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Review Article

Implementation of green chemistry approaches in chemistry labs instruction: A systematic literature review

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ABSTRACT

In recent years, the urgent need to address environmental problems has driven green chemistry in various disciplines, focusing on designing chemical products and processes that minimize hazardous materials. This research conducted a systematic literature review (SLR) to evaluate the application of green chemistry in higher education chemistry lab practices and its impact on students' conceptual understanding, practical skills, and environmental awareness. Using the PRISMA method, 46 articles were analyzed from the Scopus and ScienceDirect databases extracted from a total of 537 published between 2015 and 2024. The findings show that applying green chemistry in chemistry laboratory learning can improve students' conceptual understanding, practical skills, and environmental awareness while encouraging environmentally friendly synthesis methods. However, challenges such as limited resources and the need for additional training for lecturers still exist. Institutional support and professional development are needed to maximize implementation. In conclusion, green chemistry has great potential to create a more environmentally responsible generation of chemists, with recommendations for comprehensive integration into chemistry curricula and increased support for educators to address implementation challenges. This study provides a basis for expanding the application of green chemistry in chemistry education and preparing students to face future sustainability challenges.

Introduction

In recent years, the urgent need to address environmental problems has triggered significant changes in various scientific disciplines. Chemistry, often associated with dangerous substances and processes. The concept of environmentally friendly chemistry (green chemistry) has emerged as an approach that aims to design products and processes that minimize or eliminate the use and formation of hazardous substances (Płotka-Wasylka et al., 2021). This paradigm shift not only aims to reduce the environmental impact of chemical practices but also promotes sustainability and safety.

Green chemistry was first introduced in 1990 by Paul T. Anastas and Warner with the concept of "The Twelve Principles of green chemistry" which proposed environmentally friendly research. Green chemistry Principles using these 12 principles in the development of new methods and analytical techniques, with the purpose of reducing their environmental impacts. Thus, one of the most active areas of research and development in green chemistry is the development of analytical methodologies (de Marco et al., 2019). These principles emphasize the importance of preventing pollution in the first place by reducing the use of hazardous chemicals, designing safer chemicals, using catalysts rather than stoichiometric reagents, and preventing waste production (Zhang, 2017).

The principles of green chemistry (GCP) emphasize that pollution prevention should be addressed at the molecular level to prioritize reducing pollution sources throughout the chemical life cycle. This concept of green chemistry stems from the United States' Pollution Prevention Act introduced in the 1990s. (Oliveira et al., 2024). This law defines GCP as source

reduction, which is any practice that can prevent the release of hazardous chemicals into the environment and impact public health (USEPA, 2017). These green chemistry principles (GCP) are comprehensively applied in industrial management, government policies, educational practices, and technology development worldwide (Chen et al., 2020). Integrating the chemistry curriculum in higher education with green chemistry principles, especially in chemistry laboratory practice, is an important step. This is because education plays a major role in providing guidance for implementing more sustainable chemical practices to overcome environmental problems (Paristiowati et al., 2022).

The increasing trend of green chemistry has influenced chemistry education significantly. Universities and programs around the world have recognized the increasing need to increase awareness and implement environmentally friendly chemistry practices (Waked et al., 2019). For example, institutions such as Westminster College and the University of California, Berkeley, have integrated green chemistry courses and developed new experiments to educate students about green chemistry practices (Armstrong et al., 2019). Initiatives such as the "Green Reagents and Sustainable Processes" (GRASP) approach in the UK show how undergraduate students collaborate with staff to identify and replace potentially hazardous chemicals in their laboratory protocols with more environmentally friendly alternatives. However, despite significant progress in several regions, the application of green chemistry in chemistry education is still growing, especially in certain regions such as Latin America (Hurst et al., 2019). With increasing global awareness of issues such as climate change and the depletion of fossil fuels, the green chemistry approach is increasingly being promoted. The American Chemical Society sees the field of green chemistry as the future of chemistry open to innovation, new ideas, and revolutionary advances (Ganesh et al., 2021).

Many previous studies have implemented the green chemistry approach in the chemistry laboratory (O'Neil et al., 2021; Xiao et al., 2021; Zhang et al., 2023; Armstrong et al., 2024). These studies require systematic literature reviews to collect and better understand the findings, in contrast to traditional literature reviews, to avoid issues related to transparency, author bias, selection bias, and publication bias. Systematic literature reviews offer a more comprehensive, transparent, structured and systematic method. Although there is a need for systematic literature reviews (SLRs), currently, their number and scope is still limited in studies regarding green chemistry approaches in chemistry laboratories. Apart from that, based on previous research, there is a gap in the application of the green chemistry approach in chemistry laboratories. Gaps include difficulties in adopting new procedures, lack of awareness and education, and challenges in changing chemicals (O'Neil et al., 2021). Therefore, in this study, we conducted a systematic literature review of previous related research that examines how the green chemistry approach is implemented in practice in chemistry laboratories focused on the impact of learning on understanding students' conceptual, practical skills and environmental awareness in the last 10 years (2015-2024).

Research questions

This research conducted a systematic literature review of previous research on the green chemistry approach in higher education chemistry laboratories. The research questions for this systematic literature review are as follows: (1) Green chemistry principles apply to chemistry laboratory practice?; and (2) Green chemistry principles? in the chemistry laboratory towards understanding students' conceptual, practical skills, and environmental awareness?

Research objectives

The main objectives of this systematic literature review are as follows: (1) Evaluate the application of green chemistry principles in chemistry laboratory practice; and (2) Evaluate the learning impact of applying green chemistry principles in the chemistry laboratory towards understanding students' conceptual, practical skills and environmental awareness.

Methods

This study utilized PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis). While PRISMA is commonly applied in biomedical literature, it was also suitable for this research as it facilitated the creation of clear research questions and enabled systematic searches with the checklists and protocols provided (Sarkis-Onofre et al., 2021). Additionally, PRISMA reduces various biases and aids in synthesizing studies effectively (Howard et al., 2019). It mandates a systematic search strategy involving four key steps: identification, screening, eligibility, and evaluation of article quality.

