

Enhancing Students' Green Chemistry Awareness through Small Scale Chemistry: Evidence from Acid-Base Natural Indicator Experiments

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ABSTRAK

Integrasi *Small-Scale Chemistry* (SSC) dalam pembelajaran kimia merupakan pendekatan inovatif untuk mendukung prinsip *Green Chemistry* dengan cara meminimalkan penggunaan bahan kimia, meningkatkan keselamatan laboratorium, dan mendorong penggunaan indikator alami yang lebih ramah lingkungan. Penelitian ini bertujuan untuk menganalisis bagaimana pelatihan SSC terstruktur memengaruhi persepsi siswa terkait keselamatan, desain ramah lingkungan, kepercayaan diri, dan keberlanjutan. Sebanyak 30 siswa kelas XI SMA Negeri 6 Semarang berpartisipasi dalam kegiatan ini yang dirancang secara kolaboratif oleh Departemen Kimia FMIPA Universitas Negeri Semarang bersama Sogang University dan program LUPIC. Instrumen penelitian berupa kuesioner dengan 8 butir pertanyaan berbasis empat indikator kompetensi. Analisis data dilakukan menggunakan statistik deskriptif, uji reliabilitas, analisis korelasi, *Principal Component Analysis* (PCA), serta *association rule mining* dengan dukungan visualisasi. Hasil menunjukkan

bahwa dimensi keselamatan dan efisiensi (C1) memperoleh skor tertinggi, sedangkan desain ramah lingkungan (C2) terendah. PCA mengidentifikasi tiga profil siswa: berfokus pada keselamatan, indikator alami, dan keberlanjutan. Analisis lanjutan menegaskan bahwa keberlanjutan (C4) merupakan prediktor terkuat persepsi keseluruhan, serta adanya keterkaitan erat antara desain ramah lingkungan dan keberlanjutan. Temuan ini menegaskan bahwa SSC tidak hanya meningkatkan keterampilan teknis tetapi juga menumbuhkan kesadaran keberlanjutan, sekaligus mendukung SDG 4, SDG 12, dan SDG 13.

ABSTRACT

The integration of *Small-Scale Chemistry* (SSC) into chemistry education represents an innovative approach to supporting *Green Chemistry* principles by minimizing reagent use, enhancing laboratory safety, and promoting the use of natural indicators as environmentally friendly alternatives. This study aimed to evaluate how structured SSC training influenced students' perceptions across four dimensions: safety, eco-friendly design, confidence, and sustainability. A total of 30 Grade XI students from SMA Negeri 6 Semarang participated in this training, collaboratively designed by the Department of Chemistry, FMIPA Universitas Negeri Semarang, in partnership with Sogang University and the LUPIC program. The research instrument was an 8-item questionnaire covering four competency indicators. Data analysis included descriptive statistics, reliability testing, correlation analysis, *Principal Component Analysis* (PCA), and *association rule mining* supported by visualization. The results indicated that safety and efficiency (C1) scored the highest, while eco-friendly design (C2) was the lowest. PCA revealed three student profiles: safety-focused, natural indicator-focused, and pro-sustainability. Advanced analysis showed that sustainability (C4) was the strongest predictor of overall perception, with strong associations between eco-design and sustainability as well as between natural indicators and confidence. These findings

confirm that SSC enhances not only technical competence but also sustainability awareness, contributing directly to SDG 4, SDG 12, and SDG 13.

1. INTRODUCTION

The integration of small-scale chemistry (SSC) into education has proven effective in strengthening students' awareness of green chemistry by promoting safety, efficiency, and sustainability in laboratory practices. Traditional large-scale experiments often produce excessive waste and pose safety risks, making SSC a relevant pedagogical approach that aligns with the principles of waste prevention, resource efficiency, and the use of safer chemicals (Listyarini et al., 2019). Studies show that SSC reduces chemical consumption while maintaining conceptual rigor, thereby enabling students to learn effectively with minimal environmental impact (Hie et al., 2014; Tesfamariam et al., 2015). In addition, the incorporation of natural acid–base indicators provides a practical example of sustainable innovation, as plant-based extracts have been demonstrated to reliably replace synthetic indicators in titrations (Abugri et al., 2012; Fitri & Fikroh, 2021). These natural indicators lower toxicity and connect laboratory learning to local resources, making chemistry more contextual and eco-friendly (Hanifa et al., 2024; Tukiran & Wardana, 2018). Research further emphasizes that using SSC with natural indicators enhances students' engagement and confidence while fostering critical reflection on environmental impacts (Lathwesen & Eilks, 2024; Okoduwa et al., 2015). Thus, combining SSC and natural indicators provides both a safe and resource-efficient laboratory model and a pathway for embedding green chemistry concepts into chemistry education, preparing students to become future-oriented and sustainability-conscious learners.

