances, which helped them understand the importance of precision in using laboratory equipment (Prilliman, 2012). The study conducted by Prilliman (2012) emphasized the necessity of accurate measurements in experimental procedures. Another study by Fenk et al. (2010) highlighted the role of LC-MS in precise quantitative analysis. Students performed quantitative analysis of acetaminophen, acetylsalicylic acid, and caffeine in commercial analgesic tablets using LC-MS, demonstrating their capability to handle complex measurement techniques (Fenk et al., 2010).

Establishing empirical laws involves deriving scientific principles based on evidence and logical reasoning. This skill requires students to critically evaluate data, design experiments, and use their findings to support or refute hypotheses. Developing this skill enhances students' ability to think scientifically and draw logical conclusions from experimental data.

For example, study conducted by Cuartero & Crespo (2018) focused on evaluating potentiometric electrodes. Students critically evaluated the analytical performances of potentiometric electrodes, aiming to determine their potential use as universal detectors for anions in ion chromatography (Cuartero & Crespo, 2018). Research conducted by Greer et al. (2021), demonstrating an interdisciplinary approach to studying polymer properties. Students designed experiments to explore mechanochemical polymer properties and integrating knowledge from various disciplines (Greer et al., 2021).

Designing and conducting scientific investigations involves planning and executing experiments to explore scientific questions. This skill encompasses a range of activities from formulating research questions, selecting appropriate methodologies, collecting and analyzing data, to interpreting and presenting findings. Competence in this skill is essential for advancing scientific knowledge and applying theoretical concepts to real-world problems.

For example, research conducted by Paluri et.al (2015) has made it possible for students to demonstrate excellent laboratory practices by adhering to green chemistry principles in synthesis methods, which highlights their capability to conduct environmentally responsible scientific investigations (Paluri et al., 2015). Additionally, based on research by Xie et.al (2020) investigating chromatographic column packing materials, performing solvent selection processes, and using preparative-LC systems for larger-scale separations reflects students' proficiency in designing and conducting comprehensive scientific research (Xie et al., 2020).

Incorporating technology and mathematics is essential for modern scientific investigations. This skill involves applying mathematical concepts and utilizing technological tools to collect, analyze, and interpret data. Proficiency in this area enhances the accuracy of experimental results and enables the handling of complex datasets and sophisticated experimental setups.

For instance, students observed and analyzed various thermal processes using infrared (IR) imaging technology, demonstrating their ability to use advanced technological tools for scientific investigations (X. Xu et al., 2019). Another example of using technology and mathematics in investigations is the use of the FluSpec educational software package. This package serves as both a tutorial and a simulator for fluorescence spectroscopy experiments, providing students with theoretical discussions and practical exercises, thereby enhancing their technical and mathematical skills (Bigger et al., 2014).

Based on Table 1, 79 studies on inquiry-based experiments have shown promising results in designing and conducting scientific investigations. However, not all research on inquiry-based experiments have successfully fostered or enhanced other associated skills such as measuring metrically, establishing empirical laws based on evidence and logic, and using technology and math during investigations. These findings highlight an opportunity for future researchers to design inquiry-based experiments in chemistry or science classes that promote and enhance all four associated skills.

3.3. Level of Inquiry

Many science teachers globally employ various inquiry-based teaching methods without fully understanding how these approaches are interconnected. There is a need for a science teaching that encompasses an understanding of the hierarchy of inquiry approaches. A proposed model that addresses this need is known as Levels of Inquiry (Wenning, 2011).

Wenning (2011b) introduced an "inquiry spectrum" to describe various inquiry-based teaching and learning approaches that progress from simpler to more complex, gradually shifting control from the teacher to the student. This framework, detailed in Table 2, outlines different levels of inquiry: discovery learning, interactive demonstration, inquiry lesson, inquiry lab (guided, bounded, and free), real-world applications (textbook and authentic), and hypothetical inquiry (pure and applied).

