

 Research Article

# Impact of AI-Enhanced Training on Green Chemistry Understanding of Secondary School Chemistry Teachers

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## Abstract

Green chemistry education is increasingly recognised as essential for aligning chemistry instruction with Education for Sustainable Development goals, yet secondary chemistry teachers often lack adequate conceptual understanding and pedagogical strategies to integrate green chemistry principles into classroom practice. While artificial intelligence offers promising avenues for personalised teacher professional development, AI-enhanced training specifically targeting green chemistry competencies remains underexplored in Sub-Saharan African contexts. This study examined the impact of an AI-enhanced training programme on secondary school chemistry teachers' understanding of green chemistry principles and evaluated the effectiveness of a structured, need-based professional development intervention. A two-phase design was employed: Phase 1 used the ADDIE model to develop a training module delivered via an AI-powered Mini Course Generator platform, while Phase 2 implemented a single-group pre-test–post-test design with 43 chemistry teachers from Education District IV, Lagos State, Nigeria. Participants completed the Green Chemistry Understanding Test before and after a four-week self-paced intervention comprising three modules covering introduction to green chemistry, the twelve principles, and classroom integration strategies. The AI platform personalised learning pathways, generated contextualised materials, and provided automated feedback. Results showed statistically significant improvement from pre-test ( $M = 9.58$ ,  $SD = 2.95$ ) to post-test ( $M = 14.51$ ,  $SD = 3.21$ ),  $t(42) = -21.47$ ,  $p < .001$ , representing a 51% gain in understanding with a very large effect size (Cohen's  $d = 1.62$ ). The findings demonstrate that structured, AI-enhanced professional development can effectively address teachers' green chemistry knowledge gaps. Recommendations include scaling up AI-supported training across education districts, integrating green chemistry and AI literacy into pre-service and in-service teacher education curricula, and strengthening national curriculum frameworks to support sustainability-oriented chemistry instruction.

**Keywords:** AI-Enhanced Training, Green Chemistry, Teacher Professional Development, Secondary Education, Sustainability Education

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## 1. INTRODUCTION

Escalating environmental degradation and climate change have intensified calls to reorient school science toward sustainability and green chemistry. Green chemistry, defined as the design of chemical products and processes that reduce or eliminate hazardous substances, is now seen as a key pathway for aligning chemistry education with Education for Sustainable Development (ESD) (Basheer et al., 2025; Koulougliotis et al., 2024). A recent review of 70 studies shows that all 12 green chemistry principles have been meaningfully incorporated into secondary curricula worldwide, often via inquiry, problem, and socio-scientific issues (SSI) based approaches that link chemical concepts with issues such as hazardous waste, renewable feedstocks, recycling, and alternative energy (Koulougliotis et al., 2024). These interventions typically improve students' cognitive understanding of chemistry and their affective engagement with environmental issues (Koulougliotis et al., 2024; Okonkwo et al., 2024).

However, evidence indicates that teachers' own awareness and understanding of green chemistry and sustainability remain limited. Studies with pre-service and in-service science teachers report gaps in knowledge of green chemistry principles and restricted curricular coverage of sustainability topics, even when teachers express strong general support for environmental education (Basheer et al., 2025). Similar patterns appear in chemistry teacher education, where only a minority of pre-service chemistry teachers report high levels of understanding of AI and contemporary digital tools, and many lack confidence in integrating such tools into instruction (Harianti et al., 2025). These findings suggest that secondary chemistry teachers may be ill-equipped to design rich, context-based learning experiences that authentically embed green chemistry and ESD goals.

At the same time, artificial intelligence (AI) is rapidly reshaping education and teacher professional development. AI-supported tools can personalise learning, provide on-demand feedback, scaffold complex design tasks, and help teachers access and adapt digital resources (Shezad et al., 2025; Zhang & Zhang, 2024; Meylani, 2024). Systematic reviews and syntheses on AI in teacher education highlight that AI-driven analytics, intelligent tutoring systems, automated assessment, and generative tools can support individualised learning pathways, enhance reflective practice, and foster ongoing professional growth (Amdan et al., 2025; Meylani, 2024; Rissi et al., 2025; Tan et al., 2024; Zhang & Zhang, 2024). However, research also reveals enduring issues, such as algorithmic prejudice, data privacy, ethical issues, and teachers' lack of AI literacy and pedagogical comprehension (Harianti et al., 2025; Meylani, 2024; Shezad et al., 2025; Tan et al., 2024; Velander et al., 2023; Zhang & Zhang, 2024).