Identification

The process that involves identifying and diversifying appropriate keywords in the article search process is called identification. Identification needs to be done because in the article search process appropriate keywords are needed and can increase the accuracy of the article. In this study, 6 keywords were chosen, namely: "green chemistry", AND "chemistry" AND "laboratory", OR "laboratory practice", "Learning", OR "chemistry learning". Article searches using selected keywords were carried out in two main databases, namely Scopus and ScienceDirect. These two databases were chosen because they have the advantage of having comprehensive search strength, stable search results, and more advanced search functionality compared to other databases (Gusenbauer & Haddaway, 2021).

Screening

The screening process was carried out because the inclusion or exclusion criteria were determined to have suitable articles and form a systematic literature review (Shaffril et al., 2020). A total of 537 articles were successfully collected through the identification process and then continued with the screening process. The first criterion is the year of publication of the article which is used within the last 10 years (2015-2024). This period was chosen because it is in line with the concept of maturity of the research and many articles related to the topic studied succeeded in obtaining reliable data (Kraus et al., 2020). The second criterion is that the language used in the article must be English to avoid confusion in reading and understanding. The third criterion is to only select journal articles because this systematic literature review is the

identification of previous research findings, not a review of previous research. Therefore, only articles with relevant empirical data could be considered in this study.

Table 1. Inclusion criteria

	Inclusion criteria
Year of publication	Year of publication in the last 10 years (2015-2024)
Language	English
Publication type	Journal Article
Type of finding	Research based on empirical data
Subject Area	Chemistry
Focus findings	Data relating to the application and impact of the green chemistry approach in the chemistry laboratory toward understanding students' conceptual, practical skills, and environmental awareness

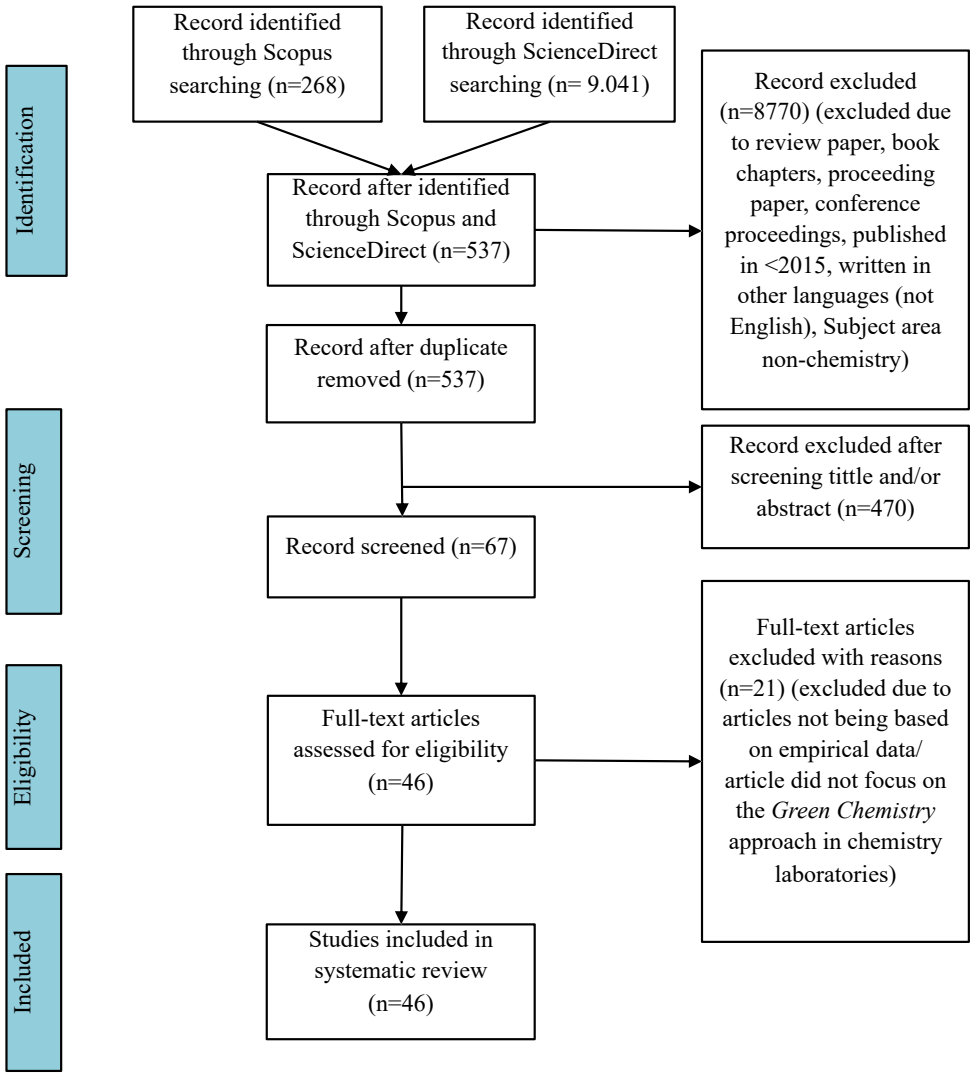

Fig-1. SLR flow diagram

This research uses inclusion criteria in the process. These inclusion criteria were important to ensure that all selected articles presented relevant findings to the systematic literature review (Table 1). In this study, selected articles focused on findings related to the impact of green chemistry approaches in chemistry laboratories, were otherwise excluded. This screening is through reviewing the title and abstract. After the screening process, 470 articles were eliminated, leaving 67 articles for the next stage.

Eligibility

67 articles had to undergo a second screening process, known as eligibility. This process serves to ensure that all selected articles are relevant according to the research that will be used in the SLR. This feasibility process is carried out by reading in depth the title of the article, abstract, methodology, results, and discussion section that will be consulted. Thus, 46 articles were obtained by excluding 21 articles because they did not focus on the green chemistry approach in organic chemistry laboratories in higher education. The SLR stages, which include identification, screening, and eligibility, are visualized through the flowchart in Fig-1.

Quality assessment

Selected articles were then assessed for quality to minimize bias and identify articles with potential methodological weaknesses (Edwards et al., 2019). Each article will be assessed for quality based on two general criteria, namely: (1) Are the research questions clearly stated? (2) Can the data obtained answer the stated research questions? Articles in this research must fulfill these two aspects before proceeding to the next stage.

The next stage is the quality assessment process and research design. The articles that will undergo further analysis are research articles where the research results are from experimental results in the laboratory so that the data obtained is more accurate, complex, and by the objectives of this research. This ensured that only articles with strong methodology and relevant data were included in this study, thereby providing a comprehensive and reliable picture of the implementation of green chemistry approaches in chemistry laboratory teaching.