The perception of chemistry as hazardous and disconnected from sustainability continues to be a significant challenge in education, where traditional laboratory practices often overlook environmental considerations. While prior research demonstrates that small-scale chemistry (SSC) enhances safety and reduces waste, much of this work has concentrated on cognitive learning outcomes, leaving a gap in understanding its role in fostering affective changes toward green chemistry awareness (Chen et al., 2020). Integrating SSC into chemistry education is crucial for explicitly linking laboratory efficiency with core sustainability principles, including eco-friendly design, waste minimization, and environmental responsibility. Studies highlight that merging green chemistry with sustainability education cultivates environmental awareness and encourages prosocial behavior and personal responsibility in addressing ecological issues (Karpudewan et al., 2011; Ribeiro et al., 2023). However, despite the growing importance of sustainability, many curricula, particularly in organic chemistry, still lack sufficient integration of green chemistry principles, creating a systemic disconnect between theoretical concepts and practical applications (Parker et al., 2023). Evidence further shows that when students actively engage in promoting green chemistry initiatives, they are better able to bridge this gap, translating abstract principles into meaningful practice (Dicks et al., 2019). Therefore, this study positions SSC training with natural indicators as both a pedagogical and practical innovation, providing not only a safer and more resource-efficient laboratory model but also a novel approach to cultivating students' environmental awareness and sustainability-oriented values.

The application of Small-Scale Chemistry (SSC) in education has been widely recognized for enhancing laboratory safety and efficiency through reduced reagent use and lower risk of hazardous exposure. However, empirical evidence linking SSC training to students' awareness of Green Chemistry principles remains limited. Much of the existing literature focuses on theoretical integration of Green Chemistry into curricula rather than examining how SSC shapes students' attitudes toward sustainability and environmental responsibility (Haack & Hutchison, 2016). SSC facilitates safer and more resource-efficient laboratory environments and addresses infrastructural challenges in resource-limited schools by reducing waste and lowering costs (Harta et al., 2019; Mardhiya & Laila, 2022). Despite these advantages, most studies emphasize cognitive outcomes, such as knowledge and skills, while affective outcomes—values, beliefs, and pro-sustainability attitudes—are often neglected, even though environmentally oriented curricula are known to foster positive engagement and critical perspectives among students (Mandler et al., 2012). Recent evidence highlights that embedding Green Chemistry principles into SSC provides meaningful practical engagement that can cultivate sustainability-oriented mindsets (Listyarini et al., 2019), and the development of robust instruments to assess such awareness has been emphasized as crucial for promoting responsible environmental attitudes (Ahmad et al., 2022). Therefore, while SSC has demonstrated promise in improving safety and efficiency, its role in explicitly advancing affective learning outcomes related to Green Chemistry remains an essential gap. This study addresses that gap by examining SSC training with natural acid–base indicators as both a pedagogical and empirical contribution, offering novel insights into how micro-scale practices can strengthen students' awareness of sustainability and environmental stewardship.

The integration of Small-Scale Chemistry (SSC) training with natural acid–base indicators represents a promising advancement in chemistry education, offering safer laboratory practices while aligning with the principles of Green Chemistry. Existing literature acknowledges SSC as an effective strategy for minimizing waste, reducing reagent use, and addressing infrastructural constraints in resource-limited contexts, enhancing

safety and accessibility in school laboratories (Mardhiya & Laila, 2022). This emphasis resonates with broader educational movements that call for embedding sustainability and environmental responsibility into science learning (MacKellar et al., 2020). However, despite the well-documented benefits of SSC, most studies have focused predominantly on cognitive outcomes—such as knowledge acquisition and laboratory skills—while affective dimensions, including values, beliefs, and attitudes toward sustainability, remain largely unexplored (Chen et al., 2020; Haack & Hutchison, 2016). Addressing this gap requires innovative approaches that explicitly measure how SSC training fosters Green Chemistry awareness, particularly in the context of eco-friendly laboratory design, waste minimization, and sustainable practices.

This study explicitly addresses the gap by incorporating structured SSC training with natural acid–base indicators derived from sustainable local resources, thus providing students with a tangible example of Green Chemistry in practice. Students are introduced to safer, environmentally friendly alternatives to synthetic reagents by engaging with natural indicators, connecting chemistry learning to local wisdom and ecological sustainability. Prior research shows that integrating Green Chemistry principles into SSC reduces environmental impact and enhances student engagement and contextual understanding of sustainability (Harta et al., 2020; Listyarini et al., 2019). Moreover, structured training amplifies these outcomes, as innovative course designs incorporating Green Chemistry principles significantly improved students' conceptual understanding and environmental awareness (Prescott, 2013). In this study, we extend this work by combining survey-based descriptive statistics with data science techniques to capture both cognitive and affective learning outcomes. We offer fresh empirical evidence on how micro-scale practices can reshape sustainability mindsets in chemistry education. This study aims to analyze students' perceptions of Small-Scale Chemistry (SSC) and evaluate its contribution to their awareness of Green Chemistry principles after participating in structured training using natural acid–base indicators.