Importantly, the literature shows that most AI research in education focuses on student-facing applications, with comparatively little attention to AI for teacher professional development (Tan et al., 2024). A systematic review of 95 studies found that about two-thirds examine AI for teaching and learning (e.g., conversational agents, analytics, immersive technologies), while only one-third address AI's role in teachers' professional learning (Tan et al., 2024). Recent work specifically on AI training for teachers indicates that appropriately designed programs can improve teachers' digital skills, reduce anxiety, strengthen positive attitudes toward AI, and enhance their capacity to develop digital materials and integrate AI tools into instruction (Abdulayeva et al., 2025; Nazaretsky et al., 2022; Rissi et al., 2025; Tütüniş et al., 2025). Mixed methods and quasi-experimental studies document significant gains in AI literacy and in behavioural intention to adopt AI when training combines conceptual grounding with authentic, problem-based activities and explicit attention to ethics (Abdulayeva et al., 2025; Naseri & Abdullah, 2024; Tütüniş et al., 2025).

Despite these developments, AI-enhanced professional development explicitly targeting green chemistry understanding in secondary chemistry teachers has not been systematically investigated. Green chemistry integration at the secondary level is well documented from the perspective of curriculum and student outcomes (Koulougliotis et al., 2024; Okonkwo et al., 2024), and teacher-focused studies show that targeted interventions on sustainability and green chemistry can substantially increase awareness and positive attitudes (Basheer et al., 2025). Simultaneously, AI-focused professional development has shown promise in developing digital competencies, AI literacy, and preparedness to employ AI in topic teaching, including science and chemistry (Abdulayeva et al., 2025; Harianti et al., 2025; Meylani, 2024; Zhang & Zhang, 2024). However, the intersection, using AI-enhanced training as a vehicle to deepen teachers' conceptual and pedagogical understanding of green chemistry, remains a clear gap. Addressing this gap is critical because secondary chemistry teachers are key gatekeepers for embedding sustainability and green chemistry in everyday classroom practice and for shaping students' environmental agency (Basheer et al., 2025; Koulougliotis et al., 2024; Okonkwo et al., 2024).

The present study is grounded in an integrated framework that combines AI literacy and teacher professional learning, green chemistry and ESD, and technology adoption perspectives. First, the study draws on emerging conceptions of AI literacy for teachers, which encompass understanding how AI systems function, critically evaluating their outputs, and using them ethically and pedagogically in classroom and professional contexts (Abdulayeva et al., 2025; Harianti et al., 2025; Naseri & Abdullah, 2024; Velander et al., 2023). Research on AI literacy in K 12 and teacher education emphasises that teachers need not become AI engineers, but should develop sufficient technological, pedagogical, and content knowledge related to AI to design meaningful learning experiences and to scrutinise AI tools' limitations and biases (Abdulayeva et al., 2025; Gibson et al., 2023; Naseri & Abdullah, 2024; Velander et al., 2023). AI-enhanced professional development, in this view, positions teachers as active co-designers and critical users of AI,

rather than passive recipients of recommendations (Abdulayeva et al., 2025; Kim, 2023; Velander et al., 2023).

Second, the study is informed by green chemistry education within ESD. Green chemistry seeks to prevent pollution at source through principles such as atom economy, safer solvents, energy efficiency, and use of renewable feedstocks (Basheer et al., 2025; Koulouglotis et al., 2024; Laurensia, 2024). When embedded in secondary chemistry curricula, these principles help students connect abstract chemical concepts with socio-environmental issues, developing values and competencies aligned with sustainability (Basheer et al., 2025; Koulouglotis et al., 2024; Okonkwo et al., 2024). From a teacher learning perspective, professional development interventions that explicitly address green chemistry content, classroom applications, and curriculum links have been shown to increase teachers' awareness of green chemistry and sustainability significantly and to strengthen their attitudes toward environmental education (Basheer et al., 2025). This suggests that green chemistry can serve as a powerful thematic context for content-focused professional learning.

Third, the study is guided by technology acceptance and adoption frameworks, especially the Technology Acceptance Model (TAM) and its extensions as applied to AI in education (Naseri & Abdullah, 2024; Şimşek et al., 2025). Metacognitive self-regulation, learning motivation, and learning agility have a significant impact on perceived utility and ease of use, which in turn shape attitudes and behavioural intention to adopt AI, according to research with pre-service teachers using generative AI tools (Şimşek et al., 2025). Reviews of AI adoption frameworks in education underline the need to attend not only to cognitive evaluations of technology, but also to social and affective dimensions such as trust, anxiety, and perceived control (Lee & Bryan, 2025; Nazaretsky et al., 2022; Naseri & Abdullah, 2024). Studies on AI EdTech show that well-designed professional development, especially when it offers transparent explanations of AI decision making and opportunities for hands-on experimentation, can enhance teachers' trust and willingness to use AI tools in their classrooms (Lee & Bryan, 2025; Nazaretsky et al., 2022).