Table 2. The scientific inquiry spectrum adapted from Wenning's Levels of Inquiry article

Discovery Learning	Interactive Demonstration	Inquiry Lesson	Inquiry Lab (guided, bounded, free)	Real-world Applications (textbook, authentic)	Hypothetical Inquiry (pure, applied)
Simpler	← Intellectual Depth →				Complex
Teacher	← Attribution of control →				Student

The inquiry spectrum represents contemporary educational perspectives on the most effective approaches for educating students (Wenning, 2011). Building on Wenning's work, we attempt to further analyze and identify the learning sequences or syntax at each level of inquiry and what students will discover during the learning process. Table 3 shows a comparison of the learning sequences/syntax for each level of inquiry.

Table 3. A comparison of the learning sequences/syntax for each level of inquiry

	Discovery Learning	Interactive Demonstration	Inquiry Lesson
Learning sequences/ syntax	Introduction to problems Exploration Investigation Validation Application of analogies	Observation Prediction Comparison of predictions Introduction of the analogy Data Analysis Drawing conclusion	Introduction and Elicitation of Preconceptions Conducting the Experiment Analyzing the results Discussion and reflection Conclusion
Aims	Constructing conceptual understanding based on first-hand experiences	Clarrifying and correcting the students' existing ideas or beliefs (preconceptions) about a topic	Engaging in experiments to derive relationships
	Inquiry Lab (guided, bounded, free)	Real-world Applications	Hypothetical Inquiry
Learning sequences/ syntax	Identifying the problem Designing experimental plan Conducting experiments Collecting and analyzing data Applying numerical and statistical methods Explaining unexpected results Reporting and defending the results	Lecture and demonstration Completing textbook-based end of chapter problems (problem based) Conducting authentic investigations (project based) Data collection Data Analysis Interpretation Conclusion	Introduction Discussion Hypothesis formation Prediction and testing Data Analysis Application Synthesis
Aims	formulating and conducting an experiment independently	applying current knowledge to new situations in a mathematical sense	Developing explanations about why things are or work the way they do.

An inquiry lab represents an advanced inquiry level where students largely work on their own to create and carry out an experimental plan, gathering relevant data in the process. They then analyze this data to discover a specific relationship between variables. This approach differs significantly from the traditional "cookbook" labs, also known as "structured inquiry," where students follow a predetermined set of instructions. The difference between these traditional labs and true inquiry-oriented labs is substantial (Wenning, 2005).

Based on Herron's work (1971), Wenning (2005) proposes that inquiry labs can be categorized into three types based on their sophistication and control: guided inquiry, bounded inquiry, and free inquiry, as shown in Table 4. This table illustrates how the source of the question or problem and the procedures evolve as labs become more advanced. Each type represents a step in moving from structured inquiry practice to greater student independence. A guided inquiry lab is a progression from the inquiry lesson and, along with the bounded inquiry lab, serves as a transitional phase towards the free inquiry lab. In the free inquiry lab, students operate independently, even identifying the research question or problem themselves. With each successive type, the teacher's structure diminishes, and students gain more independence in their thinking and actions (Wenning, 2005). We also classified 79 articles according to three types of inquiry labs, as shown in Table 4.

Table 4. The list of articles according to three types of inquiry labs

Inquiry Lab Type	Questions/Problem Source	Procedures	Total of articles	References
Guided Inquiry	Teacher determines the research problem to be investigated	Directed by several questions identified by the teacher and supplemented with comprehensive pre-laboratory orientation.	68	a. Students were introduced to the investigation of drug release through diffusion in hydrogels by manipulating gel concentration and enzyme concentration. The problem was defined by the instructor, and students were guided through structured experimental designs involving nine predefined conditions. Hypothesis generation was student-driven, but experimental procedures and setup were largely teacher-directed. Pre-laboratory orientation provided conceptual background and procedural clarity, ensuring students had sufficient support to focus on data analysis and scientific reasoning. (Sylman & Neeves, 2013). b. In this experiment involving the Wittig reaction, students were assigned specific research questions related to stereoselectivity and the influence of substituents. While students engaged in critical aspects of scientific inquiry such as hypothesis formation, experimental execution, and data interpretation the overarching research question and procedural boundaries were established by the instructor. The structured framework provided just enough autonomy to encourage scientific thinking while maintaining control over safety and feasibility (MacKay & Wetzel, 2014).
Bounded Inquiry	Teacher determines the research problem to be investigated	Directed by a single question identified by the teacher, with limited pre-laboratory orientation.	10	a. This activity required students to categorise inorganic chemical reactions based on observed properties. After completing a structured set of initial experiments, students transitioned into a semi-independent phase where they designed their own experiments using the techniques they had just practiced. This do-it-yourself component represents bounded inquiry because students were working within a known conceptual framework and problem context, but without step-by-step instructions. They were expected to extrapolate from their experience to explore new scenarios, a critical element in developing experimental autonomy. (Craig & Hill, 2012) b. This study tasked students with designing green chemistry synthetic pathways using only starting and target compounds (given as CAS numbers). While the overarching goal was predefined, students had to independently identify feasible reactions, reagents, and green chemistry principles

