Assessment of Senior High School Students' Knowledge of Green Chemistry Principles in Winneba

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Abstract: *This study investigated the awareness, understanding, and attitudes toward green chemistry principles (GCP) among 326 senior high school (SHS) students in Winneba, Ghana. Using a descriptive cross-sectional survey, data were collected from three schools via a validated questionnaire covering demographics, GCP knowledge, sources of information, and attitudes toward sustainable practices. Using SPSS for the data analysis, the study revealed a significant increase in GCP knowledge with academic level, with SHS 3 students outperforming lower levels, but no significant differences by gender or age. Students showed strong understanding of foundational principles such as "Prevent Waste," but weaker grasp of advanced concepts like maximizing atomic economy and catalysis application. Classroom instruction was the primary source of knowledge, followed by television/radio and textbooks. Attitudes toward green chemistry were overwhelmingly positive, indicating readiness for curriculum integration. Findings emphasize the need for earlier and more practical GCP instruction, integration of multimedia resources, and equitable outreach.*

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1. Introduction

In recent years, there has been a growing interest in providing knowledge and critical thinking for young learners and industries so that they can meet the challenges of modern society, such as green chemistry education (Liu et al, 2023). For instance, the 2024-2033 UN Decade of Sciences for Sustainable Development advocate the promotion of multidisciplinary to teach or introduce green chemistry principles (GCP) at high school or secondary school level. Mammino (2025) contends that green chemistry has become the center of focus since the global concern over the deterioration of the environment, climate change, and overutilization of natural resources. In caring for the environment there was the need for value education in green chemistry principles, sustainability, and a proper priority of the education system to provide Education for Sustainable Development (ESD), (Sánchez, González-Gómez & Jeong, 2022).

Green chemistry, or sustainable chemistry, is a science-based strategy for addressing these problems. Invented in the 1990s by John Warner and Paul Anastas, green chemistry relies on twelve principles that promote waste reduction, energy conservation, renewable feedstocks, and safer products and chemicals. By applying these principles to chemical research, manufacturing, and training, society can achieve a reduction in environmental impact while promoting innovation and sustainability. Mitarlis et al.

(2023) had argued that the principles of green chemistry could be transformed for application in the attitude and behavior of human beings towards maintaining the environment, which could be achieved through green education.

The last few years have seen the education system all over the world realize that the curriculum should include ideas of sustainability, like green chemistry. This is particularly vital at the senior high school level when students begin handling advanced scientific concepts and making choices that determine their study and professional lives. Early exposure to green chemistry not only improves scientific literacy but also instills environmentally friendly responsibility, allowing students to adopt the sustainable manner of working and living in their professional and personal life. In Ghana, and especially Winneba, there is scant empirical research on the extent to which senior high school students understand and utilize the tenets of green chemistry. Though environmental education is extensively accepted, the depth of knowledge of students in this specialized area is yet to be thoroughly researched. Their knowledge levels can be a significant compass for curriculum design, teacher training, and policy measures towards producing an environmentally conscious generation of citizens and professionals of tomorrow. This study aims to: (1) ascertain the level of awareness and understanding of green chemistry principles among senior high school students in Winneba, (2) investigate the sources of knowledge of students about green chemistry, and (3) investigate attitudes towards environmentally friendly practices in science teaching. The research covers the missing link in the empirical literature on senior high school students in Winneba regarding knowledge of the concept of green chemistry. Itmeasurement of students' awareness, modes of knowledge, and relationship between knowledge and sustainable practice will benefit curriculum development, teacher training, and education policy. The following sections are structured into literature review, methodology and results and discussion and conclusion.