Data extraction and analysis

After the quality assessment is carried out, the data mining process begins with articles that have passed the evaluation. Considering that the focus of this systematic literature review (SLR) is to review findings related to the implementation of green chemistry approaches in chemistry laboratory teaching, data mining is focused on three main parts of each article: abstract, research objectives, methods, and findings. The summary of the findings from the 46 SLR articles is presented through Table 2 in the results and discussion. Where necessary, other sections of the article that presented relevant data were also read and analyzed. The data that has been extracted is then placed in a table to facilitate the subsequent analysis process. The data analysis process is carried out after all relevant data has been extracted. Given that this SLR is an integrative review covering a variety of research designs, qualitative synthesis was chosen as the best analysis method (Dhollande et al., 2021).

Although there are various methods of analysis in qualitative synthesis, thematic analysis is identified as one of the most effective techniques for analyzing findings from various research designs (Flemming et al., 2019). Thematic analysis can identify patterns based on similarities and relationships between the extracted findings.

In this study, to develop relevant themes, the extracted findings were examined and data with similarities or relationships were collected into one data set. The data set is then given an appropriate theme. From this process, two main themes emerged, namely: (1) application of the green chemistry approach in chemistry laboratories, (2) the impact of practical chemistry teaching approaches green chemistry towards understanding students' conceptual, practical skills and environmental awareness. The findings from each theme were then examined again to form subthemes. Through this process, several sub themes were identified and retained due to their relevance to the research questions. Finally, two experts, one in the field of SLR and one in the field of green chemistry education, validated all themes and subthemes to ensure that this analysis could provide comprehensive and in-depth insight into the implementation of green chemistry approaches in chemistry laboratory teaching.

Results and Discussion

Implementing the green chemistry approach in laboratory teaching in the last 10 years (2015-2024), 46 selected and relevant articles were selected. Of the 4 6 selected articles, 2 articles were published in 2024, 6 articles were published in 2023, 5 articles were published in 2022, 2 articles were published in 2021, 8 articles were published in 2020, 12 articles were published in 2019, 1 article was published in 2018, 5 articles were published in 2017, 2 articles were published in 2016, and 3 articles were published in 2015. The following is a summary of the findings from the 46 selected SLR articles which are available in Table 2.

The results of the literature review show that learning using the green chemistry approach has a significant positive impact on student learning outcomes in various aspects. Based on analysis of the 46 references studied, it was found that there was an increase in the conceptual understanding of students who were involved in green chemistry- based learning and applied it in real contexts. Research by Liu et al. (2023) showed that green chemistry learning-based projects significantly increased students' understanding of environmentally friendly electrochemical concepts. The next finding is that learning outcomes using the green chemistry approach can develop students' practical skills. In addition to theoretical understanding, students also demonstrate improvements in their technical and practical skills. For example, Amaris et al. (2017) reported that students were able to synthesize and characterize silver nanoparticles using environmentally friendly methods, which also taught them the importance of environmental impact analysis.

Another impact from the results of implementing learning using the green chemistry approach is that it can increase environmental awareness for students. Some studies, such as those by Cooper et al. (2019), highlight students' increasing awareness of the environmental impacts of traditional chemistry experiments. Learning green chemistry helps students be more critical in evaluating environmental impacts and encourages them to look for more sustainable solutions. Thus, it is recommended that the many positive impacts from the results of the chemistry learning approach in the laboratory using the green chemistry approach be included in the curriculum. The integration of green chemistry principles into laboratory and classroom curricula has proven effective in enriching the student learning experience. For example, Sues et al. (2015) reported that teaching ligand substitution reactions using iron-based catalysts not only improved students' technical skills, but also strengthened the connection between theory and real-world applications.

Implementation evaluation green chemistry principles in practice laboratory chemistry

Evaluation implementation green chemistry principles in practice laboratory chemistry show positive results in various aspects, including efficiency reaction, safety work, and impact environment. Studies show that adopting laboratories principles can reduce the use of material chemistry hazardous and waste generated, as well increase sustainability of chemical processes. Examples in reducing use of material chemistry are dangerous, namely in application to use more