Inquiry Lab Type	Questions/Problem Source	Procedures	Total of articles	References
				to apply without specific procedural guidance. This provided an authentic experience in planning synthetic strategies, evaluating safety and sustainability, and troubleshooting unexpected outcomes, all within a controlled learning environment. (Edgar, et al., 2014).
Free Inquiry	Students determines the research problem to be investigated	Directed by a single question identified by the student, without any pre-laboratory orientation.	1	a. In this innovative study, undergraduate students conducted chemistry experiments in their own kitchens during a course adapted for non-traditional lab settings. Each student developed a unique research question related to food chemistry, designed their own procedures using household materials, and collected empirical data. Students documented their methods and findings in the format of a professional ACS-style research manuscript. This experience demanded full engagement with the scientific method; problem formulation, hypothesis testing, method validation, and formal scientific communication without relying on traditional laboratory infrastructure (Jones, 2011).

Guided inquiry involves the teacher determining the research problem and providing comprehensive pre-laboratory orientation and structured questions. This approach ensures that students have a clear direction and adequate support while exploring scientific concepts. For example, in Sylman & Neeves (2013), students engaged in structured discussions and performed experiments with instructor guidance, formulating hypotheses on how gel and enzyme concentrations affect drug release by diffusion. Similarly, MacKay and Wetzel (2014) had students investigate the Wittig reaction's selectivity, where they developed hypotheses, conducted experiments, and analyzed data with some guidance. These examples highlight the effectiveness of guided inquiry in fostering student engagement and understanding while maintaining a structured learning environment (MacKay & Wetzel, 2014).

Bounded inquiry also involves the teacher determining the research problem, but with more limited pre-laboratory orientation and less guidance. This approach allows students more freedom to explore within a defined framework. For instance, in (Craig & Hill, 2012), students classified inorganic reactions into categories and then applied the techniques to a self-designed experiment, blending structured learning with independent exploration. Another example involved students devising a synthetic plan using green chemistry principles with minimal guidance (Edgar et al., 2014). Bounded inquiry serves as a transitional phase from guided towards free inquiry, offering a structured yet flexible environment where students can exercise creativity and problem-solving skills.

Free inquiry, with only one article focusing on this type, places the responsibility of determining the research problem entirely on the students, with no pre-laboratory orientation. This approach fosters the highest level of independence and creativity. An example is undergraduate students using their kitchens as safe laboratories to conduct experiments. They developed hypotheses, treated food items as chemicals, and appliances as laboratory equipment, collected empirical data, and presented their findings in a professionally written manuscript adhering to ACS guidelines (Jones, 2011). Free inquiry promotes deep engagement, critical thinking, and a true sense of ownership over the scientific process, preparing students for real-world research and problem-solving.

3.4. Sustainability Literacy

Barnes (2014) defines sustainability as a comprehensive concept that addresses social, economic, and environmental aspects of issues affecting the planet's long-term livability for humans and other species. In this context, sustainability literacy means having the competence and understanding of sustainability (Barnes, 2014). Sustainability literacy can also be defined as knowledge, skills, and mindsets that drive an individual's commitment to building a sustainable future, enabling them to make effective decisions toward this goal (Décamps et al, 2017). Sustainability literacy encompasses the knowledge, skills, and understanding required to create a more sustainable future. This includes literacy in reading and writing about sustainability and an integrative way of communicating, thinking, and appreciating the world (Sekhar & Raina, 2021).