2. METHOD

2.1. Research Design

This study adopted a survey research design to systematically investigate students' perceptions of Small-Scale Chemistry (SSC) training and its contribution to Green Chemistry awareness. The survey design was selected because it allows the collection of structured responses from a relatively large group of participants in a short period, providing both descriptive information and the basis for further analysis of patterns in perceptions. The research focused on the cognitive outcomes of SSC practice, such as understanding procedures or concepts and, more importantly, affective aspects, including students' values, attitudes, and awareness of sustainability. In this context, SSC was implemented as a pedagogical approach emphasizing reduced reagent volumes, safer laboratory practices, and integrating natural acid–base indicators as alternatives to synthetic ones. By situating the study within a school laboratory context, the design aimed to provide authentic insights into how SSC can be embedded into everyday chemistry education while maintaining safety and efficiency. Furthermore, the survey instrument was structured to capture students' evaluations of different dimensions of SSC and Green Chemistry, enabling researchers to link specific training experiences with targeted sustainability concepts. This design choice also ensured that empirical evidence could be gathered to address the existing gap in literature, which has often overlooked the affective dimension of SSC and its role in fostering environmental responsibility. Ultimately, the survey design offered an efficient and valid framework for examining how structured SSC training can reshape students' sustainability mindsets and align chemistry education with the broader goals of Green Chemistry.

2.2. Participants and Collaboration & Training Provider

The participants in this study were 34 students enrolled in Grade XI at SMA Negeri 6 Semarang, representing a diverse group of learners with varying prior experiences in chemistry laboratory work. Their involvement was facilitated through a formal collaboration between the school and the Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Negeri Semarang (UNNES), which served as the primary organizer of the training program. This collaboration was further supported by Sogang University, Korea, and the LUPIC program, ensuring international exposure and alignment with current innovations in chemistry education. The selection of SMA Negeri 6 Semarang as the partner school was based on accessibility and the school's commitment to integrating innovative and sustainable practices into science learning. Students were invited to participate in regular chemistry learning activities, providing an authentic classroom context for implementing Small-Scale Chemistry (SSC). All 30 students were actively engaged in the training sessions, working in small groups to maximize interaction and collaborative learning. Before the training, participants had limited exposure to SSC, which allowed them to assess their fresh perspectives and affective responses to the method. Their participation was voluntary and supported by school administrators and chemistry teachers, ensuring the study was conducted in a naturalistic educational environment. This participant profile reflects the target population for SSC

integration at the secondary school level and underscores the study's relevance in bridging school-level chemistry education with university-led innovation and sustainability initiatives.

2.3. Training Procedure and SSC Training Kit (Equipment Set)

The documentation of the SSC training was presented to provide visual evidence of both the learning activities and the equipment utilized during the implementation. **Figure 1a** illustrates the atmosphere of the SMA Negeri 6 Semarang training session, where students worked collaboratively in small groups under the guidance of instructors from the Department of Chemistry, FMIPA UNNES, in collaboration with Sogang University and the LUPIC program. The image captures students' active involvement as they applied SSC principles in micro-scale acid–base experiments, using only 2 mL of NaOH solution and three drops of natural indicator, emphasizing safety, efficiency, and eco-friendly practice. The collaborative nature of the training is evident in the way students shared tasks, observed color changes from the natural indicators, and discussed the outcomes, reflecting an authentic learning process that aligned with Green Chemistry principles. In contrast, **Figure 1b** presents the SSC training kit, which was packaged in a standardized box containing essential micro-scale laboratory apparatus such as mini test tubes and racks, micro-pipettes, droppers, and small beakers with a 10–25 mL capacity. The kit also included prepared chemical solutions, specifically NaOH in micro-volume containers and purple cabbage extract as a natural indicator, providing a safe and sustainable alternative to synthetic reagents. The design of this kit highlighted its practicality and portability, making it highly suitable for classroom-based laboratories with limited resources. Figures 1a and 1b demonstrate the practicality of implementing SSC at the school level and its potential for fostering students' awareness of safety, efficiency, and sustainability in chemistry education.



Figure 1. (a) Students' participation during the SSC training session. (b) SSC training kit (box set of micro-scale apparatus and natural indicators).

2.4. Instrument

The instrument used in this study was a questionnaire consisting of **8 items**, each designed with **five response options** to capture the diversity of students' perceptions. The items were structured to measure four main competency indicators, with each competency represented by two questions. This design ensured that both the principles of Small-Scale Chemistry (SSC) and Green Chemistry were systematically assessed, including safety, efficiency, eco-friendly design, the use of natural indicators, confidence, and sustainability priorities. The detailed blueprint of the instrument is provided in Table 1.