Table 2. Summary of findings from 46 selected SLR articles

Study	Aim	Methodology/ Sample	Findings
(Cosio et al., 2020)	This research aims to illustrate the concepts of aerobic oxidation, catalysis, and sustainable synthesis, introduce practical sustainable synthesis, and develop students' laboratory skills and analysis of experimental results.	The two-part laboratory module involves Pd-catalyzed C−N cross-coupling reactions and hypervalent iodine-catalyzed C−H/N−H coupling, with evaluation of the sustainability of the reactions using green chemistry metrics.	As a result, this module is effective in teaching sustainable synthesis, providing advanced laboratory skills, and increasing students' understanding of green chemistry principles and evaluating the sustainability of reactions.
(Davila-Diaz, 2024)	This research aims to strengthen knowledge about aqueous reactions through micro-scale experiments that provide concrete examples and increase understanding of chemistry for students and the general public.	Activities involve the use of reagents in small quantities for demonstration of aqueous reactions, carried out in a manner that reduces waste and adheres to green chemistry principles.	The result is that micro-scale activities have proven effective in increasing students' understanding and engagement with chemistry, with the use of small reagents that are environmentally friendly and well accepted in various educational contexts.
(Cosio et al., 2020)	This research aims to demonstrate the use of solar reflectors as an alternative electrical heat source for the Diels-Alder reaction and promote environmentally friendly chemistry with renewable energy solutions.	The experiment compares the use of solar heat sources and electricity in the Diels-Alder reaction between maleic anhydride and anthracene, with product analysis using NMR spectroscopy, FTIR, and melting point determination.	The result was that both heating methods produced equally effective products, and this experience increased students' awareness of sustainable chemistry practices using renewable energy.
(Biswas & Mukherjee, 2017)	This research aims to integrate green chemistry principles into undergraduate laboratory courses by teaching more environmentally friendly and efficient chemistry practices.	The experiments involved a modified two-step synthesis of aniline to 4-bromoacetanilide using environmentally friendly techniques, such as the use of Zn dust and CAN, as well as product characterization through functional group, melting point and IR spectroscopy tests.	The experiment succeeded in creating awareness of the principles of green chemistry among students, with 89 out of 100 students obtaining high marks, and the modified synthesis method proved effective and suitable for undergraduate laboratories.
(Wu et al., 2019)	This research aims to introduce students to green chemistry concepts by enabling them to design and modify experiments, thereby increasing their understanding of and confidence in science.	The research involved integrating green chemistry modules into two laboratory courses, with data collected through online surveys and evaluations of student writing from 2,823 participants during fall 2017 to fall 2018.	The results showed that the majority of students demonstrated a fundamental understanding of green chemistry, with 98% presenting that understanding in their abstracts, 94% asking appropriate research questions, and 68% using appropriate methods, as well as significant improvements in understanding of concepts such as E-factor and atomic economics .
(Liu et al., 2019)	This research aims to introduce students to the 12 Principles of Green Chemistry and modern solid-state analysis techniques, as well as provide practical experience in the synthesis and characterization of environmentally friendly porous materials.	Students synthesize the porous material HKUST-1 using ultrasonic-assisted synthesis methods, characterize the material with modern solid-state analytical techniques, and use HKUST-1 to remove organic pollutants from aqueous solutions.	Students gain a deep understanding of green chemistry principles and their application in materials synthesis and solid-state analysis, as well as effectively apply the HKUST-1 porous material to remove pollutants from water, while completing experiments in a time-efficient manner.
(Landstrom et al., 2019)	This research aims to develop undergraduate chemistry laboratory experiments that highlight green chemistry principles using safe surfactants in organic reactions to increase students' understanding of sustainability and method safety.	Students carry out nucleophilic aromatic substitution (S_NAr) reactions with and without TPGS-750-M surfactant in an aqueous environment, monitor the reaction with thin layer chromatography (TLC), and analyze the product using infrared (IR) spectroscopy and melting point.	Students demonstrated a better understanding of green chemistry principles and surfactant effectiveness, with 95% recognizing the role of surfactants in reaction efficiency and 53% recognizing their environmental benefits, as well as improving reactivity predictions based on experimental results.
(Hie et al., 2015)	This research aims to present a modern laboratory experiment in organic chemistry, focusing on the Suzuki-Miyaura cross-coupling reaction with nickel catalysis and a green alcohol solvent, to introduce students to contemporary engineering, green chemistry, and pharmaceutical relevance.	Research involves hands-on experiments using modern laboratory techniques for the Suzuki-Miyaura reaction with training in reaction setup, monitoring, purification, and structural analysis using NMR.	Students demonstrate an increased understanding of modern organic chemistry techniques and green chemistry principles, as well as realizing the relevance of these practices in pharmaceutical research and environmental sustainability, with evaluations highlighting the benefits of nickel catalysis and green solvents.
(Obhi et al., 2019)	This research aims to develop a comparative assignment that	The research uses a case study format in which students	The results show that students have a strong understanding

Study	Aim	Methodology/ Sample	Findings
	integrates laboratory and classroom for a final year organic synthesis course, allowing students to examine the principles of green chemistry and the sustainability of synthetic procedures.	perform Buchwald-Hartwig amination and nucleophilic aromatic substitution analysis, use industry guidelines, calculate process mass intensity (PMI), and apply the 12 Principles of Green Chemistry.	of sustainability, appreciate the practical knowledge and industry perspective gained, and are able to critically analyze reactions by considering green chemistry principles in their evaluations.
(Baldwin et al., 2022)	This research aims to present laboratory experiments that enable undergraduate students to synthesize amide products in a modern and environmentally friendly manner, as well as improve their understanding of organic chemistry and green chemistry principles.	The research involved the synthesis of amides from 2-furoic acid and amines using TCFH-NMI reagents at room temperature, with emphasis on minimal solvent use, rapid product isolation, and product characterization using NMR, IR, and MS.	The results show that students succeeded in understanding reaction mechanisms, carrying out acylation, isolating and characterizing amide products, and showing increased awareness of green chemistry principles and commitment to sustainable practices in their education and careers.
(Abraham, 2020)	This research aims to introduce laboratory experiments that assess safer and biological alternatives to the tie dye process in nucleophilic aromatic substitution reactions (SN Ar), while increasing students' understanding of the principles of green chemistry.	The research involved laboratory experiments in which students used water-soluble reactive dyes for the tie-dye process, allowing them to apply the concepts of biodegradability and reuse.	The results showed that students experienced an increased understanding of green chemistry principles and collaborated in finding solutions to remove excess dye, strengthening their practical application and awareness of the use of safer alternatives and the life cycle of materials.
(Rattanakit & Maungchang, 2019)	This research aims to teach the principles of spectrophotometry and its practical application in determining iron(III) levels in water samples, by introducing the concept of green chemistry through the use of natural reagents.	The study used Indian Gooseberry extract as a green reagent in a UV-vis spectrophotometry technique to detect iron(III) in water samples.	The results showed that using the Indian gooseberry extract method proved to be effective, environmentally friendly, and cost-effective in iron(III) analysis, as well as introducing students to safe and sustainable analysis techniques while reducing the use of hazardous chemicals.
(Dicks et al., 2019)	This research aims to describe the integration of a systems thinking approach to green chemistry at various levels in the University of Toronto's Department of Chemistry over 20 years, and its impact on teaching and research.	Research involves the integration of green chemistry principles into courses, laboratory activities, and initiatives by GCI, as well as analysis of impacts on education, research, culture, and student outcomes.	The findings in this research are that the integration of green chemistry increases students' understanding of global challenges, encourages sustainable research progress, fosters a culture of sustainable thinking, and prepares students for interdisciplinary work, with approximately 10 of the 29 former GCI members applying this concept in their careers.
(Keen et al., 2020)	This research aims to explore the effectiveness of integrating green chemistry principles in an electrochemistry laboratory course to increase student engagement, understanding, and interest.	The research used a quasi-experimental design with control and treatment groups, comparing a green chemistry-based electrochemical laboratory with a traditional laboratory manual, and collecting data through surveys, worksheets and statistical analysis.	The results showed that students in the green chemistry-based laboratory group showed better understanding, higher interest, and greater relevance to real-world applications, and considered the laboratory to be of higher quality compared to traditional laboratories.
(Andrew et al., 2022)	This research aims to develop a more environmentally friendly synthesis method of bupropion hydrochloride for undergraduate teaching laboratories, with a focus on integrating sustainability concepts in chemistry education.	The research involves laboratory experiments in which students synthesize bupropion hydrochloride and evaluate the process using green chemistry principles such as atomic economy and process mass intensity.	The results show that the adapted synthesis process is more environmentally friendly but still produces significant waste and requires excess tert-butylamine, revealing challenges in achieving full sustainability and increasing student awareness of the environmental impacts in chemistry.
(Ritter & Abraham, 2022)	This research aims to test the effectiveness of a green chemistry context-based laboratory in increasing students' understanding and interest in electrochemistry.	The study used a treatment-control design with undergraduate students, compared a green chemistry-based electrochemistry laboratory with a traditional laboratory, and analyzed data from worksheets, surveys, and interviews using statistical tests and qualitative analysis.	The results showed that the treatment group demonstrated better performance, deeper understanding, and greater interest in electrochemistry regarding real-world applications, underscoring the benefits of integrating green chemistry principles in the laboratory to improve the relevance and quality of chemistry education.
(Othman et al., 2024)	This research aims to develop an alternative method for analyzing functional groups in organic compounds that is in line with the principles of green chemistry, reducing the use of excess reagents and waste.	The research used micro-scale experiments with 44 organic compounds, 17 chemical tests modified to use minimal reagent volumes, carried out on grooved tiles for efficiency and waste reduction.	Findings demonstrate that microscale methods are efficient, safe, and economical for functional group analysis, while supporting environmentally friendly laboratory practices and increasing student understanding of organic chemistry.
(Hopson et al., 2018)	This research aims to introduce undergraduate students to advanced NMR spectroscopy, specifically the 1-D selective nuclear Overhauser effect (NOE), to help with the structural characterization of compounds and teach the principles of	The research involved the synthesis of organic compounds via acylation and bromination, followed by analysis using 1-D NOE NMR spectroscopy, TLC, melting point determination, and IR spectroscopy.	The findings show that 1-D NOE NMR spectroscopy is effective for determining structural features and regioselectivity, as well as demonstrating the principles of green chemistry with the use of safer reagents, increasing