The study achieved its objectives by designing and implementing an AI-enhanced, need-based training module that directly targeted the documented gaps in secondary chemistry teachers' green chemistry knowledge and competencies.

### 1.1. Research Objectives

The specific objectives of the study were to:

1. Develop an AI-enhanced, need-based training programme (module) aimed at improving the green chemistry competencies of secondary school chemistry teachers.
2. Implement the developed module and assess its effectiveness in enhancing teachers' understanding of green chemistry principles.

### 1.2. Research Questions

1. How can an AI-enhanced, need-based training programme be designed to improve the green chemistry competencies of secondary school chemistry teachers?
2. To what extent does the implemented training module enhance secondary school chemistry teachers' understanding of green chemistry?

### 1.3. Hypothesis

There is no significant difference in green chemistry understanding of chemistry teachers before and after the training programme (intervention).

## 2. METHODOLOGY

### 2.1. Research Design

The study employed a two-phase research design to develop and assess the impact of an AI-enhanced training program on the chemistry teachers' understanding of Green Chemistry in Lagos State. Phase 1 involved instructional design and development using the ADDIE model, while Phase 2 used a single-group pre-test–post-test design with participants completing standardised assessments before and after the four-week intervention delivered through personalised sessions via an AI-powered Mini Course Generator app.

### 2.2. Population for the Study

The study targeted secondary school chemistry teachers in Lagos State, and the accessible population comprised chemistry teachers in Education District IV, Lagos State.

### 2.3. Sample and Sampling Technique

The study sample comprised 43 chemistry teachers from secondary schools in Education District IV, Lagos State. A two-stage purposive sampling method was used. First, Education District IV was selected from the six districts based on the researcher's access, administrative cooperation, and school proximity, which aided coordination and data collection. Second, at least one chemistry teacher from each of the 43 schools in the district was chosen. Where schools had multiple chemistry teachers, one was selected based on availability and willingness to join the professional development programme. This ensured all schools were represented while keeping data collection feasible.

The sample included 28 female teachers (65.1%) and 15 male teachers (34.9%), with teaching experience ranging from 2 to 24 years (average 8.7 years). Most teachers, 31 (72.1%), had a Bachelor's degree, while 12 (27.9%) had a Master's degree. All participants were from public schools. A large majority, 38 teachers (88.4%), had never received formal training in green chemistry principles, showing the need for this intervention.

### 2.4. Research Instrument

The research instrument was the Green Chemistry Understanding Test (GCUT), comprising 10 multiple-choice items on green chemistry principles, sustainable practices, and environmental applications. Items were adapted from an established Green Chemistry High School Test Questions Library developed by the American Chemical Society (ACS) to assess teachers' understanding. Each correct answer was awarded 2 marks, with scores ranging from 0 to 20.

The stimulus instrument was an AI-enhanced need-based training programme delivered via the Mini Course Generator app. Using artificial intelligence, the platform generated personalised learning paths based on each teacher's knowledge gaps, allowing progression only after satisfactory completion of each module. Teachers accessed the platform via links or QR codes provided during school visits, with the researcher offering navigation guidance and technical support. The platform was compatible with mobile phones, tablets, and computers. The training consisted of short modules completed at the teachers' own pace over four weeks (30–60 minutes daily).

#### 2.4.1. Validity of Green Chemistry Understanding Test (GCUT)

To establish the construct validity of the GCUT, a pilot study was conducted with a sample of 25 in-service chemistry teachers from non-participating institutions. An Exploratory Factor Analysis (EFA) was performed using Principal Axis Factoring (PAF) with oblique rotation to identify the underlying factor structure. The analysis confirmed that the GCUT items aligned with the fundamental domains of Green Chemistry understanding, which include:

1. Green Chemistry Principles: Knowledge of the 12 principles of green chemistry.

2. Sustainable Practices: Understanding of environmentally friendly chemical processes.
3. Environmental Applications: Application of green chemistry concepts in real-world scenarios.
4. Risk Assessment: Evaluation of chemical hazards and safer alternatives.

To confirm the suitability of the dataset for factor analysis, the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was found to be 0.76, indicating a meritorious level of factorability. Additionally, Bartlett's test of sphericity was significant ( $\chi^2 = 892.45$ ,  $df = 45$ ,  $p < 0.001$ ), confirming that the dataset was appropriate for factor analysis. Items with low factor loadings (below 0.40) were removed from the instrument to improve its validity.

#### 2.4.2. Reliability of Green Chemistry Understanding Test (GCUT)

The test-retest method was used to ensure the reliability of the GCUT. The test was administered to a group of 25 in-service chemistry teachers with a one-week interval between the first and second administrations. The internal consistency was measured using Kuder-Richardson 20 (KR-20), yielding a coefficient of 0.87 ( $p < 0.05$ ), indicating strong reliability.