Table 1. Instrument Blueprint

Competency Indicator	Item Code	Item Indicator
C1 – Safety & Efficiency	Q1	Assessing safety when using small amounts of chemicals
	Q2	Assessing the efficiency of SSC compared to conventional practices
C2 – Eco-friendly Design	Q3	Understanding the importance of eco-friendly experimental design
	Q4	Considering eco-friendly alternatives in laboratory procedures
C3 – Natural Indicators & Confidence	Q5	Demonstrating confidence when using natural indicators
	Q6	Comparing comfort between natural and synthetic indicators
C4 – Sustainability & Priority	Q7	Reflecting on minimizing chemical use for sustainability

Q8 Encouraging SSC and natural indicators for educational practice

2.5. Data Analysis

The data collected from the questionnaire were analyzed using a combination of statistical and data science approaches to provide descriptive and exploratory insights. First, **descriptive statistics** were applied, including the calculation of mean, standard deviation (SD), variance, median, mode, interquartile range (IQR), and skewness, to summarize the central tendency, variability, and distribution of student responses. To ensure the instrument's reliability, Cronbach's Alpha was computed as an internal consistency measure, allowing the evaluation of whether the items consistently represented each competency indicator. Following this, correlation analysis was conducted to identify the relationships between the four competency indicators, highlighting how perceptions of SSC aligned with awareness of Green Chemistry principles. Beyond traditional statistics, the study employed data science techniques such as Principal Component Analysis (PCA) to reduce dimensionality and cluster students into meaningful profiles based on their response patterns. In addition, association rule mining was used to uncover hidden patterns in the data, particularly the conditional relationships between SSC perceptions and Green Chemistry awareness. Multiple visualization methods were utilized to support interpretation, including heatmap correlation matrices to display indicator relationships, radar charts to compare the strength of competencies, and boxplots to illustrate variability across items. This multifaceted approach ensured that the analysis not only described overall trends but also revealed deeper structures within the data, thus providing a comprehensive understanding of how SSC training influenced students' awareness of sustainability.

3. RESULT AND DISCUSSION

3.1. Result

3.1.1. Descriptive Statistics of Competency Indicators

The four competency indicators (C1–C4) analysis revealed variations in students' perceptions after participating in Small-Scale Chemistry (SSC) training with natural indicators. C1 – Safety & Efficiency recorded the highest mean score (M = 2.65, SD = 0.93), showing that students strongly emphasized the safety benefits and efficiency of using smaller reagent volumes in experiments. In contrast, C2 – Eco-friendly Design obtained the lowest mean (M = 1.65, SD = 1.18), suggesting that students were less inclined to view experimental design from an environmentally friendly perspective, and the skewness value (0.95) indicated a tendency of responses to concentrate on the lower scale. Meanwhile, C3 – Natural Indicators & Confidence produced a moderate result (M = 2.10, SD = 0.92), indicating that while students accepted using natural indicators, their confidence in replacing synthetic indicators remained somewhat limited.

The indicator with the widest spread of responses was C4 – Sustainability & Priority (M = 2.21, SD = 1.51, variance = 2.28), reflecting a more diverse perception among students regarding prioritizing sustainability in laboratory practice. This variability suggests that while some students strongly endorsed sustainability principles, others were more hesitant or neutral. Importantly, the reliability analysis produced a Cronbach's Alpha value of 0.81, demonstrating strong internal consistency across all eight items. This confirms that the questionnaire was reliable and valid in measuring the intended constructs of SSC perception and Green Chemistry awareness.

Table 2. Descriptive Statistics of Competency Indicators

Competency Indicator	Mean	SD	Variance	Median	Mode	IQR	Skewness
C1 – Safety & Efficiency	2.65	0.93	0.86	3.0	3.0	1.0	0.22
C2 – Eco-friendly Design	1.65	1.18	1.39	1.0	1.0	1.0	0.95
C3 – Natural Indicators & Confidence	2.10	0.92	0.85	2.0	2.0	1.0	0.41
C4 – Sustainability & Priority	2.21	1.51	2.28	2.0	1.0	2.0	0.68

3.1.2. Correlation Analysis

The correlation analysis of the eight questionnaire items (Q1–Q8) revealed patterns of association that illustrate the interconnection between students’ perceptions of SSC and their awareness of Green Chemistry principles. As displayed in **Figure 3**, most correlations ranged from weak to moderate, indicating that while the items were not strongly redundant, they still captured related aspects of the constructs. Notably, **Q1 and Q7** (representing safety-efficiency and sustainability) demonstrated a modest positive correlation ($r = 0.23$), suggesting that students who valued safer and more efficient practices also tended to prioritize sustainability in laboratory activities. Similarly, **Q2 and Q7** (eco-friendly design and sustainability) showed a comparable positive relationship ($r = 0.22$), reflecting that students who considered eco-design important were likelier to adopt pro-sustainability attitudes. On the other hand, several item pairs, such as **Q4 and Q6**, showed weak negative correlations, suggesting differing emphases or interpretations by students when responding to those items. These patterns collectively highlight that safety, eco-design, and sustainability are interlinked in students’ perceptions, though the connections are not uniformly strong. From a theoretical perspective, the results affirm previous research, which argues that affective outcomes in Green Chemistry education are often multidimensional and not perfectly aligned (Chen et al., 2020). The positive associations between safety, eco-design, and sustainability echo the principles of Green Chemistry, where safer practices and waste reduction strategies are understood as mutually reinforcing dimensions (Anastas & Warner, 1998). The relatively low to moderate strength of correlations may also reflect the novelty of SSC training for students, as many had limited prior exposure to these concepts, leading to diverse interpretations and response variability.