Study	Aim	Methodology/ Sample	Findings
	green chemistry.		students' understanding of NMR techniques and organic synthesis.
(Verdía et al., 2017)	This research aims to present an undergraduate green chemistry project involving the synthesis of 3-(methoxycarbonyl) coumarin using ionic liquids as a solvent and catalyst to provide practical experience in the principles of green chemistry.	The research involved three main experimental sessions: the synthesis of ionic liquid [MMIm][MSO4], its application in the Knoevenagel condensation reaction, and the use of ionic liquid for the synthesis of 3-(methoxycarbonyl)coumarin.	The findings show that [MMIm][MSO4] is effective as a solvent and catalyst, resulting in the synthesis of 3-(methoxycarbonyl)coumarin in high yield and purity, as well as minimizing harmful reagents and increasing atomic efficiency.
(Mohan & Mejia, 2020)	This research aims to highlight the importance of integrating green chemistry principles in undergraduate organic chemistry laboratory experiments to improve safety, reduce waste disposal costs, and instill sustainability principles in students.	This research adapts conventional synthesis methods by replacing toxic solvents, using microwave-assisted organic synthesis, and developing metrics to evaluate the environmental friendliness of experiments.	The findings show a gap between industry and academia in adopting environmentally friendly practices in laboratories, emphasizing the need for the use of safer reagents and environmentally friendly metrics to minimize waste in undergraduate laboratories.
(Xiong et al., 2023)	This research aims to provide practical training to undergraduate students in green organic electrochemistry through a comparison of traditional bromination and electrochemical methods, with a focus on the principles of green chemistry and sustainability.	The research involved two bromination methods: direct using liquid bromine and electrochemical using bromine salts, including electrochemical reactor assembly and column chromatography.	The results show that students evaluated the bromination method and found the electrochemical method to be more sustainable, with better atom economy, less hazardous reactants, and without the need for a catalyst, reflecting their understanding of the principles of green chemistry and sustainability.
(Pfab et al., 2019)	This research aims to explore the negative impact of human formation in biomass valorization, and introduce the concept of green chemistry and systems thinking to students through laboratory experiments.	The research involves laboratory experiments for undergraduate students, including techniques such as thin layer chromatography (TLC), vacuum filtration, and solvent extraction, with a focus on sugar dehydration and humin formation.	Humin formation, which reaches 10-50%, reduces biomass conversion efficiency and challenges the economic feasibility of the process, while students gain a practical understanding of organic chemistry techniques and an awareness of the negative impacts of biomass conversion methods.
(Reyes et al., 2023)	This research aims to improve understanding and application of green chemistry principles through laboratory experiments that emphasize mechanochemistry and solvent-free synthetic methods.	The research involves mechanosynthesis experiments in the laboratory, where students explore solvent-free reactions, calculate green chemistry metrics, and discuss solvent selection.	The results showed that students showed a positive response to mechanosynthesis, recognized its benefits in reducing solvent use, and expressed a desire for more education about green chemistry in their curriculum.
(Cooper & Walser, 2019)	This research aims to demonstrate the advantages of using CO_2 in green chemistry experiments and facilitate discussions about the principles of green chemistry through a systems thinking approach.	The research involved a comparative analysis between traditional HCl experiments and those using CO_2, with a focus on resources, energy, and waste, to assess the environmental impact of the experiments.	The use of CO_2 increases students' understanding of rovibrational spectroscopy and encourages them to consider the global implications of experiments, reducing reliance on hazardous reagents, as well as conserving resources and reducing waste.
(X. Wang et al., 2020)	This research aims to demonstrate the effectiveness of ultrasonic-assisted transesterification as a green method for producing biodiesel, while increasing students' understanding of organic synthesis and green chemistry principles.	The research involved biodiesel synthesis using an ultrasonic cleaner to facilitate transesterification between vegetable oil and methanol with KOH as a catalyst, involving six types of oil in a 3-hour laboratory experiment.	This method reduces the separation time of biodiesel products, produces high-quality biodiesel with nearly 100% purity and little waste, and provides students with practical experience in the principles of green chemistry and the effects of ultrasonic irradiation.
(P. Sharma & Ponnusamy, 2022)	This research aims to develop a quantitative evaluation tool to measure the greenness of products and processes based on the 12 principles of green chemistry, as well as increase student awareness about the impact of green chemistry.	The research uses a green chemistry evaluation matrix that includes metrics such as atomic economy, catalysis, and design for degradation, taking into account factors such as feedstock mass, waste, and product degradation.	The results show that the DOZEN TM 2.0 tool is effective in assessing the sustainability of chemical processes, enabling the identification of areas of improvement in environmental impact and resource efficiency, and demonstrating sustainability improvements through comparison between the original and re-engineered processes.
(Gormong et al., 2021)	This research aims to explore green reaction media for the copolymerization of bio-based monomers in an educational	The research involved the radical copolymerization of β-myrcene and dibutyl itaconate via aqueous emulsion	Students successfully observed swelling trends according to solvent polarity and monomer ratio through 1H NMR