The primary role of education is to empower individuals and future leaders to tackle the complex and critical challenges of the 21st century, fostering change and collectively constructing a sustainable future. Higher education, in particular, plays a significant role in this mission by educating and creating agents of change. The connection between higher education and sustainability has never been more vital. This importance is specifically emphasized in SDG 4, which focuses on Quality Education (Décamps et al., 2017). However, chemistry education itself faces significant challenges in both teaching approaches and curriculum. Students encounter several problems: an overload of content, numerous isolated facts, difficulty in transferring their knowledge to solve problems that are presented in different ways, a lack of relevance to everyday life, and an excessive focus on preparing for further studies in chemistry rather than developing sustainability literacy (Mahaffy et al., 2014).

Engaging students in hands-on experiments that highlight environmental issues makes them more likely to adopt sustainable behaviors. Awareness is the first step towards changing behavior, which is essential for achieving sustainability literacy (Ling et al, 2021; Xia et al, 2016). Inquiry-based experiments requires students to use cognitive abilities and scientific reasoning to address experimental questions, fostering critical thinking and problem-solving skills essential for sustainability literacy (Leibfarth et al., 2018; Paluri et al., 2015). Inquiry lab approach emphasize students and teachers as learning partners, encouraging active participation and engagement, which can lead to a deeper understanding of sustainability concepts (Leibfarth et al., 2018; Paluri et al., 2015). By connecting laboratory experiments to real-world applications, students can see the practical implications of sustainability and are more likely to appreciate its importance (Leibfarth et al., 2018; Paluri et al., 2015).

Inquiry-based labs often incorporate green chemistry principles, such as using environmentally friendly reducing agents and sustainable materials, which helps students understand and apply these principles in real-world scenarios. Inquiry-based labs guide students to consider factors related to continuous production, providing a broad perspective on decision-making for sustainable chemistry that leads to improving sustainability literacy (Leibfarth et al., 2018; Paluri et al., 2015). Despite all the advantages of inquiry-based experiments in promoting sustainability literacy, only 3 articles (Ballard, 2011; Leibfarth et al., 2018; Zuin et al., 2019) out of 79 articles we reviewed, integrated sustainability into experiments/laboratories, with only one article promoting sustainability literacy. Sustainability is discussed in the study conducted by (Ballard, 2011), emphasizing the use of a benign iron catalyst for the laboratory experiment, which aligns with green chemistry principles. The importance of considering sustainability during laboratory experiments is highlighted to promote greener practices and reduce environmental impact, showcasing the significance of using benign catalysts like iron compounds in organic chemistry reactions.

Zuin (2019) focusing on the importance of incorporating green and sustainable chemistry principles into laboratory experiments to promote sustainability in education and future professionals. The laboratory experiment based on a citrus biorefinery model aimed to show students how waste can be repurposed to obtain valuable compounds, contributing to environmental protection and sustainable practices. Considering sustainability during laboratory experiments is crucial as it helps students understand the importance of sustainable practices, waste management, and the potential for creating commercially viable products from waste materials, aligning with global sustainability goals (Zuin et al., 2019).

Based on the study conducted by (Leibfarth et al., 2018), the laboratory experiment focused on engaging students in considering sustainability in their evidence-based scientific decision-making. Students were evaluated on their sustainability literacy and were guided to consider factors for scale-up, improvements in pumping technology, mixing in large volumes, and continuous purification, emphasizing sustainability in their final laboratory reports. The progression of the laboratory experiment empowers students to make decisions about their experimental conditions and illustrates the translation of their investigations into a real-world application, emphasizing sustainability in the conversion of reclaimed vegetable oil into biodiesel (Leibfarth et al., 2018). Based on the analysis of the sustainability literacy aspect. More studies are still needed to incorporate sustainability literacy into inquiry-based experiments or labs. There are many opportunities for future researchers to design inquiry-based experiments or inquiry labs that can improve and promote sustainability literacy in chemistry/science students.

3.5. Network Overlay and Density Visualization Results

The network visualization was generated with VOS Viewer, as presented in Figure 5. The network visualization illustrates the relationships and co-occurrences between key terms in a body of academic literature. In this visualization, nodes represent key terms or concepts, and edges represent the co-occurrences or relationships between these terms. The size of each node indicates the frequency of the term's occurrence, with larger nodes representing more frequently occurring terms. The edges' thickness indicates the strength of the co-occurrence relationships, with thicker edges representing stronger relationships.

