

Integrating Microscale and Green Chemistry to Support Science Process Skills

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ABSTRAK

Penelitian ini bertujuan untuk mengkaji integrasi pendekatan mikroskala dan green chemistry dalam pengembangan keterampilan proses sains (KPS) melalui metode Systematic Literature Review (SLR) dengan protokol PRISMA. Data diperoleh dari database Scopus, ERIC, dan Google Scholar dengan rentang publikasi tahun 2016–2026. Proses seleksi dilakukan melalui tahap identifikasi, penyaringan, kelayakan, dan inklusi hingga diperoleh 25 artikel yang memenuhi kriteria. Hasil kajian menunjukkan bahwa pendekatan mikroskala secara konsisten mendukung peningkatan pemahaman konsep, keterlibatan peserta didik, serta kualitas aktivitas eksperimen melalui penggunaan bahan kimia dalam jumlah kecil dan prosedur yang lebih aman. Integrasi prinsip green chemistry tidak hanya memperkuat kesadaran lingkungan, tetapi juga mendorong praktik pembelajaran yang lebih bertanggung jawab. Lebih lanjut, pemanfaatan teknologi sederhana seperti smartphone dalam praktikum mikroskala turut memperkaya proses observasi dan analisis data. Temuan kajian ini menunjukkan bahwa integrasi pendekatan mikroskala dan green chemistry memiliki potensi yang kuat dalam mendukung pengembangan keterampilan proses sains serta relevan untuk pembelajaran kimia yang berorientasi pada keberlanjutan dan tuntutan abad ke-21.

Kata Kunci: mikroskala; green chemistry; keterampilan proses sains; SLR; PRISMA

ABSTRACT

This review explores how microscale and green chemistry approaches contribute to the development of science process skills (SPS) in chemistry learning. The study was conducted using a Systematic Literature Review (SLR) based on the PRISMA protocol. Data were collected from the Scopus, ERIC, and Google Scholar databases covering publications from 2016 to 2026. The article selection process involved identification, screening, eligibility, and inclusion stages, resulting in 25 articles that met the established criteria. Most of the reviewed studies reported that microscale approaches helped students understand concepts more clearly and become more involved in laboratory activities. The use of smaller amounts of chemicals also made experiments safer and easier to manage in classroom settings. Green chemistry principles were also associated with increased environmental awareness and more responsible laboratory practices among students. Several studies further showed that simple technologies, including smartphones, could support observation and data analysis during experiments. The reviewed studies suggest that integrating microscale and green chemistry approaches can support science process skills while promoting more sustainable chemistry learning in line with current educational needs.

Keywords: *microscale; green chemistry; science process skills; SLR; PRISMA*

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INTRODUCTION

Chemistry learning in the 21st century is no longer viewed merely as a process of transferring information from teachers to students. More importantly, learning is directed toward how students construct knowledge through meaningful learning experiences. Science process skills (SPS) are now considered important competencies in chemistry education.

Science process skills include a range of abilities, from observing and classifying to designing and conducting experiments. These skills play an important role not only in understanding chemical concepts but also in developing critical and reflective scientific thinking. Nevertheless, classroom practice still reveals a gap between curriculum expectations and their implementation, particularly in the development of science process skills (Urbano et al., 2022).

In many classrooms, chemistry learning still tends to emphasize final outcomes, such as test scores or theoretical mastery of concepts. As a result, scientific thinking processes, which should form the core of science learning, often receive limited attention. In fact, deeper conceptual understanding develops through active engagement in scientific processes themselves.

This issue can also be seen in laboratory activities. Rather than functioning as a medium for exploration, laboratory work is often carried out procedurally. Students follow predetermined steps with limited opportunities to question or interpret the processes involved. This model is commonly referred to as the cookbook approach, in which students act more as executors of procedures than as active participants in scientific inquiry (Varadarajan & Ladage, 2022).

In addition to pedagogical issues, limited facilities also affect the quality of laboratory activities. Not all schools have adequate access to laboratory equipment and chemicals, leading teachers to rely more on demonstrations than direct experimentation. Over time, limited laboratory access may restrict students' learning experiences, particularly in developing critical thinking and problem-solving skills.

On the other hand, chemistry learning cannot be separated from environmental issues. Conventional laboratory practices generally involve relatively large quantities of chemicals that may generate hazardous waste. Unfortunately, waste management is not always handled properly, especially in schools with limited facilities. As a result, a dilemma emerges between instructional needs and environmental responsibility (Zuin et al., 2021).