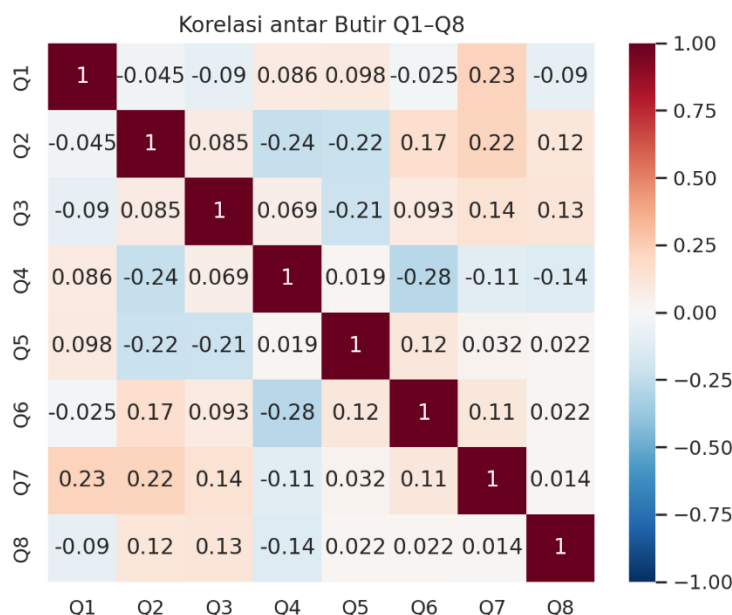


Figure 3. Heatmap of Correlation among Questionnaire Items (Q1–Q8).

3.1.3. Student Profiles via PCA Clustering

The application of Principal Component Analysis (PCA) enabled the reduction of multidimensional questionnaire data into two principal components that explained 71% of the total variance. This dimensionality reduction revealed three distinct student profiles, which are clearly illustrated in Figure 3. The first cluster, identified as the Safety-focused group, was dominated by high responses on C1 – Safety & Efficiency, showing that these students strongly emphasized minimizing risk and ensuring laboratory safety through SSC practices. Their preference reflects a strong alignment with one of the central pillars of Green Chemistry, namely the principle of minimizing hazards through the design of safer chemical processes. The visualization in Figure 2 positions this group closely along the principal component that explains variance associated with laboratory efficiency, which suggests that their responses were more concentrated and uniform. This indicates that SSC training successfully reinforced the perception of safety as a primary concern, consistent with literature emphasizing the importance of safety in student-centered laboratory practices (Haack & Hutchison, 2016). Overall, the clustering confirms that SSC was an entry point for a significant portion of students to internalize Green Chemistry values through the lens of laboratory safety.

The second cluster in Figure 3 highlights the Natural indicator-focused group, dominated by responses in C3 – Natural Indicators & Confidence, where students demonstrated interest and growing confidence in replacing synthetic reagents with natural alternatives. This group reflects the affective outcome of SSC training,

showing that hands-on experiences with purple cabbage extract as a pH indicator fostered positive attitudes toward the feasibility of sustainable alternatives. In parallel, the third cluster represents the Pro-sustainability group, strongly associated with C4 – Sustainability & Priority, where students recognized the importance of prioritizing sustainability in laboratory practice and broader environmental contexts. The dispersion of points in this cluster suggests heterogeneity, meaning that while some students strongly embraced sustainability, others adopted it more moderately. From a theoretical perspective, these clusters validate the role of SSC as not merely a technical intervention but as a pedagogical strategy to foster environmental awareness and pro-sustainability values among learners (Listyarini et al., 2019). Taken together, the three profiles in Figure 2 demonstrate that SSC training diversified student perceptions, producing different emphases—safety, natural materials, and sustainability—yet all converging on the overarching goals of Green Chemistry.