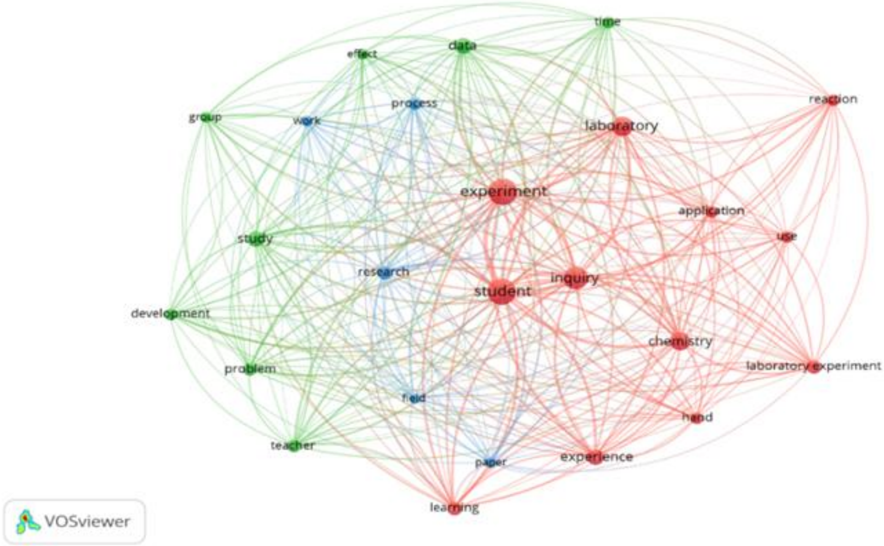

Figure 5. The Network Visualization

The visualization reveals several clusters, each represented by different colors. These clusters indicate groups of terms that frequently co-occur and are likely related in the context of the research. For instance, the red cluster appears to be centered around terms like "laboratory," "experiment," "inquiry," and "chemistry," suggesting a strong focus on laboratory-based experimental inquiry in chemistry education. The green cluster includes terms such as "development," "problem," "group," and "teacher," indicating a focus on problem-solving, group work, and teacher roles in educational development. The blue cluster, which is smaller, includes terms like "process," "research," and "field," indicating a focus on the research process or laboratory process.

The central terms "experiment," "student," and "learning" are pivotal, as indicated by their large size and central location. These terms likely represent the core focus of the articles analyzed, with other terms and clusters radiating outwards, showing the interconnections between different aspects of educational research and practice. This network visualization highlights the interconnected nature of educational research themes, emphasizing the central role of experiments and student learning while also showing researchers' diverse methodologies.

Network overlay is presented in Figure 6. In this network overlay, the terms are color-coded to show their occurence from 2016 to 2019. In 2016, shown in dark blue, the essential terms were "teacher," "inquiry," "chemistry," and "laboratory experiment," indicating a focus on educational roles, experimental methods, and chemistry. In 2017, marked by turquoise, the focus shifted to understanding "process," solving "problems," and studying different "fields."