Study	Aim	Methodology/ Sample	Findings
	context, with a focus on the integration of sustainable polymer chemistry into undergraduate teaching laboratories.	copolymerization and bulk polymerization, as well as analysis of the effects of reaction conditions on the resulting materials.	analysis, with 87% of students assessing the experiment as a valuable addition to the curriculum and demonstrating an understanding of green chemistry and the relationship between solvent polarity and material swelling.
(Sues et al., 2015)	This research aims to present a two-part laboratory experiment for advanced inorganic chemistry students, focusing on iron catalyst synthesis and ligand substitution reactions, as well as strengthening the theoretical concepts and practice of green chemistry.	Experiments involve the synthesis of phosphonium dimer precursors and catalytically active species with carbonyl ligands, using drying, degassing and Schlenk-line techniques for sensitive materials.	The experiments were successfully carried out by advanced students, demonstrating a good understanding of ligand substitution mechanisms and the relevance of multistep synthesis, as well as connecting inorganic chemistry concepts with state-of-the-art research in catalysis.
(Xiong et al., 2023)	This research aims to explore project-based learning in green electrochemistry to improve students' understanding of green chemistry principles and their technical skills through hands-on research experiences.	Research involves literature reviews, experimental procedures, and project-based learning, including laboratory safety training, organic experimental methods, data analysis, essay writing, and presentations.	The results showed a significant increase in students' understanding of green chemistry principles and technical skills, with a structured approach to planning, implementation and reporting that strengthened cognitive and technical skills.
(Fennie & Roth, 2016)	This research aims to investigate amide formation reactions from a green chemistry perspective to help chemistry and biochemistry students assess the sustainability and economic aspects of various synthetic methods.	Students performed three types of amide formation reactions with hydrocinnamic acid and benzylamine, evaluated the methods based on green chemistry metrics such as atomic economy and mass intensity of the process, and calculated the cost of the synthesis.	The findings suggest that the boric acid-catalyzed route is the most environmentally friendly and inexpensive method, while the HATU and hydrochloric acid routes are less sustainable due to cost and environmental metrics, as well as the use of organic solvents.
(Abraham, 2020)	This research aims to develop a series of organic chemistry laboratory experiments that integrate environmentally friendly and sustainable chemistry concepts while maintaining standard techniques and concepts.	This research uses practical laboratory techniques such as distillation, recrystallization, extraction, filtration, chromatography, and various forms of spectroscopy to analyze single plant metabolites.	Findings showed that students achieved a good understanding of green chemistry principles with an average score of 75.6% to 79.8%, and positive feedback indicated intellectual stimulation and increased critical thinking regarding sustainable solutions.
(RK Sharma et al., 2019)	This research aims to design green chemistry laboratory experiments that increase students' understanding in nanotechnology and catalysis, use potato extract for the synthesis of magnetic nanoparticles (MNP) and support sustainable practices.	This research involved the synthesis of MNPs from potato extract and testing their effectiveness in dye degradation for treating wastewater, with experiments carried out over two laboratory periods.	Findings showed that the majority of students achieved excellent dye degradation within 30 minutes, demonstrated the effectiveness of the synthesized MNPs, and reported positive experiences and new understanding of nanotechnology and environmental remediation.
(Contreras-Cruz et al., 2019)	This research aims to evaluate the effectiveness of undergraduate laboratory experiments using photoredox catalysis with a blue LED photoreactor to photo aromatize 1,4-DHP to pyridine derivatives, as well as improve students' understanding of photochemistry and green chemistry principles.	The research method involved laboratory sessions in which second-year students conducted experiments with guidance, were introduced through online articles and pre lab classes, and assessed using post-laboratory questionnaires.	Findings showed that more than 70% of students understood photoredox catalysis and experimental conditions, produced high-purity pyridine derivatives, and demonstrated new enthusiasm and awareness about the use of visible light as a "clean reagent" in green chemistry.
(Lu et al., 2017)	This research aims to describe laboratory experiments that use thiourea as a sulfur source in the formation of C−S bonds via nucleophilic aromatic substitution and thia-Michael addition reactions, while teaching the principles of green chemistry to final year students.	The research method involves carrying out two reactions in Triton	Findings showed that 93% of students were able to write reaction mechanisms correctly, 80% recognized water as an environmentally friendly alternative solvent, and 70-100% achieved proficiency in interpreting NMR spectra, with 80% of students meeting the set pedagogical goals.
(Knutson et al., 2019)	This research aims to provide an interesting experiment to increase students' awareness of green chemistry strategies in designing environmentally friendly plastics and highlight opportunities for STEM students to contribute to a sustainable future.	The research method involved the synthesis of bioplastics from citric acid and glycerol, with students conducting experiments in groups, using UV-visible spectroscopy and smartphone colorimetry for analysis.	Findings showed that 70% of students were aware that bioplastics from citric acid/glycerol degraded the fastest, and 71% of students were able to create linear plots with good correlation for at least two of the three samples, indicating an effective understanding and analysis of the environmental impacts of bioplastics.
(Quinson, 2023)	This research aims to explore the synthesis of surfactant-free gold nanoparticles to improve students' understanding of experimental design and critical thinking in nanoscience	The research method involves a structured laboratory exercise with two parts, in which students first learn the synthesis protocol and then design their own	Findings show students demonstrate deep engagement, critical thinking, and strong collaboration, with an increased understanding of the importance of protocols, the impact of