2. Literature Review

2.1 The Concept of Green Chemistry

Green chemistry, or sustainable chemistry, was conceived in the 1990s as an advanced and innovative approach of saving the environment through encouraging the growth of chemical science. Source pollution avoidance is the cornerstone philosophy of green chemistry, in contrast to traditional approaches that focus primarily on treating or remediating environmental damage after it has occurred (Anastas & Eghbali, 2010). The United States Environmental Protection Agency (EPA) formally coined

the term *green chemistry* in the 1990s to describe chemical research and engineering practices that prevent pollution and reduce toxicity across the entire lifecycle of chemical products from design and manufacture to use and disposal (EPA, 1996). Within this framework, green chemistry operates at the intersection of industrial ecology and sustainable manufacturing, advocating for safe, non-polluting, and resource-efficient processes that generate minimal waste (Manahan, 2005; Manahan, 2006). The concept was popularized by Anastas and Warner (1998), who articulated twelve guiding principles aimed at minimizing waste, reducing hazardous substances, enhancing energy efficiency, and promoting the use of renewable resources in chemical processes. These principles serve not only to mitigate the environmental impact of chemical manufacturing but also to provide a structured framework for integrating sustainability into research, industrial practice, and education. As a discipline, green chemistry encompasses the search for innovative and environmentally benign alternatives to conventional chemical practices. This includes replacing toxic solvents, developing environmentally friendly reaction media, and employing catalytic and energy-efficient processes that align with its twelve foundational principles (Anastas & Warner, 1998; Anastas & Eghbali, 2010).

For over three decades, the core mission of green chemistry has been closely associated with the reduction or elimination of toxic substances and the prevention of pollution, objectives deeply rooted in environmental policies and regulations established since the 1980s (Constable, 2021; U.S. EPA, 2021). Recently. the significance of green chemistry has extended beyond industrial practice into science education. It is increasingly recognized as an essential component of secondary and tertiary science curricula (Mammino, 2021), where early exposure to its concepts can deepen students' understanding of the interrelationship between chemistry and sustainability. Such integration fosters environmentally responsible attitudes and equips learners with the skills necessary to address global environmental challenges (Mitarlis et al., 2023). International initiatives, like the United Nations' Decade of Science for Sustainable Development, also recognize the incorporation of sustainability and green chemistry ideas into educational frameworks in order to prepare future scientists and active citizens (Liu et al., 2023).

2.2 The 12 Principles of Green Chemistry

First articulated by Paul Anastas and John Warner in 1998, the 12 Principles of Green Chemistry form a whole system for designing processes and products that avoid or

minimize the generation of toxic chemicals. (Anastas & Warner, 1998). These principles form the foundation of sustainable chemistry, guiding chemists and industry practitioners toward innovations that align with environmental and human health objectives (Anastas & Eghbali, 2010). According to Juanjuan and Shengli (2020), Anastas and Warners's 12 principles were the initial guidelines for new synthetic methodology and analytical technique development evaluation and remain the preeminent internationally accepted green chemistry principles. Since their introduction, the 12 Principles of Green Chemistry have inspired a new wave of research in the field. Hjeresen et al. (2000) condensed these principles into 12 key words for simplicity and clarity. However, Gałuszka et al. (2013) believed that the original principles could not be applied in their entirety to analytical chemistry; hence, they adapted them in accordance with contemporary needs in chemical engineering, production, and green analytical chemistry and thus formulated "Twelve Principles of Green Analytical Chemistry." The first principle emphasizes waste prevention rather than treatment, advocating for processes that minimize the formation of byproducts (Anastas & Warner, 1998). The second is the principle of atom economy, meaning synthetic processes would utilize all materials to the greatest extent possible in the final product, with the minimum waste. The third and fourth are the design of simpler chemical syntheses and the design of safer chemical products that decrease toxicity but not performance. Energy efficiency is mentioned in the sixth principle that promotes conducting reaction conditions at atmospheric temperature and pressure to reduce environmental and economic costs (Lancaster, 2016). The seventh principle advocates for the use of renewable feedstocks, such as plant-based raw materials, to minimize reliance on non-renewable resources. The eighth principle underscores the reduction of derivatives, discouraging unnecessary modification steps that consume reagents and generate waste. The ninth principle recommends the use of catalysts (including biocatalysts) over stoichiometric reagents, as catalysts are reusable and reduce waste generation (Manahan, 2005). The tenth principle deals with the design of chemicals that degrade into innocuous products on use, preventing accumulation in the environment. The eleventh principle promotes real time process analysis for the identification and elimination of the creation of dangerous byproducts. Finally, the twelfth principle promotes inherently safer chemistry for accident prevention, which involves the employment of the chemical selection and processes that reduce the potential for chemical accidents, explosions, and releases.