In response to these challenges, green chemistry approaches have increasingly been introduced into chemistry education. Green chemistry emphasizes the use of safer materials, efficient resource utilization, and waste reduction. In educational contexts, green chemistry serves not only as a technical solution but also as a means of fostering environmental awareness among students (Karpudewan et al., 2021).

Aligned with these principles, microscale laboratory practices have emerged as a safer and more efficient alternative. By using smaller amounts of chemicals, experiments can be conducted with lower risk without reducing the essence of the concepts being studied. In addition, this approach allows more students to participate directly in laboratory activities, making learning experiences more accessible and equitable (Hugerat, 2020).

Recent technological developments have further expanded the potential of microscale approaches. The use of simple devices such as smartphones enables observation and data analysis to be conducted more accurately. This creates opportunities for chemistry learning that is not only safe and environmentally friendly but also aligned with technological advancements (Liu et al., 2025).

Even so, previous studies on microscale and green chemistry approaches still show varied findings. The effectiveness of these approaches largely depends on how learning activities are designed and how teachers facilitate the learning process. This means that success is influenced not only by the approaches themselves but also by the context of their implementation (Utmeemang, 2024).

Most previous studies still discuss microscale and green chemistry approaches separately. In fact, integrating both approaches may provide more comprehensive impacts on chemistry learning. This indicates that there is still room for further investigation in this area (Gericke et al., 2022).

Based on these considerations, this study aims to systematically examine the role of microscale and green chemistry approaches in the development of science process skills through an SLR method based on the PRISMA protocol. Unlike previous studies, this review integrates both approaches within a single analytical framework to identify patterns of findings, limitations, and pedagogical implications in chemistry learning.

METHOD

This study employed a Systematic Literature Review (SLR) method based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol.

The use of this protocol was intended to ensure that the literature search, selection, and analysis processes were conducted systematically and transparently.

Data sources were obtained from the Scopus, ERIC, and Google Scholar databases, covering publications from 2016 to 2026. The selected time range was based on the relevance of recent developments in research related to microscale laboratory practices, green chemistry, and science process skills in chemistry education. The literature search used Boolean keyword combinations, namely “microscale chemistry” OR “small-scale laboratory” AND “green chemistry” AND “science process skills” AND “chemistry education.” These keyword combinations were intended to identify studies relevant to the integration of microscale approaches, green chemistry, and science process skills in chemistry learning.

The inclusion criteria consisted of: (1) studies discussing microscale laboratory practices in chemistry education; (2) studies integrating green chemistry principles; (3) studies measuring science process skills or learning outcomes; and (4) indexed articles available in full text. Meanwhile, studies unrelated to chemistry education contexts, not based on instructional implementation, or not peer-reviewed were excluded from the analysis.

The selected articles were further reviewed based on their relevance to the study objectives, clarity of methodology, and contribution to chemistry learning research.

The article selection process followed four PRISMA stages: identification, screening, eligibility, and inclusion. At the identification stage, 215 articles were obtained from all databases. After removing duplicate records, 180 articles remained for further screening. Subsequently, 110 articles were excluded based on the relevance of their titles and abstracts to the focus of the study. During the eligibility stage, 70 articles were analyzed through full-text reading, and 45 articles were excluded because they did not meet the inclusion criteria. As a result, 25 articles were included in the final analysis.

Data analysis was conducted qualitatively through thematic synthesis by grouping research findings into several aspects, namely cognitive, affective, science process skills, and environmental impacts. Through this process, recurring patterns across studies were identified to obtain a more comprehensive understanding of the role of microscale and green chemistry approaches in chemistry learning.

RESULT AND DISCUSSION

Result

The article selection process followed the PRISMA stages of identification, screening, eligibility, and inclusion. The initial search identified 215 articles, which were gradually screened until 25 articles met the criteria for further analysis. The complete selection process is presented in Figure 1.