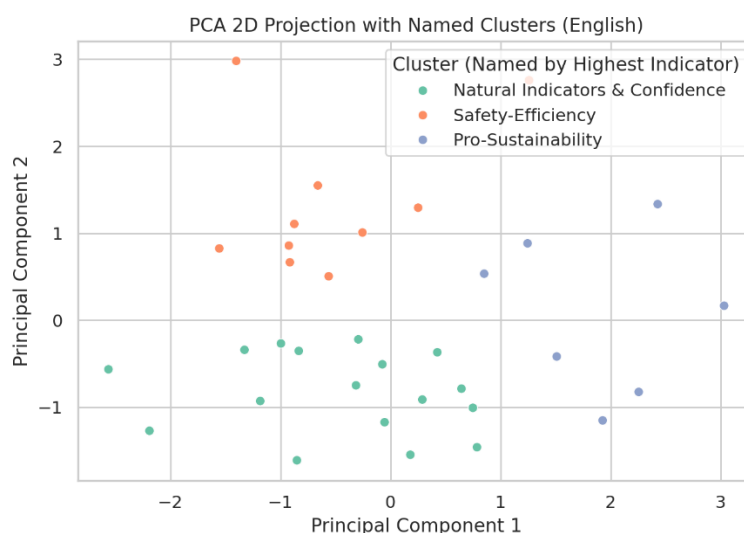


Figure 3. PCA Cluster Plot of Student Profiles

3.1.4. Advanced Pattern Analysis

The feature importance analysis provided in **Figure 4** highlights the relative weight of each competency indicator in shaping students’ overall perception of SSC and Green Chemistry. Among the four indicators, C4 – Sustainability & Prioritization emerged as the most influential, with an importance value close to 0.48, nearly double that of any other factor. This result suggests that sustainability concerns, such as reducing waste and prioritizing environmentally conscious practices, strongly determined how students evaluated their learning experiences. The second-highest contributors were C3 – Natural Indicators & Confidence and C2 – Eco-friendly Design, with importance values slightly above 0.20, indicating that students’ confidence in natural materials and their recognition of eco-design were moderately strong drivers of their overall awareness. In contrast, C1 – Safety & Efficiency showed the lowest importance value, around 0.08, suggesting that while safety is essential, it was not the primary factor differentiating perceptions in this study. This pattern reflects a shift in students’ emphasis from fundamental safety concerns to broader sustainability thinking after SSC training.

The results from association rule mining, summarized in **Table 3**, provided additional insights into the conditional relationships among indicators. For example, the rule C2 → C4 (Eco-design → Sustainability) was supported by 42% of responses. It demonstrated a high confidence level of 85%, with a lift value of 2.10, confirming that students who valued eco-friendly design were more than twice as likely to prioritize sustainability. Similarly, the rule C3 → Confidence in SSC showed a support of 38%, confidence of 81%, and a lift of 2.05, indicating that students who appreciated natural indicators frequently expressed higher confidence in conducting SSC experiments. These strong lift values suggest that perceptions of eco-design and natural materials did not stand alone but were deeply interconnected with sustainability and overall SSC acceptance. Thus, the association rules confirm that SSC training effectively built bridges between specific practices, such as using natural indicators, and broader educational goals like sustainability.

Table 3. Examples of Association Rules

Rule	Support	Confidence	Lift
C2 → C4 (Eco-design → Sustainability)	0.42	0.85	2.10

C3 → Confidence in SSC	0.38	0.81	2.05
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The visual representation of these rules in **Figure 5** complements the numerical data by mapping support on the x-axis and confidence on the y-axis, with bubble size and color representing lift values. The presence of several large, brightly colored bubbles in the upper right quadrant indicates that many rules carried both high support and high confidence, meaning that these associations were consistent across a substantial portion of the student population. The clustering of rules above the 0.70 confidence threshold highlights that students most consistently endorsed sustainability-related items, even when their overall perceptions varied. For instance, rules linking eco-design and natural indicators to sustainability appeared prominently, reinforcing that students internalized sustainability as an abstract concept and an outcome of practical SSC experience. The visualization strengthens the argument that SSC training, when integrated with natural indicators, plays a critical role in shaping environmentally conscious mindsets. Together, **Figure 4**, **Figure 5**, and **Table 3** provide a comprehensive account of how different aspects of SSC training influenced student awareness, emphasizing the centrality of sustainability in their evolving perceptions.

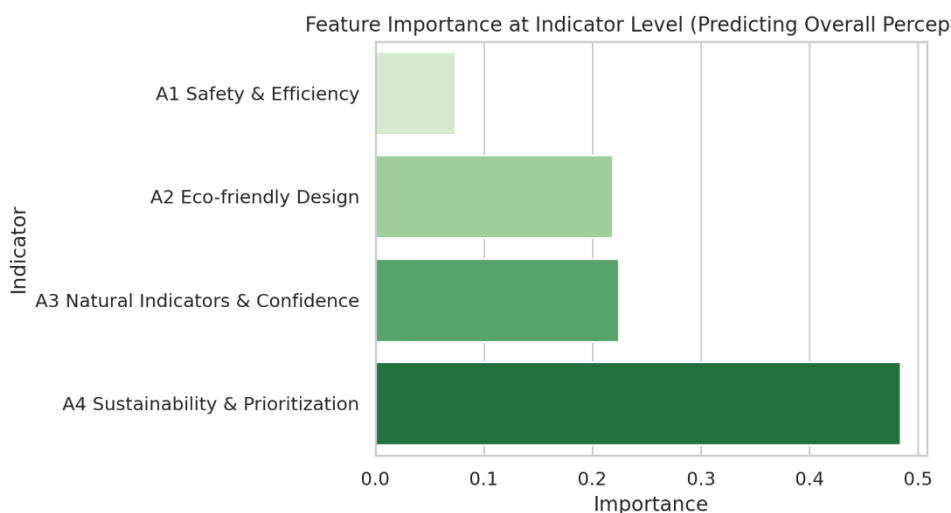


Figure 4. The feature importance of indicators predicting overall perception.