#### 2.4.3. Validity of AI-Enhanced Need-Based Training Programme (Module)

Content validity of the training programme was established by ensuring its alignment with the Nigerian chemistry curriculum and Green Chemistry principles. The module was reviewed by an expert in science education and environmental chemistry, who assessed its clarity, relevance, and ability to enhance teachers' Green Chemistry understanding. Her recommendations were incorporated to refine the content, ensuring that the training programme effectively delivered both theoretical knowledge and practical application of sustainable chemistry principles.

### 2.5. Data Collection/Research Procedure

The procedure lasted six weeks: Week 1 for pre-test administration, Weeks 2–5 for training, and Week 6 for post-test administration, ensuring consistent implementation and individualised learning. The study was conducted in three phases:

#### Pre-Intervention Phase:

Week 1: This phase involved obtaining ethical approval and formal permissions from the appropriate educational authorities and school administrators within Education District IV of Lagos State. During this phase, the standardised GCUT was administered as a pre-test to all participating chemistry teachers to establish baseline data.

#### Intervention Phase:

Week 2: Upon scanning their personalised QR codes, teachers accessed the first module covering foundational concepts in green chemistry. They engaged with multimedia content, including an introductory video by Dr. Paul Anastas (Director, Yale Centre for Green Chemistry and Green Engineering) explaining green chemistry definitions, global significance, and alignment with Sustainable Development Goals. Teachers completed reading materials on core concepts before attempting Formative Quiz 1, which required a minimum passing score of 70% to unlock subsequent content. Upon completion, they submitted Course Feedback/Rating 1, evaluating content clarity and delivery quality.

Weeks 3–4: Teachers progressed to an in-depth exploration of all twelve green chemistry principles, supported by curated instructional videos from authoritative sources, including Yale University, the American Chemical Society, the University of Toronto, Green Chemistry Tool-Kit, and Cleva Force. Content included practical applications such as identifying safer laboratory alternatives, calculating atom economy, implementing waste management strategies, sourcing renewable feedstocks, and designing energy-efficient processes. Teachers analysed up-to-date case studies of successful industrial green chemistry initiatives and examined their applicability to Nigerian contexts. Each week concluded with Formative Quiz 2 (principle-focused assessment) and Course Feedback/Rating 2.

Week 5: The final module focused on practical implementation within the Nigerian secondary chemistry curriculum. Teachers viewed researcher-demonstrated video experiments, including (1) preparation of biodegradable plastic from cassava starch, and (2) natural indicators for acids and bases. They studied integration strategies for specific O-level topics —acids, bases, and salts; polymerisation; esterification; electrolysis; pollution; and reaction rates, and developed original lesson plans embedding green chemistry principles. Teachers were encouraged to physically replicate the demonstrated experiments and document their experiences through video recordings or written reflections shared on the platform. The module concluded with Formative Quiz 3, Course Feedback/Rating 3, a Final Module Quiz (ten-item summative assessment), and an Overall Course Rating.

Key features throughout the intervention: Self-paced progression allowed teachers to control their daily engagement (30–60 minutes recommended); mastery-based gating required satisfactory quiz completion before advancing to subsequent modules.

Post-Intervention Phase:

After the training programme, the GCUT was re-administered in randomised form as a post-test to assess changes in participants' understanding of green chemistry principles.

## 2.6. Method of Data Analysis

Data were analysed using the Statistical Package for the Social Sciences (SPSS, version 27.0). Descriptive statistics, including mean scores and standard deviations, were used to summarise teachers' performance in the pre-test and post-test. Paired sample t-tests were conducted to determine significant differences in teachers' understanding of green chemistry before and after the intervention, with  $\alpha = .05$  adopted as the level of statistical significance for all hypothesis tests. Effect size was calculated using Cohen's *d* to assess the practical significance of the observed changes. The magnitude of Cohen's *d* was interpreted using conventional criteria: small effect (0.20–0.49), medium effect (0.50–0.79), and large effect ( $\geq 0.80$ ) (Cohen, 1988).

## 2.7. Development of the AI-Enhanced Need-Based Training Programme (Module)

The AI-enhanced, need-based training programme was developed following the ADDIE instructional design model. The analysis phase was informed by findings from a previously published needs assessment of secondary school chemistry teachers in Education District IV, Lagos State (Owoyemi & Akinde, 2026). The identified gaps in teachers' understanding of green chemistry principles and challenges in classroom application guided the overall focus and scope of the training programme.

During the design phase, the training structure, learning objectives, and content sequencing were specified based on the identified needs. In the development phase, the content was organised into three main modules: introduction to green chemistry, principles of green chemistry, and integration of green chemistry into classroom practice. Artificial intelligence features embedded in the Mini Course Generator platform were used to generate contextualised learning materials, personalise learning pathways, and provide automated feedback, ensuring structured progression through the modules.