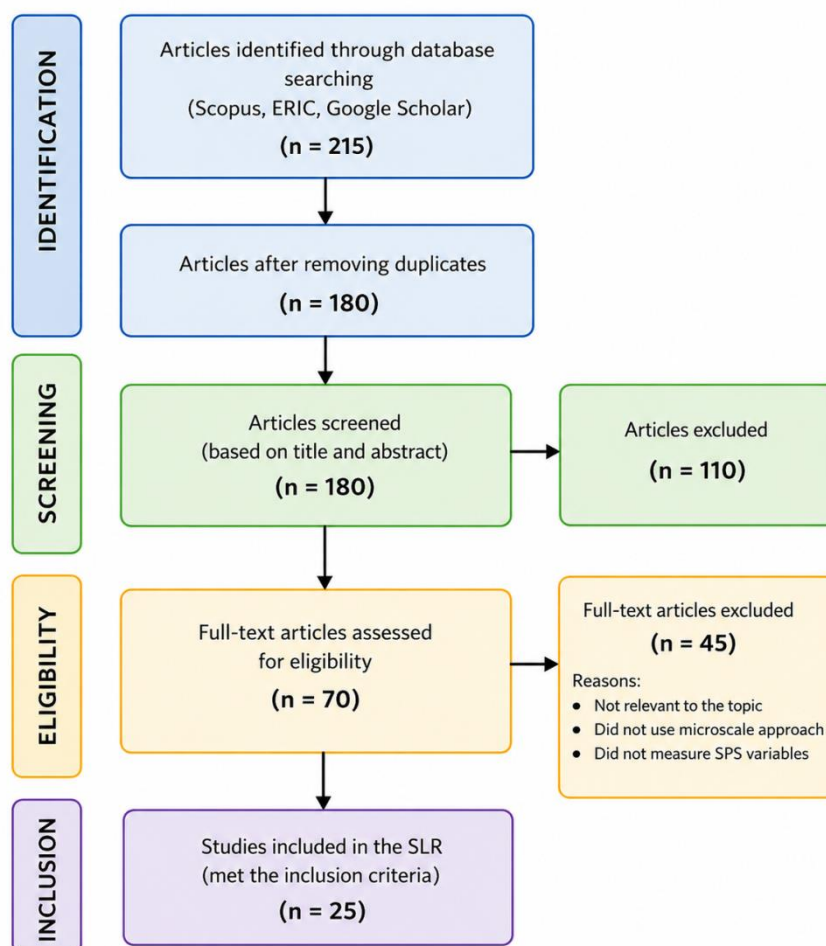


Figure 1. Flow Diagram of Article Selection Based on the PRISMA Protocol

The 25 selected articles showed variations in research contexts, ranging from secondary education to higher education, and involved experimental, developmental, and review-based approaches. Table 1 presents a synthesis of the characteristics and main findings of the analyzed studies, while also illustrating the trends of impacts identified in cognitive, affective, science process skills, and environmental aspects. This presentation facilitates the identification of contribution patterns associated with microscale and green chemistry approaches in chemistry learning.

Table 1. Synthesis of Microscale and Green Chemistry Studies in Chemistry Learning

No	Author(s)	Study Focus	Main Findings	Impact Focus
1	Ali et al. (2023)	Chemistry laboratory learning	Increased motivation and understanding through active engagement in laboratory activities	Cognitive, Affective
2	Allanas et al. (2024)	Green chemistry-based microscale learning	Strengthened conceptual understanding and awareness of green chemistry principles	Cognitive, Environmental
3	Freese et al. (2024)	Sustainable laboratory practices	Highlighted the importance of environmentally friendly laboratory practices	Environmental
4	Urbano et al. (2022)	Microscale approach in general chemistry	Improved student engagement and conceptual understanding	Cognitive, Affective
5	Utmeemang & Buaraphan (2024)	Small-scale experiments	Improved learning outcomes and students' scientific attitudes	Cognitive, Affective
6	Karpudewan et al. (2021)	Green chemistry integration	Promoted environmental awareness in chemistry learning	Affective, Environmental
7	Wijaya et al. (2024)	Microscale learning and motivation	Reported trends of increased motivation and learning outcomes	Cognitive, Affective
8	Gericke et al. (2022)	Science laboratory activities	Emphasized the role of laboratory work in conceptual understanding	Cognitive
9	Idrus et al. (2020)	Green chemistry module	Improved students' creativity and conceptual understanding	Cognitive, Affective
10	Varadarajan & Ladage (2022)	Problem-based laboratory learning	Developed science process skills through problem-based approaches and scaffolding	SPS
11	Eryilmaz & Misir (2023)	Green chemistry laboratory practices	Increased environmental awareness among pre-service teachers	Affective, Environmental
12	Sharma et al. (2021)	Green chemistry education	Emphasized the urgency of integrating green chemistry into education	Environmental
13	Hugerat (2020)	Microscale laboratory practices	Demonstrated efficiency, safety, and support for active learning	Cognitive, Affective
14	Irwansyah et al. (2021)	Microscale laboratory design	Effectively supported chemistry learning implementation	Cognitive
15	Abdullah et al. (2019)	Microscale experiments	Improved conceptual understanding through direct experience	Cognitive
16	Nurbaity et al. (2022)	Microscale chemistry kits	Improved students' science process skills	SPS