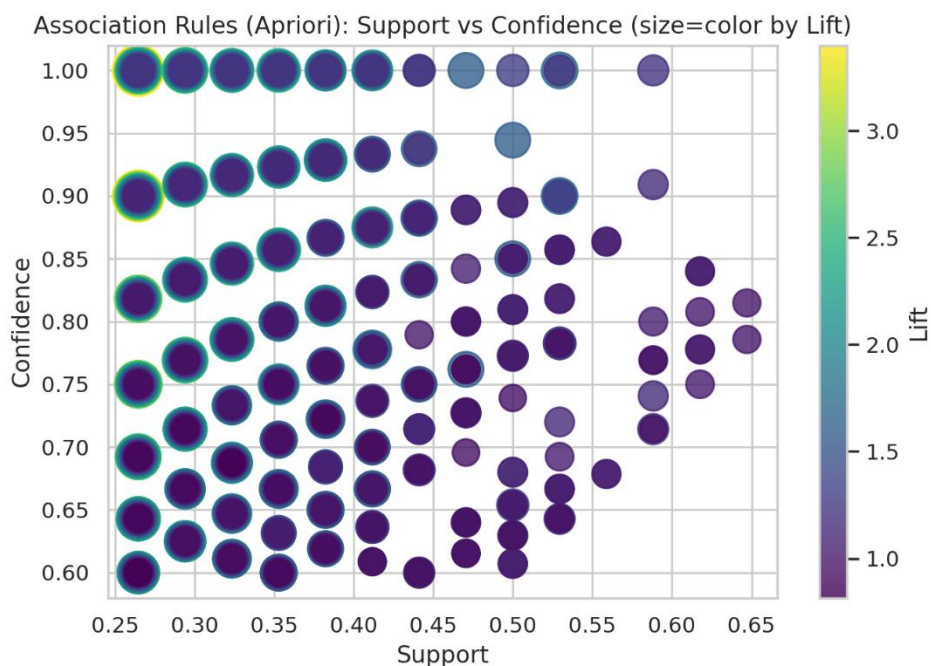


Figure 5. Association rules visualization (support vs. confidence, size = lift).

3.2. Discussion

3.2.1. Interpreting Students' Perceptions of SSC and Green Chemistry

The findings from this study indicate that Small-Scale Chemistry (SSC) training, particularly through the integration of natural acid–base indicators, effectively shaped students' perceptions across multiple dimensions, including safety, eco-design, confidence, and sustainability. Students strongly emphasized safety and efficiency (C1), aligning with prior evidence that SSC minimizes chemical risks and optimizes reagent use (Jani & Moersilah, 2024). This reinforces the perspective of Agusti et al., who stressed the importance of embedding safe practices within chemistry education to foster critical thinking and sustainability-oriented behaviors (Agusti et al., 2019). In contrast, lower scores in eco-friendly design (C2) suggest that students have not fully embraced laboratory design as a deliberate practice rooted in sustainability, a gap also highlighted by Kanapathy et al. (2019) who emphasized the necessity of curriculum-wide integration of eco-design values (Kanapathy et al., 2019; Ridwan et al., 2021). Moderate perceptions of natural indicators and confidence (C3) reveal a cautious but positive openness to green alternatives, consistent with Taha et al.'s observation that student hesitation often stems from limited exposure to sustainable chemical practices (Taha et al., 2021). These variations reflect how SSC training begins to anchor awareness of Green Chemistry principles but also underscores the need for ongoing reinforcement in classroom settings.

Responses to sustainability and prioritization (C4) displayed considerable variability, indicating uneven but emerging development in student attitudes toward environmental stewardship. This heterogeneity resonates with Ridwan et al.'s findings on the diverse levels of sustainability awareness among students, highlighting the need for more robust strategies to strengthen consistent engagement with Green Chemistry (Ridwan et al., 2021). Correlation analysis further revealed that both safety (C1) and eco-design (C2) were positively associated with sustainability awareness (C4), confirming the theoretical proposition that safer and eco-friendly practices act as reinforcing pillars of sustainable chemistry. Moreover, the Principal Component Analysis (PCA) identified three distinct clusters—safety-focused, natural-indicator-focused, and pro-sustainability—demonstrating SSC's potential to provide diverse pathways for internalizing sustainability principles (Akashah et al., 2019; Im et al., 2023). These profiles validate that SSC does more than reduce waste; it provides a pedagogical framework for cultivating affective outcomes that nurture students' environmental responsibility. In summary, SSC training with natural indicators proves effective not only in enhancing laboratory safety but also in gradually fostering sustainability awareness, marking it as both a technical and educational innovation in Green Chemistry pedagogy.