The implementation phase involved delivering the training programme over four weeks using a self-paced format. Participants engaged with instructional videos, interactive quizzes, practical demonstrations of selected green chemistry experiments, and classroom integration strategies aligned with the Nigerian secondary school chemistry curriculum.

In the evaluation phase, the training programme was reviewed by a science education and environmental chemistry expert to assess content clarity, curricular relevance, and alignment with green chemistry principles. Feedback from this review informed minor refinements to the module before full implementation. A detailed outline of the training modules and content structure is provided in Appendix A.

### 3. RESULTS

#### 3.1. Descriptive Analysis of Variables in the Study

Table 1 indicates that the implemented training programme led to substantial improvements in the green chemistry competencies of participating teachers. The mean score increased from the pre-test ( $M = 9.58$ ,  $SD = 2.95$ ) to the post-test ( $M = 14.51$ ,  $SD = 3.21$ ), demonstrating a notable enhancement in conceptual understanding. The range of scores expanded from 10 to 12, with upward shifts in both the minimum (4 to 8) and maximum (14 to 20) values, reflecting performance gains across the cohort. Although the standard deviation increased slightly, this likely reflects a broader distribution of higher post-test scores. Reductions in skewness and kurtosis values suggest a more symmetric and balanced score distribution following the intervention.

**Table 1.** Descriptive Analysis of Green Chemistry Teacher Understanding Before and After Intervention

Pretest (Before)		Posttest (After)	
Mean	9.581395	Mean	14.51163
Standard Error	0.44923	Standard Error	0.489505
Median	10	Median	14
Mode	8	Mode	14
Standard Deviation	2.945801	Standard Deviation	3.209896
Sample Variance	8.677741	Sample Variance	10.30343
Kurtosis	-1.22194	Kurtosis	-0.83002
Skewness	0.098519	Skewness	0.031733
Range	10	Range	12
Minimum	4	Minimum	8
Maximum	14	Maximum	20
Sum	412	Sum	624
Count	43	Count	43

#### 3.2. Analysis of Research Hypothesis

H0: There is no significant difference in green chemistry understanding of chemistry teachers before and after the training programme (intervention).

**Table 2.** T-Test Analysis of Teachers' Green Chemistry Understanding Before and After the Training Programme (Intervention)

Measure	Mean Difference	SD	SE	95% CI Lower	95% CI Upper	<i>t</i>	<i>df</i>	<i>p</i>	Cohen's <i>d</i>
Pre-Post	-4.93	1.51	0.23	-5.39	-4.47	-21.47	42	<.001	1.62

SD = standard deviation; SE = standard error; CI = confidence interval. Cohen's *d* was calculated using the pooled standard deviation.

Table 2 shows that the training programme substantially improved chemistry teachers' understanding of green chemistry. A paired-samples t-test indicated a significant increase from pre-test ( $M = 9.58$ ,  $SD = 2.95$ ) to post-test ( $M = 14.51$ ,  $SD = 3.21$ ),  $t(42) = -21.47$ ,  $p < .001$ . The effect size was very large (Cohen's  $d = 1.62$ , 95% CI [1.35, 1.89]), exceeding the threshold for large effects ( $\geq 0.80$ ), with a mean gain of 4.93 points (95% CI [4.47, 5.39]), representing a 51% improvement in conceptual understanding. The null hypothesis is therefore rejected, indicating that the training programme had a statistically significant and practically meaningful effect on teachers' green chemistry understanding.

### 4. DISCUSSION OF FINDINGS

The statistically significant gain of nearly five points (51% improvement) from pre to post test, with a very large effect size (Cohen's  $d = 1.62$ ), indicates a strong impact on teachers' green chemistry understanding. This magnitude is comparable to, or greater than, gains reported in other green chemistry interventions at secondary and higher education levels, where structured, conceptually focused designs also yielded substantial pre-post improvements in knowledge and application of green chemistry principles (Koulougliotis et al., 2024; Vaz et al., 2025; Vogelzang et al., 2020).

Studies with university students using problem-based or context-based green chemistry instruction similarly report marked improvements in recognising and justifying green chemistry principles, although some principles (e.g., atom economy, catalysis) remain conceptually demanding (Vaz et al., 2025). The current findings align with that pattern: a broad, statistically robust gain suggests that a targeted training design can overcome previously documented superficial or fragmented teacher understanding of green chemistry (Carangue et al., 2021; Ibrahim et al., 2025). In contrast to work showing that in-service and preservice teachers often have only limited or superficial knowledge of green chemistry and struggle to integrate it meaningfully into instruction (Carangue et al., 2021; Ibrahim et al., 2025), the large effect size here suggests that a focused professional development intervention can address this gap effectively.