17	Hidayat et al. (2024)	Green chemistry-based microscale learning	Reduced laboratory risks while improving learning effectiveness	Cognitive, Environmental
18	Sari & Ramadani (2024)	Microscale eco-pedagogy	Increased students' environmental awareness	Affective, Environmental
19	Wong et al. (2023)	Microscale learning and sustainability	Supported sustainability-oriented chemistry learning	Environmental
20	Tan & Lee (2025)	Microscale titration	Improved experimental accuracy and precision	SPS, Cognitive
21	Liu et al. (2025)	Digital microscale laboratory	Improved observation accuracy through technology integration	Cognitive, SPS
22	Zimmerman & Smith (2025)	Zero-waste laboratory	Significantly reduced laboratory waste	Environmental
23	Matlin et al. (2025)	Systems thinking in chemistry	Integrated sustainability into chemical thinking frameworks	Cognitive, Environmental
24	Sudarmo et al. (2023)	Microscale laboratory equipment	Supported laboratory implementation in schools and universities	Cognitive
25	Prasetya et al. (2024)	Microscale green solvents	Produced more environmentally friendly laboratory activities	Environmental

Further examination of the studies revealed relatively consistent trends, particularly in improving conceptual understanding, student engagement, and the quality of experimental activities following the implementation of microscale and/or green chemistry approaches.

To better understand the patterns of findings, the synthesis was organized into four major aspects. Table 2 not only summarizes the findings but also illustrates how learning mechanisms and pedagogical implications are interconnected within the implementation of microscale and green chemistry approaches.

Table 2. Synthesis of Findings Based on Learning Aspects

Aspect	Findings Pattern	Learning Mechanism	Pedagogical Implications
Cognitive	Most studies reported improvements in conceptual understanding, particularly in connecting macroscopic, submicroscopic, and symbolic representations, although the level of improvement varied.	Microscale experiments allow repeated practice with rapid feedback, enabling students to gradually refine their understanding.	Laboratory activities should be designed to encourage conceptual exploration rather than merely procedural verification.

Affective	Many studies reported increased motivation and engagement, mainly because laboratory activities became safer and more accessible.	More flexible learning environments increase students' confidence to participate actively in experiments.	Teachers need to ensure that all students have active roles during laboratory activities so that engagement is not only superficial.
SPS	Improvements in science process skills appeared in several studies, particularly in observation and data interpretation, although the results were not always consistent across contexts.	More independent experimental activities create opportunities for students to engage in scientific processes.	The development of SPS requires structured inquiry-based approaches rather than simply changing the scale of experiments.
Environmental	Nearly all studies reported reductions in chemical use and laboratory waste, along with increased awareness of sustainability issues.	The integration of green chemistry principles connects chemical concepts directly with environmental impacts.	Laboratory activities should be designed not only as experimental practices but also as opportunities to develop environmental literacy.

In the cognitive aspect, most studies reported improvements in conceptual understanding, especially in connecting macroscopic, submicroscopic, and symbolic representations. This pattern appeared in studies that linked repeated experimentation with enhanced conceptual understanding.

From the affective perspective, most studies consistently reported increased student motivation and engagement. Safer and simpler laboratory environments were frequently associated with greater student confidence during experimentation. Meanwhile, in terms of science process skills, several studies reported improvements in observation, data interpretation, and conclusion-drawing abilities. Nevertheless, not all studies measured SPS directly, so findings related to this aspect should still be interpreted cautiously.

Findings related to environmental aspects indicate that microscale and green chemistry approaches generally reduce chemical consumption and laboratory waste while also increasing students' awareness of sustainability issues. The synthesis suggests that microscale and green chemistry approaches influence not only learning outcomes but also the ways students interact with scientific processes. Although the findings show generally

positive trends, variations across studies indicate that their effectiveness is strongly influenced by how learning activities are designed and implemented.

These variations further suggest that the implementation of microscale and green chemistry approaches cannot be separated from the learning context and pedagogical strategies applied. Therefore, further discussion is necessary to better understand how these approaches shape chemistry learning processes in more meaningful ways.