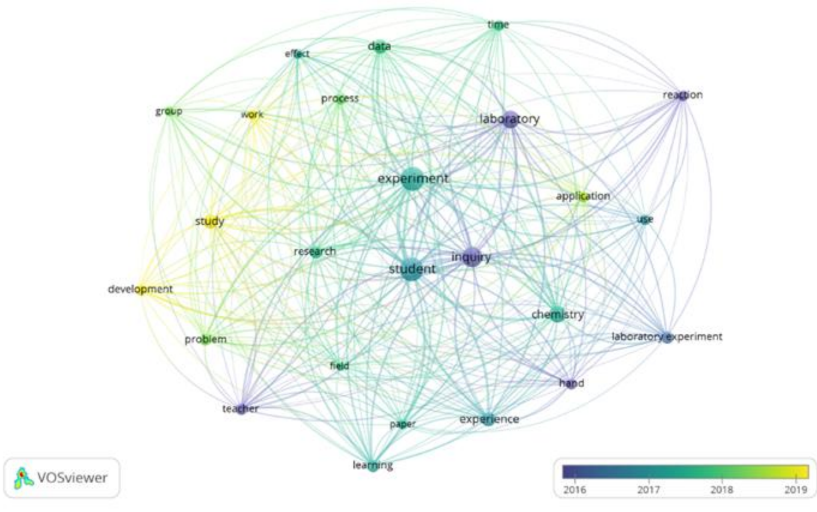

Figure 6. Network Overlay

In 2018, represented in green, the emphasis is on "research" activities, "development" processes, and "group" dynamics or collaborations. In 2019, shown in yellow, the focus moves to the "application" of knowledge, conducting "studies," and understanding the "effects" of various educational or experimental approaches. Throughout these years, key terms like "experiment," "student," "learning," and "experience" remain important, highlighting their central role in the research on education and inquiry-based laboratory experiments.

This density visualization in Figure 7 illustrates the frequency and intensity of terms in the context of inquiry-based experiments to enhance sustainability literacy. Bright colors, such as yellow, indicate areas of high term occurrence, while fading colors, from green to blue, denote lower occurrences. Central terms like "experiment," "student," "inquiry," and "laboratory" appear in bright colors, underscoring their frequent appearance and pivotal role in the research. This suggests a strong emphasis on experimental methods, student engagement, and inquiry-based learning, all crucial for enhancing sustainability literacy.

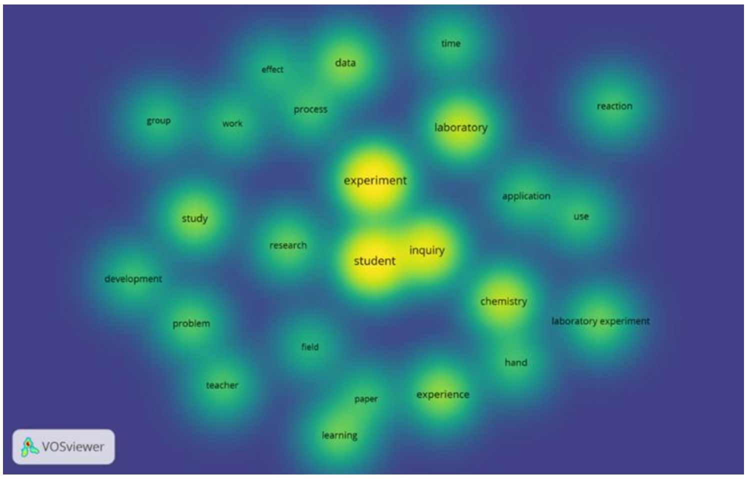

Figure 7. Density Visualization

However, it is important to note that terms directly related to "sustainability" do not appear in the visualization. This absence indicates that while the focus on experimental and inquiry-based learning is strong, the explicit integration of sustainability concepts and terminology may be lacking in the analyzed literature. This gap suggests an opportunity for future research to more explicitly link these educational methods with sustainability literacy, ensuring that the development of sustainable knowledge and practices is directly addressed and emphasized in educational contexts.

3.6. Author and Co-author Relationship

The co-authorship network visualization in Figure 8 provides a clear depiction of collaborative relationships among researchers, classified into two clusters. The red cluster is significantly larger and more densely connected, featuring prominent authors such as Mendelsohn, Erlinger, and Burnham. Their research discussed the use of continuous flow technology as a promising strategy in chemical education and research, focusing on undergraduate students' involvement in designing, developing, and implementing batch and flow experiments for an upper-level organic chemistry laboratory (Zhang et al., 2021).