The improvement also speaks directly to calls for systematic teacher capacity building in green chemistry. Research across Malaysia and the Philippines has shown inadequate teacher preparation, limited access to structured materials, and a lack of standardised modules as key barriers to implementation (Carangue et al., 2021; Ibrahim et al., 2025). By demonstrating substantial gains among Nigerian secondary school teachers within a relatively short, four-week intervention, this study provides empirical support for the proposition that well-designed professional development can quickly advance teacher competence in an area where baseline knowledge is typically low (Carangue et al., 2021; Ibrahim et al., 2025).

The ADDIE guided design of the training programme is consistent with established professional development models in green chemistry education. New York State's statewide programme, for example, used multi-day, hands-on workshops that introduced green chemistry principles, provided replacement experiments, and emphasised collaborative learning; long-term follow-up indicated continued use of green chemistry practices and sustained teacher engagement (Cannon et al., 2023). Similarly, the present module combined principled content (introduction and principles of green chemistry) with practice-oriented components (classroom integration and experiments), aligning content, pedagogy, and curriculum in ways that have been identified as critical for sustainable impact (Cannon et al., 2023; Koulougliotis et al., 2024; Vogelzang et al., 2020).

The needs assessment basis of the analysis phase responds to widely documented gaps. Mixed-method work on teachers' knowledge and competencies reports that teachers across rural and urban settings are generally aware of green chemistry but lack understanding of core principles and practical strategies for embedding them in lessons (Carangue et al., 2021; Ibrahim et al., 2025). By explicitly using a local needs assessment to set the focus and scope of the module, this study operationalises repeated recommendations for contextualised, needs-driven professional development and contributes an example from a Sub-Saharan African context, where empirical work on green chemistry teacher training is still sparse (Carangue et al., 2021; Ibrahim et al., 2025; Koulougliotis et al., 2024).

AI-enhanced professional development offers distinct advantages for addressing secondary chemistry teachers' knowledge gaps in green chemistry through its capacity for personalisation, adaptive scaffolding, and immediate feedback. Recent evidence indicates that AI-supported training systems can generate contextualised learning materials and personalise learning trajectories based on individual knowledge gaps, which is particularly critical for complex, interdisciplinary content such as green chemistry principles (Ding et al., 2024; Dogan et al., 2025). The Mini Course Generator platform employed in this study exemplifies this capability by using AI to diagnose participant understanding and adjust content delivery accordingly, ensuring that teachers progress through material at appropriate difficulty levels while receiving automated, targeted feedback. This aligns with findings from systematic reviews indicating that AI-enhanced professional development improves teacher self-efficacy, higher-order thinking, and technological-pedagogical content knowledge when implemented through structured, scaffolded approaches (Lu et al., 2024; Tan et al., 2024).

Additionally, AI tools enable the integration of domain-specific content, such as green chemistry experiments and curriculum alignment strategies, within flexible, self-paced formats that accommodate teachers' varying schedules and prior knowledge levels (Palencia et al., 2025; Yıldırım & Akcan, 2024). The substantial gains observed in this study suggest that when AI is embedded within a coherent instructional framework rather than deployed as an ad hoc resource, it can effectively bridge the documented gap between teachers' general awareness of sustainability concepts and their specific pedagogical competencies in green chemistry instruction.

A distinctive contribution of this study is the integration of AI-supported instructional design and delivery through the Mini Course Generator platform. Recent literature underscores AI's promise for enhancing science and chemistry education by generating contextualised materials, supporting problem solving, and enabling adaptive feedback (Almasri, 2024; Lee & Perret, 2022; Quang et al., 2025). Systematic reviews show that AI tools are increasingly used to design quizzes, analyse student performance, and personalise learning paths, often with positive effects on learning outcomes and engagement (Almasri, 2024). In teacher education specifically, AI-generated instructional videos and AI-supported resources have been found to improve self-efficacy, task performance, and knowledge retention among pre-service science teachers (Pellas, 2025), while blended AI/IoT-based training programmes for in-service STEM teachers in Vietnam report high satisfaction and increased confidence in classroom application (Thanh et al., 2025).

The present findings are consistent with this emerging evidence base. AI features were used to generate contextualised content, personalise learning trajectories, and provide automated feedback, which aligns with recommended uses of AI for differentiated instruction and timely scaffolding in professional development (Almasri, 2024; Lee & Perret, 2022; Thanh et al., 2025). At the same time, descriptive survey studies in chemistry education indicate that many teachers have low AI technological and pedagogical competence, particularly in African contexts, and report difficulty using AI for simulations, visualisations, or personalised learning experiences (Palencia et al., 2025). The strong learning gains observed in this study, therefore, contrast with the low competence baseline reported elsewhere and suggest that embedding AI within a structured pedagogical framework, rather than expecting teachers to appropriate tools independently, may be critical for realising AI's benefits (Alwakid et al., 2025; Feldman-Maggor et al., 2024; Harianti et al., 2025; Yıldırım & Akcan, 2024).