Discussion

The synthesis of the 25 reviewed articles indicates that microscale and green chemistry approaches influence not only learning outcomes but also the ways students engage with scientific processes. In many studies, microscale approaches are no longer viewed merely as techniques for reducing chemical use, but rather as part of instructional strategies that encourage more active student involvement. The use of smaller quantities of materials allows laboratory activities to be conducted more safely, flexibly, and efficiently, giving students greater opportunities to participate directly in experimentation. This is important in chemistry learning because activities such as observing, testing predictions, and discussing experimental results form part of the scientific knowledge construction process. The reviewed studies indicate that microscale laboratory practices can make laboratory activities more efficient and meaningful for students. When laboratory risks are minimized, students also tend to participate more actively (Urbano et al., 2022).

Despite this potential, the improvements reported across studies do not always follow the same pattern. In some contexts, microscale approaches significantly improve conceptual understanding, while in others the improvements remain relatively limited. Differences across studies indicate that the success of laboratory activities is determined not merely by the scale of experimentation, but also by how learning processes are designed and facilitated by teachers.

The variation across studies also reflects that the effectiveness of microscale and green chemistry approaches cannot be separated from their implementation contexts. Factors such as instructional design, teacher readiness, and laboratory culture may influence the development of students' science process skills.

When laboratory work remains focused on mechanical procedures, students tend to follow instructions without engaging deeply in scientific thinking processes. As a result, laboratory activities risk becoming purely technical exercises and losing their primary role as

spaces for knowledge construction. This variation appears closely related to how laboratory activities are designed. In contexts where laboratory work remains procedural, even on a small scale, the improvements observed are generally limited to lower-level cognitive aspects (Utmeemang & Buaraphan, 2024). Reducing the scale of experiments alone does not automatically improve the quality of learning.

From a cognitive perspective, microscale approaches offer advantages in terms of experimental cycles. Students can repeat experiments within relatively short periods of time, allowing them to receive feedback more quickly. Repeated experimentation enables students to revise their understanding gradually. In several studies, this pattern contributed to reducing misconceptions because students had opportunities to re-examine their observations (Abdullah et al., 2019).

The reviewed studies show that laboratory activities that provide opportunities for repetition and reflection can help students develop deeper conceptual understanding. The effectiveness of laboratory work lies not only in obtaining successful experimental results, but also in how students interpret the scientific processes they experience during learning. This reflects the importance of meaningful laboratory experiences in chemistry learning.

The integration of green chemistry introduces a different dimension to chemistry learning. Green chemistry is not solely related to material efficiency or waste reduction, but also encourages students to consider the consequences of the scientific activities they perform. In this sense, learning extends beyond understanding “how reactions occur” to questioning “what consequences arise from these processes” (Karpudewan et al., 2021).

Within the context of 21st-century education, this approach becomes increasingly important because students are expected not only to understand scientific concepts but also to develop awareness of sustainability and environmental responsibility. Because of this, green chemistry can help students develop scientific literacy that is more closely connected to real environmental issues.

From the affective aspect, several studies indicate that microscale laboratory practices tend to increase student motivation and engagement. Safer and less complex experimental environments make students more confident in observing, experimenting, and discussing ideas. Opportunities for direct involvement in experiments also strengthen students’ sense of ownership of the learning process (Ali et al., 2023).

Learning experiences that encourage active participation may also shape students’ attitudes toward chemistry learning. When students feel safer and more comfortable during

laboratory activities, they tend to become more willing to explore ideas, ask questions, and discuss the results of their observations.

Although microscale laboratory activities show positive impacts on motivation and engagement, the development of science process skills does not always occur optimally. In some contexts, students appear more active during laboratory work, but their activities remain limited to carrying out procedural steps.

The development of science process skills requires learning environments that provide opportunities for students to ask questions, design procedures, interpret data, and draw conclusions independently. The findings suggest that the quality of learning interactions plays a more important role than simply changing the scale of laboratory activities (Varadarajan & Ladage, 2022). These findings also highlight that teachers continue to play a central role in determining the success of laboratory-based learning. Teachers function not only as providers of procedures but also as facilitators who support students in developing scientific ways of thinking through inquiry and reflection.

Integrating microscale and green chemistry approaches becomes particularly interesting because both approaches offer laboratory efficiency while creating opportunities for more reflective and contextual learning. When integrated, these approaches show stronger potential for supporting the development of science process skills. Microscale practices create conditions that allow students to conduct experiments directly, while green chemistry provides a framework emphasizing efficiency and responsibility.

This combination encourages students not only to follow procedures but also to reflect on the processes they experience. Laboratory work is therefore no longer viewed merely as a means of verifying concepts, but rather as a medium for creating more meaningful and contextual learning experiences.