Study	Aim	Methodology/ Sample	Findings
	education.	experimental studies, while reflecting on their experimental design choices and implications.	Green Chemistry, and safe and sustainable experimental design.
(Knutson et al., 2017)	This research aims to develop chemical experiments that combine the principles of science and engineering to introduce basic concepts of polymers and green chemistry to students, as well as increase awareness of the environmental impact of plastic and sustainable alternatives.	This research involved a four-part laboratory experiment focusing on polymeric medical suture threads, including fabrication, strength testing, degradation, and improvement of thread properties using poly(ε-caprolactone) (PCL) and polylactide (PLA), while prioritizing safety.	The results showed that the laboratory experiments increased students' understanding of polymers and green chemistry, with positive feedback on practical and theoretical activities, as well as demonstrating the effectiveness of absorbable PCL threads and degradation, strengthening the link between chemistry and real-world applications in medical technology and sustainability.
(Ang, 2021)	This research aims to integrate green chemistry principles into laboratory teaching to increase understanding and application of these concepts in organic chemistry as well as promote awareness of sustainable practices.	This research uses a multi-outcome experiment (MOE) approach, where students work in groups on experiments with different starting materials, completing pre-laboratory assignments and laboratory reports to strengthen understanding of green chemistry principles.	Results showed students felt more confident and demonstrated increased understanding and application of green chemistry principles following laboratory experiments, with the integration of green chemistry in the curriculum considered beneficial for deepening their understanding.
(Wójcik et al., 2022)	This research aims to develop and validate an electrochemical sensor to distinguish seasonal changes in honey samples from one apiary, as well as assess the quality and authenticity of honey using green chemistry principles.	This research uses precious metal electrodes (iridium, platinum and their mixtures) for voltammetric analysis of honey, processes electrochemical data with PCA and classifies with convolutional neural networks (CNN) to differentiate 12 types of honey with 100% accuracy.	The results showed that the iridium-platinum mixed electrode was significantly more effective in detecting electrochemical signals from honey, with the CNN model achieving 100% accuracy in differentiating honey types and complying with green chemistry principles without supporting electrolytes, indicating potential for application to other complex organic samples.
(Lasker et al., 2019)	This research successfully integrated toxicology and green chemistry in the curriculum through SDS-based activities and sunscreen products, which effectively increased students' understanding of the impact of chemicals on health and the environment, as well as strengthening laboratory and critical thinking skills.	The research methodology shows that the MoDRN model is effective in integrating toxicology and green chemistry into the curriculum through SDS analysis, sunscreen efficiency tests, pre-lab lectures, data collection, and an interdisciplinary approach, which increases student understanding and promotes safer and friendlier chemistry practices.	This research shows that MoDRN activities significantly improved students' understanding and behavior regarding the health of chemical products, with 97% of students experiencing a positive impact on health choices and 84% switching to safer zinc oxide-based sunscreens, while strengthening critical thinking skills in analyzing SDS and assess chemical hazards.
(Leslie & Tzeel, 2016)	This research aims to describe a guided investigation-based experiment that explores the hydration of phenylacetylene using a gold(III) catalyst, to improve students' understanding of organic reactions and green chemistry principles in an introductory organic chemistry laboratory.	The research methodology involves the hydration of phenylacetylene using an acid gold(III) catalyst, with reaction monitoring through metallic gold precipitation, product extraction, and GC, IR, and NMR analysis, while emphasizing green chemistry principles and implemented within 2 hours without special equipment, and involves prediction and application of knowledge to other addition reactions in post-lab assignments.	Research shows that phenylacetylene hydration experiments using gold(III) and $H_2SO_{4\ catalysts}$ are effective in producing regioselective products such as acetophenone, with accurate identification via GC, IR, and NMR, and have succeeded in increasing students' understanding of alkyne chemistry and green chemistry principles, making it an ideal example for an introductory organic chemistry course.
(Lapanantnoppakhun et al., 2020)	This research aims to increase students' understanding of the impact of chemicals on health and the environment through the integration of toxicology and green chemistry in the curriculum, as well as deepening safety awareness, laboratory skills and critical thinking regarding chemical products.	The research methodology involves the development and implementation of an educational module by MoDRN that integrates toxicology and green chemistry in the curriculum, using SDS analysis and sunscreen testing to increase student understanding of the impacts of chemicals and facilitate active learning, critical discussion and safety awareness.	Research shows that MoDRN activities significantly improve students' understanding and behavior regarding chemical health, with 97% feeling laboratory experiments had a positive impact on health choices and 84% choosing zinc oxide-based sunscreens, while strengthening critical thinking skills in analyzing SDS and chemical hazards .
(Lin et al., 2023)	The aim of this research is to introduce a paper-based microfluidic device (μPAD) and iodometric titration as a laboratory experiment for prospective chemistry teachers, in order to stimulate interest in analytical chemistry, implement green chemistry education, and introduce microfluidic analysis in the secondary school curriculum.	The research method involves prospective chemistry teachers carrying out iodometric titrations on μPADs, writing experimental reports, designing experiments, and being evaluated based on their understanding of the principles and ability to design experiments.	The results showed that students achieved accurate analytical results and demonstrated a high awareness of the importance of reagent reduction in green chemistry education, with 84% recognizing its importance and 60% believing μPAD experiments are suitable for green chemistry education, with many willing to use them in their

Study	Aim	Methodology/ Sample	Findings
			classes in future.
(Harrypersad & Canal, 2023)	The aim of this research is to present a ruthenocene synthesis experiment that integrates green chemistry principles into the curriculum to increase students' understanding of complex inorganic chemistry and environmental awareness.	Research methods involve air-sensitive reactions, product purification by sublimation, ruthenocene analysis by IR, NMR, and MS, as well as comparison of experimental methods with those based on the 12 principles of green chemistry.	The results showed that students showed increased awareness of green chemistry, concluding that the ruthenocene synthesis method used was more environmentally friendly due to reduced waste and the use of safer solvents, and expressed a desire to apply green chemistry principles in their experiments.
(Amaris et al., 2017)	This research aims to introduce first year chemistry students to nanoscience through a green chemistry approach, with a focus on the synthesis, characterization, ecotoxicity testing of silver nanoparticles, as well as the relationship of chemical concepts to biology, materials science, and the environment.	This research uses a series of laboratory experiments for first-year chemistry students to introduce nanoscience through green chemistry.	The results showed that first-year chemistry students successfully synthesized, characterized, and evaluated the ecotoxicity of silver nanoparticles, as well as designed their own experiments with a Green Chemistry approach, which strengthened their understanding of experimental design, scientific processes, and the impact of silver nanomaterials in consumer products and the environment.
(Mooney et al., 2020)	This study aims to provide a green chemistry analysis of the environmental impact of a third year student's traditional organic chemistry synthesis of (E)-stilbene and to establish whether this impact can be minimized using alternative synthetic strategies, specifically Wittig-based methods.	The methodology involves a comparison of traditional methods and a Wittig-based one-pot synthesis in aqueous media via Life Cycle Analysis (LCA) as well as student participation in data collection, learning assessment, and efficiency and environmental impact analysis.	The results showed that the Wittig-based method had a significantly lower environmental impact, produced pure (E)-stilbene with consistent results, and improved students' understanding of green chemistry.