Moreover, position papers and empirical work highlight that effective AI integration depends on teachers' technological–pedagogical–content knowledge (TPACK) and AI literacy, including awareness of issues such as bias and over-reliance on AI outputs (Feldman-Maggor et al., 2024; Harianti et al., 2025; Yau et al., 2022; Yıldırım & Akcan, 2024). While the present study did not directly measure AI-related competencies, its design responds to calls for framework-guided AI-enhanced professional development by aligning AI use with specific learning objectives in green chemistry and embedding it within a coherent instructional sequence. This stands in contrast to descriptive studies where AI is used more ad hoc for lesson planning or task design without a strong pedagogical model (Almasri, 2024; Quang et al., 2025).

## 5. PRACTICAL IMPLICATIONS

The findings of this study carry significant implications for multiple stakeholders invested in advancing sustainable chemistry education and teacher professional development. For researchers, the study underscores the need for longitudinal investigations tracking the sustainability of knowledge gains and their translation into classroom practice over extended periods. Future studies should employ rigorous quasi-experimental or experimental designs with control groups to isolate the specific effects of AI-enhanced training, and extend this work to diverse geographical and institutional contexts to enhance generalisability. Mixed-methods approaches incorporating classroom observations, teacher interviews, and student outcome measures would provide deeper insight into the mechanisms through which AI-enhanced professional development influences pedagogical practice.

For educators, the results demonstrate that AI-powered platforms can effectively support self-paced, personalised professional learning in complex, interdisciplinary domains such as green chemistry. Teachers are encouraged to leverage such tools for just-in-time learning, utilising AI-generated feedback and adaptive pathways to address individual knowledge gaps. The study also highlights practical strategies for integrating green chemistry principles into existing curriculum topics, such as acids and bases, electrolysis, and polymerisation, without requiring a complete curriculum overhaul.

For school administrators, the findings support investment in technology infrastructure and professional development resources that enable AI-enhanced learning. Administrators should prioritise creating time and structural support for teacher participation in such programs and foster school-level communities of practice where teachers can share green chemistry resources and implementation experiences. Ensuring reliable internet connectivity and device access is essential for equitable participation.

For policymakers, the study provides empirical justification for scaling AI-enhanced professional development in green chemistry across education districts and states. Policymakers should work to ensure equitable distribution of technology resources, particularly in under-resourced contexts, and consider establishing incentive structures, such as certification or career progression pathways, that recognise teachers' engagement with sustainability-oriented professional development. Systemic integration of green chemistry into teacher evaluation and school accountability frameworks would further reinforce priority status.

For curriculum developers, the findings highlight the necessity of embedding green chemistry principles explicitly within national and state chemistry syllabi, rather than treating sustainability as peripheral or optional content. Developers should create context-appropriate instructional materials that align green chemistry concepts with local environmental challenges and available resources. Additionally, assessment frameworks should be revised to include sustainability-oriented learning outcomes, thereby creating curricular alignment between intended, implemented, and assessed dimensions of green chemistry education.

## 6. LIMITATIONS OF THE STUDY

This study was conducted within a single education district (Education District IV) in Lagos State, which may limit the generalisability of the findings to other districts with different demographic or institutional characteristics. The sample size was relatively small, comprising 43 chemistry teachers, which could affect the extent to which the results represent the wider population of secondary school chemistry teachers in Nigeria. Additionally, the study adopted a single-group pre-test–post-test design without a control group, making it difficult to attribute observed improvements solely to the intervention without accounting for potential external influences. These limitations should be taken into account when interpreting the findings and considering their applicability to broader educational contexts.

## 7. RECOMMENDATIONS

Replication studies should be conducted across multiple education districts in Lagos State and other Nigerian states using larger, more diverse samples to enhance the generalisability of findings. Future investigations should employ more rigorous experimental or quasi-experimental designs, including control groups that receive traditional professional development or no intervention, to isolate the specific effects of AI-enhanced training on green chemistry understanding.

Longitudinal studies tracking teachers over extended periods would provide valuable insights into the sustainability of knowledge gains and the extent to which improved understanding translates into actual classroom implementation of green chemistry principles. Additionally, mixed-methods research incorporating classroom observations, interviews, and analysis of lesson plans would offer a deeper understanding of how AI-enhanced training influences pedagogical practices and student learning outcomes in green chemistry.