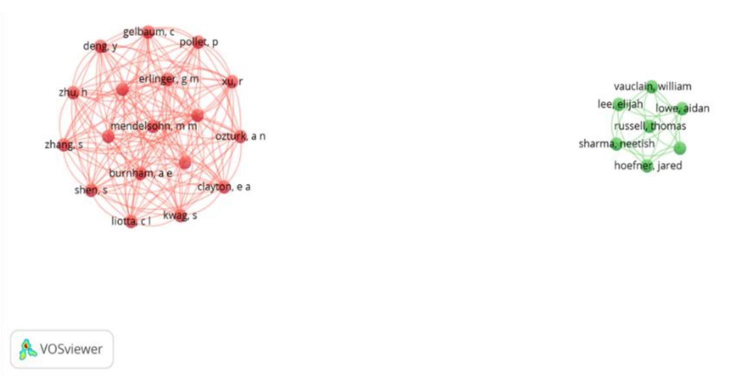

Figure 8. Author and Co-author Relationship

The green cluster is smaller but also tightly connected. Key authors in this group include Russell, Thomas, Hoefner, Jared, and Sharma, Neetish. Their project involved students in designing experiments to test mechanochemical polymer properties using principles from chemistry, physics, calculus, and software programming courses. The research project allowed students to engage with physical materials and understand how fundamental concepts from chemistry, physics, and math come together in the design and use of polymer materials (Greer et al., 2021).

The red cluster's work on continuous flow technology and the green cluster's project on mechanochemical polymer properties both demonstrate the effectiveness of integrating students into the research process. These initiatives highlight how inquiry-based experimental designs can significantly enhance learning by allowing students to engage with complex, real-world problems. Advanced inquiry-based experiment design, as seen in these two clusters, facilitates interdisciplinary learning and practical application of theoretical concepts, fostering a deeper understanding of the subject matter.

3.7. Limitation and Implication

While this systematic review provides valuable insights into the current landscape of inquiry-based experiments and their connection to sustainability literacy, there are notable limitations that should be acknowledged. First, the scope of the reviewed literature is restricted primarily to articles indexed in the Scopus database. Although Scopus is a reputable and comprehensive source of peer-reviewed literature, it may exclude relevant studies published in regional or discipline-specific journals that are not indexed within it. Consequently, this could result in a narrowed representation of global research efforts, particularly from developing countries where alternative databases or local journals are more commonly used. Furthermore, the review includes articles published only up to the year 2024, which may overlook the most recent developments, particularly as the field of sustainability education is rapidly evolving in response to global environmental and educational challenges.

Despite these limitations, the study yields important implications for future research in chemistry education and sustainability literacy. By systematically mapping out existing studies, this review reveals both a concentration of research efforts in specific regions (notably the U.S.) and the dominance of guided inquiry approaches, with relatively limited integration of sustainability literacy as an explicit learning objective. These findings underscore a significant opportunity for researchers and educators to design and implement inquiry-based experiments, particularly in chemistry labs that not only foster scientific investigation skills but also explicitly target sustainability outcomes. The identification of underrepresented areas such as free inquiry labs and the minimal occurrence of sustainability-focused inquiry projects signals a compelling and untapped potential. Future research can build upon this foundation by exploring innovative, student-centered experimental designs that align with green chemistry principles, promote systems thinking, and meaningfully contribute to the development of sustainability literacy among learners.

4. Conclusion

Inquiry-based experiments are designed to foster deep scientific knowledge and essential scientific skills. They range from structured approaches, where the teacher maintains significant control, to more advanced (student-centered) where learners take a full charge of their experimental designs. The literature review conducted in this study shows that inquiry-based experiments significantly enhance students' understanding of scientific concepts, motivation, and essential scientific skills such as hypothesis formulation, experiment design, data collection, and analysis.

Despite the advantages of inquiry based experiments, this review reveals a gap in integrating sustainability literacy into inquiry-based experiments. Although some studies have incorporated green chemistry principles and real-world applications, only a few explicitly promote sustainability literacy. This highlights an opportunity for future research to design inquiry-based experiments that more directly address sustainability literacy. By doing so, educators can help students connect theoretical knowledge with practical applications, fostering critical thinking, problem-solving skills, and a deeper understanding of sustainability concepts, which are essential for building a sustainable future.

Author Contributions

Ari Syahidul Shidiq: Project administration, Conceptualization, Methodology, Software. Zamira Zia'ul Huda: Data curation, Writing - Original draft preparation. Sri Yamtinah: Methodology, Validation, Supervision. Maria Ulfa: Software, Supervision. Mohammad Masykuri : Validation, Writing - Reviewing and Editing, Resources. Agung Nugroho Catur Saputro: Resources, Writing - Reviewing and Editing. All the authors have read and approved the final manuscript.

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