catalyst safe and effective For speed up reaction chemistry without sacrifice results or quality product end (Hie et al., 2015; Casio et al., 2020). This matter not only reduces the impact environment, but also saves source power and cost operational. Next, the next principle of green chemistry is to use a friendly solvent environment and materials chemistry is not poisonous. For example, use supercritical CO_2 as solvent in extraction compound organic, which is more friendly environment compared to solvent organic traditional (Cooper & Walser, 2019), using fluid ionic as solvent and catalyst, which are alternative friendly environment compared to with solvent more traditional dangerous (Verdia et a., 2017), replacing solvent poisonous with method synthesis organic help wave micro , which is alternative more friendly environmental and hazardous (Mohan et al., 2020), use method transesterification help ultrasonic with oil vegetable as material raw, friendly environment and produce biodiesel with a little waste (Wang et al., 2020), and using water as solvent friendly alternative environment in experiment laboratory chemistry (Lu et al., 2017).

Besides that, implementation methods like the atomic economy had proven lower footsteps carbon from activity laboratories (Cooper et al., 2019; Sharma et al., 2022; Xiong et al., 2023). From the side safety, implementation of green chemistry is also successful in reducing risk accidents and exposure to substances dangerous for worker laboratories, creating an environment more work safe (Ritter & Abraham, 2022; Mohan et al., 2020; Liu et al., 2023). However, challenges in matter cost initiation and adaptation procedure new Still become necessary obstacles noticed in evaluation more continued (Ritter & Abraham, 2022). This suggests that although this approach has great potential, institutional support and professional development for faculty are critical to its success. Overall, the application of green chemistry provides impact significant and promising in increasing quality and safety practice laboratory chemistry.

Green chemistry principles in the chemistry laboratory towards understanding students' conceptual, practical skills and environmental awareness

The results of this review confirm the importance of integrating green chemistry principles in the chemistry laboratory curriculum. In practice, the application of green chemistry has been proven to not only improve understanding students' conceptual and practical skills but also instill a deep awareness of the environment in every chemical process. These findings are consistent with previous literature showing that active learning methods, such as green chemistry-based projects, are more effective in building the deep understanding and technical skills required by students to operate in the world of modern chemistry.

Based on the results of the literature review, several references show that the application of green chemistry principles in chemistry laboratories has succeeded in increasing students' conceptual understanding. For example, research by Harrypersad & Canal (2023) shows that the integration of green chemistry principles in the complex inorganic chemistry curriculum succeeded in increasing students' awareness of the importance of reducing waste and using safer solvents, which ultimately increased their understanding of green chemistry. In addition, research by Amaris et al. (2017) also found that this approach strengthened first-year students' understanding of experimental design and scientific processes, especially in the context of the impact of nanomaterials on the environment.

The results of the analysis of several references in the literature review show that the application of green chemistry principles in chemistry laboratories has an impact on improving students' practical skills. Like, research by Xiong et al. (2023) aims to provide students with practical training in green organic electrochemistry, where they learn to compare traditional bromination and electrochemical methods with a focus on sustainability and green chemistry principles. Students are involved in laboratory experiments that include practical techniques such as thin layer chromatography (TLC), vacuum filtration, and solvent extraction, focusing on developing practical skills while introducing the concept of green chemistry (Pfab et al., 2019). In addition, other assessments also emphasize mechanochemistry- based laboratory experiments and solvent-free synthetic methods, which enable students to improve their practical skills in applying green chemistry principles (Bru et al., 2023). Other research also corroborates that first-year chemistry students who are introduced to nanoscience through laboratory experiments involving synthesis and ecotoxicity testing nanoparticles, can strengthen their practical skills in designing experiments with a green chemistry approach (Amaris et al., 2017).

The impact of applying green chemistry principles in chemistry laboratories on students' environmental awareness. Research that has been carried out has succeeded in proving that the application of green chemistry can increase students' environmental awareness. For example, research conducted by Harrypersad & Canal (2023) states that the synthesis method used is more environmentally friendly and increases student awareness of the importance of reducing waste and using safer solvents. Other research shows that students successfully designed their own experiments with a green chemistry approach, which strengthened their understanding of the impact of silver nanomaterials on the environment (Amaris et al., 2017), and nanotechnology and environmental remediation (Sharma et al., 2019). Additionally, there has been increased student awareness of the importance of green chemistry impact protocols and safe and sustainable experimental design (Knutson et al., 2017; Quinson, 2023). Students also gain a comprehensive understanding of sustainability aspects and positive impacts on the UN Sustainable Development Goals (SDGs) (Reyes et al., 2023).

Overall, the results of this study provide a strong foundation for expanding the application of green chemistry learning in chemistry education, with a focus on improving students' conceptual understanding, practical skills and environmental awareness. With the right approach, green chemistry can be an effective tool in shaping students' skills and awareness, while preparing them for future sustainability challenges. In addition, further research is needed to explore optimal ways of integrating green chemistry into a variety of different scientific disciplines and educational contexts.

Conclusion

This study underlines the importance of integrating green chemistry principles in chemistry education. Findings from the literature review indicate that the green chemistry approach significantly improves conceptual understanding, practical

skills, and environmental awareness. Application of green chemistry principles not only enriches students' learning experiences but also prepares them for future sustainability challenges. However, challenges such as limited resources and the need for additional training for lecturers must be addressed to ensure successful implementation. Institutional support and professional development are key to overcoming these challenges. Overall, the integration of green chemistry in the chemistry curriculum has great potential to form a generation of chemists who are more environmentally responsible and better prepared to face the challenges of sustainability. Effective implementation can advance chemistry education by providing students with relevant practical skills and increasing their awareness of the environmental impacts of chemistry practice.

Conflict of Interests

The author declares that there is no conflict of interest in this research and manuscript.

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