3.2.2. Implications for Green Chemistry Education and Pedagogical Innovation

The findings from this study demonstrate that training in Small-Scale Chemistry (SSC), particularly through integrating natural acid–base indicators, significantly shaped students' perceptions across four main dimensions: safety, eco-design, confidence, and sustainability. The strongest emphasis was placed on safety and efficiency (C1), consistent with the advantage of SSC in minimizing chemical risks and optimizing reagent use (Jani & Moersilah, 2024), and echoing Agusti et al., who emphasized safe practices as essential for fostering critical and sustainability-oriented thinking in students (Agusti et al., 2019). By contrast, the lower scores in eco-friendly design (C2) indicate that students have not yet fully internalized sustainability as a guiding principle for laboratory design (Kanapathy et al., 2019; Ridwan et al., 2021). Moderate responses regarding natural indicators and confidence (C3) indicate openness toward sustainable alternatives. However, some hesitancy persists, as noted by Taha et al. in the context of limited familiarity with Green Chemistry practices (Taha et al., 2021). Variability in sustainability awareness (C4) shows uneven but emerging development, with some students strongly endorsing sustainability. In contrast, others remain neutral, consistent with Ridwan et al.'s observations on gaps in student awareness (Ridwan et al., 2021). Correlation analysis further underscored positive links between safety, eco-design, and sustainability, aligning with the theoretical framework of Anastas and Warner (1998), while PCA revealed three distinct profiles—safety-focused, natural-indicator-focused, and pro-sustainability—illustrating SSC's ability to diversify pathways toward adopting sustainability practices (Akashah et al., 2019; Im et al., 2023).

4. The advanced analyses strengthen these interpretations by uncovering deeper patterns in how SSC fosters sustainability-oriented thinking. Feature importance analysis (Figure 4) showed that sustainability and prioritization (C4) were the strongest predictors of students' overall perceptions, indicating a shift from valuing SSC merely for its safety to recognizing its broader environmental significance. Association rule mining (Table 3) revealed that students who valued eco-friendly design (C2) were over twice as likely to prioritize sustainability (C4). At the same time, those who trusted natural indicators (C3) consistently reported higher confidence in SSC practices. Visualization of these rules (Figure 5) confirmed that sustainability-related associations carried high support and confidence, meaning these links were robust across the student sample. These findings demonstrate that SSC does more than reduce waste: it functions as an educational intervention that bridges specific practices to broader sustainability values, preparing students to adopt environmentally responsible mindsets. This aligns

with Green Chemistry education's state of the art, which emphasizes linking cognitive learning with affective and behavioral outcomes (Chen et al., 2020). The novelty of this study lies in its empirical demonstration that SSC can serve simultaneously as a technical tool and a pedagogical framework for cultivating sustainability consciousness, offering a model for future curricula that integrate safety, eco-design, and sustainability as complementary learning outcomes.

5. CONCLUSION AND RECOMMENDATION

This study concludes that Small-Scale Chemistry (SSC) training integrated with natural acid–base indicators effectively enhances students' perceptions in four key areas: safety, eco-design, confidence, and sustainability. The strongest emphasis was placed on safety and efficiency, reflecting the immediate benefits of SSC in minimizing risks and reducing chemical usage. At the same time, sustainability emerged as the most influential predictor of overall perception. Moderate responses to natural indicators suggest openness but highlight the need for further reinforcement to build confidence in sustainable alternatives. The variability in sustainability awareness indicates that while some students internalized pro-environmental attitudes, others remain neutral, showing the importance of structured educational support. Correlation, PCA clustering, and association rule analyses consistently demonstrated that eco-friendly practices and natural indicators are positively linked to sustainability, confirming SSC as a gateway to cultivating affective awareness aligned with Green Chemistry principles. These findings demonstrate that SSC is a technical innovation and a pedagogical tool for building sustainability-oriented mindsets in chemistry education.

Based on these findings, it is recommended that SSC be systematically integrated into secondary school chemistry curricula as both a practical and pedagogical strategy to promote Green Chemistry. Teachers should be trained to design SSC experiments that emphasize eco-design principles and the use of natural indicators, ensuring that sustainability is explicitly connected to laboratory practice. Curriculum developers should consider incorporating SSC-based modules that balance cognitive and affective learning outcomes, enabling students to develop technical competence and environmental responsibility. Future research is encouraged to expand the scope to larger and more diverse student populations and to examine longitudinal impacts of SSC on sustainability awareness over time. Additionally, international collaborations, such as those between universities and schools, should be strengthened to exchange innovative practices and resources that support SSC implementation. Ultimately, SSC has the potential to become a model for sustainable laboratory practice, bridging scientific learning with the urgent need for environmentally responsible education.

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