Institutional and policy-level recommendations emerge from this study's limitations. Educational authorities should prioritise scaling up AI-enhanced professional development programmes in green chemistry across all education districts, ensuring equitable access to technology infrastructure and internet connectivity that enable teachers in diverse contexts to participate effectively. Teacher education institutions should integrate AI literacy and green chemistry competencies into pre-service and in-service training curricula as core components rather than optional additions.

Additionally, establishing district- and state-level communities of practice would support ongoing peer learning and sustained implementation of green chemistry teaching beyond initial training interventions. Finally, curriculum developers and examination bodies should strengthen the integration of green chemistry principles into the secondary school chemistry syllabus and assessment frameworks, creating systemic incentives for teachers to deepen their understanding and embed sustainability-oriented chemistry education in their instructional practice.

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**Data Availability Statement.** The data supporting the results reported in this manuscript are based on teachers' contributions and performance records. These data are not publicly archived but are available upon reasonable request.

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## Appendix A. Overview and Content Structure of the AI-Enhanced Training Module

**Table 3.** Framework of the AI-Enhanced Training Package/Module – Overview & Synopsis

Sections	Module/ Course Overview	Module/ Course Synopsis & Description
Introduction to Green Chemistry	Definitions of GC Significance of GC in Today's World Goals of GC Formative Quiz 1 Course Feedback/ Rating 1	This section laid the groundwork by introducing the concept of GC, its definitions, significance in today's world, and the overarching goals it seeks to achieve. Teachers explored how green chemistry aligns with SDGs and the global effort to reduce environmental impact. It included an instructional video of a brief overview of GC by T. Anastas, Director, Centre for Green Chemistry and Green Engineering at Yale University.
Principles of Green Chemistry	Overview of the 12 Principles of GC: <ul style="list-style-type: none"> <li>• <i>Prevention of Waste,</i></li> <li>• <i>Atom Economy,</i></li> <li>• <i>Less Hazardous Chemical Syntheses,</i></li> <li>• <i>Designing Safer Chemicals,</i></li> <li>• <i>Safer Solvents &amp; Auxiliary,</i></li> <li>• <i>Energy Efficiency,</i></li> <li>• <i>Use of Renewable Feedstocks,</i></li> <li>• <i>Reduce Derivatives,</i></li> <li>• <i>Catalysis,</i></li> <li>• <i>Design for Degradation,</i></li> <li>• <i>Real Time Analysis for Pollution Prevention,</i></li> <li>• <i>Inherently Safer Chemistry for Accident Prevention.</i></li> </ul> Case Studies of Successful GC Initiatives – Up to date Formative Quiz 2 Course Feedback/ Rating 2	This section provides an in-depth overview of the twelve principles of GC, showcasing how these can be applied to real-world scenarios. It included other RSTNs such as identifying and sourcing green alternatives for lab experiments, waste management strategies and their implications, applying principles of atom economy, energy efficiency, identifying, sourcing renewable resources and adapting green product design, etc. Teachers also explored case studies of successful GC initiatives, offering practical insights into implementing these principles effectively. It included instructional videos from GC resources such as Cleva Force, Green Chemistry Tool-Kit, Yale University, American Chemical Society and Green Chemistry Initiatives – University of Toronto, Canada.
Green Chemistry & the Classroom	Green Chemistry Experiments I – II (Demonstrated videos by the researcher) Classroom Strategies for GC Implementing GC into Chemistry Lessons Integrating GC into some Selected Topics – such as <ul style="list-style-type: none"> <li>• <i>Acid, Base &amp; Salts,</i></li> <li>• <i>Polymerisation,</i></li> <li>• <i>Esterification,</i></li> <li>• <i>Electrolysis,</i></li> <li>• <i>Pollution, and</i></li> <li>• <i>Rate of Chemical Reaction.</i></li> </ul> Practical Illustrations of Integration into Chemistry Lessons Lesson Plan Strategies for GC Incorporation Formative Quiz 3 Course Feedback/ Rating 3	This section focuses on integrating GC into the classroom, emphasising its application in the Nigerian Chemistry Curriculum. It included RSTNs, such as how to incorporate GC principles into Chemistry lessons – plan, instructional strategy and materials, training on conducting green experiments and assessing environmental impact during lab activities. The researcher demonstrated two (2) GC experiments, which are Preparation of Biodegradable Plastic from Cassava Starch and Natural Indicators for Acids and Bases. Teachers explored other practical methods to incorporate GC concepts into selected topics in the O-level Nigerian chemistry curriculum and designed a lesson plan that fosters sustainable practices. Classroom strategies and practical experiments were provided to facilitate effective, sustainable/ GC incorporation.
Training Module Assessment	Final Module Quiz Overall Course Rating	Brief ten-item quiz for formative and summative assessment

GC – Green Chemistry, SGDs – Sustainable Development Goals, RSTNs-Required Specific