Nevertheless, it should be noted that not all studies directly measured science process skills. Some studies still relied on indirect indicators, such as learning outcomes or motivation, as the basis for drawing conclusions. This approach has limitations because not all aspects of scientific skills can be adequately represented through such indicators (Gericke et al., 2022). Therefore, interpretations of the findings should be approached cautiously. The use of indirect indicators also suggests that measuring science process skills remains a challenge in chemistry education research. SPS are not only associated with final outcomes but also involve thinking processes and scientific activities that occur throughout learning.

From an environmental perspective, microscale approaches are consistently reported to reduce chemical use and laboratory waste. These findings reinforce the idea that chemistry laboratory activities function not only as a means of understanding concepts but also as opportunities to develop environmental awareness and attitudes. A broader implication lies in changes in students' perspectives toward chemical practices themselves. When experiments are designed according to green chemistry principles, students begin to recognize that laboratory activities are closely connected to environmental responsibility (Freese et al., 2024).

As a result, chemistry learning can move beyond concept mastery and encourage the development of scientific attitudes and sustainability awareness. Technological developments further strengthen the effectiveness of these approaches. The use of smartphones in laboratory activities, for example, allows observations to be conducted with greater accuracy. In addition, collected data can be analyzed directly, making learning processes more evidence-based. This integration demonstrates that chemistry laboratory activities can evolve alongside technological advances without losing their scientific essence (Liu et al., 2025).

The use of simple technologies also creates opportunities for more flexible and accessible learning, particularly in schools with limited conventional laboratory facilities. However, technological integration also presents challenges. Not all schools have equal access to digital devices, and not all teachers are familiar with integrating technology into learning activities. In some cases, technology may even become an additional burden when not supported by adequate readiness.

This highlights that instructional innovation depends not only on technological tools but also on the readiness of human resources. Teachers require training and continuous support to effectively integrate technology into chemistry learning. Such challenges show that educational innovation depends not only on technology, but also on institutional support and teacher readiness. Beyond technological factors, institutional support also plays an important role.

Although microscale approaches are relatively cost-efficient, their implementation still requires adjustments to laboratory equipment and materials. Without adequate facilities and policy support, the implementation of these approaches may not run optimally. This suggests that the successful implementation of microscale and green chemistry approaches depends not only on instructional design but also on wider educational support systems.

From a methodological perspective, most of the analyzed studies were still short-term in nature. As a result, the long-term impacts on science process skills cannot yet be fully confirmed. Therefore, further longitudinal studies are needed to provide more comprehensive insights. These findings also indicate that several aspects still require careful consideration in interpreting the results. This review has limitations, particularly regarding the variation of research methods analyzed and the limited number of longitudinal studies directly measuring science process skills. In addition, many studies still focus on learning outcomes and motivation, while exploration of students' scientific thinking processes during laboratory activities remains relatively limited.

The findings of this review indicate that microscale and green chemistry approaches have strong potential to improve the quality of chemistry learning. In practice, however, this potential depends greatly on how both approaches are integrated into instructional design.

Without careful planning, these approaches risk becoming merely technical innovations that do not significantly contribute to the development of science process skills. Therefore, the implementation of microscale and green chemistry approaches should not focus solely on laboratory efficiency, but also on creating learning experiences that encourage active participation, scientific reflection, and sustainability awareness.

The reviewed studies further demonstrate that microscale and green chemistry approaches are relevant not only as laboratory innovations but also as part of broader efforts to develop more meaningful and sustainable chemistry learning.

CONCLUSION

This review indicates that microscale and green chemistry approaches serve as technical alternatives while also helping create more meaningful learning experiences. The integration of both approaches supports student engagement in scientific processes while encouraging more reflective understanding of concepts and experimental impacts. Nevertheless, their effectiveness strongly depends on the instructional design applied. Therefore, these approaches should be positioned as part of integrated pedagogical strategies rather than merely procedural innovations. The implementation of microscale and green chemistry approaches should be directed toward inquiry-based learning that explicitly targets science process skills. Teachers need to design laboratory activities that encourage students to observe, analyze, and draw conclusions independently. In line with this, institutional support and teacher competency development remain important factors for ensuring consistent

implementation. Future studies are recommended to employ longitudinal designs and more specific instruments for measuring science process skills. This review provides a synthesized overview of how the integration of microscale and green chemistry approaches can support chemistry learning that is more active, reflective, and oriented toward sustainability.

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