Over the past two decades, these principles have been widely adopted in industrial, academic, and regulatory contexts. They have influenced curriculum development in chemistry education (Mammino, 2021), driven innovation in cleaner production technologies (Zuin et al., 2021), and informed environmental policy frameworks aimed at pollution prevention (Constable, 2021). The Twelve Principles of Green Chemistry can be stated in simple phrases as follow:
1. Prevent waste
2. Maximize atomic economy
3. Designing safe chemicals and chemical products
4. Design a less dangerous chemical synthesize
5. Use safe solvents and reaction conditions
6. Improve energy efficiency
7. Using renewable raw materials
8. Avoid chemical derivatives:
9. Using a catalyst instead of a stoichiometric reagent:
10. Design chemicals and products that can decompose after use:
11. Analyze in real-time to prevent pollution:
12. Minimize the potential accidents
(Manahan, 2006; Anastas & Warner, 1998).

2.3 Integration of Green Chemistry in Science Education

The integration of Green Chemistry (GC) into science education has gained increasing attention as part of broader efforts to advance environmental sustainability through educational reform. Higher education institutions play a pivotal role in these efforts by fostering environmentally responsible practices within both formal and informal learning contexts. One example is the implementation of eco-campus programs, which aim to embed environmental values into campus operations and culture. These programs typically set strategic objectives such as campus greening, waste management toward zero waste, water recycling, pollution-free air quality, safe and efficient campus transportation, energy conservation, improved water quality, environmental culture in teaching and learning, research aligned with eco-campus goals, and continuous evaluation of institutional sustainability plans (Syaiful, 2015).

Embedding GC principles into educational programs supports the realization of these eco-campus goals and aligns with the objectives of the United Nations Sustainable Development Goals (SDGs). In this context, Green Chemistry Education (GCE) has emerged as an innovative pedagogical approach for integrating environmental conservation concepts into science learning (Zuin et al., 2021). While initially embedded primarily in degree programs for chemists, chemical engineers, and technologists (Twelve More Green Chemistry, 2001), GCE

has gradually expanded to include broader science education contexts. The United States has been at the forefront of integrating GC concepts into chemistry curricula, influencing adoption in other regions such as Germany, which pioneered their inclusion in undergraduate programs (Zuin et al., 2021) and later incorporated them into high school curricula (Wihardjo et al., 2017; Aubrecht et al, 2015).

Despite these advances, the adoption of GCE remains limited in many African countries, including Ghana, Nigeria and Mali (Lasker et al, 2019). Factors contributing to this gap include inadequate teacher knowledge and awareness of GC principles (Anggraeni, and Moersilah, 2024), congested curricula with reduced contact hours, limited access to instructional resources (Haack, 2016), and insufficient contextualization of science topics (Nersesian et al., 2019). In Ghana, efforts to integrate GC into science education are emerging, but not explicitly or as a standalone course in the SHS. The integrated science syllabus has sufficient green chemistry lessons embedded in it.

2.4 Studies on Assessing Senior High Students' Knowledge on Green Chemistry Principles

The successful integration of new content into science curricula must be accompanied by systematic assessment strategies capable of evaluating learning effectiveness and guiding curriculum refinement. Assessment does more than measure students' mastery of concepts; it provides critical feedback for improving instructional design and ensuring that pedagogical approaches meet learning objectives (Armstrong et al., 2018). In curriculum evaluation, diagnostic tools are frequently employed to examine student performance and gauge the impact of instructional interventions (Gron et al., 2013). Given that green chemistry represents a relatively recent and evolving dimension of chemistry education, its incorporation into the curriculum warrants carefully designed and robust assessment approaches.

Many efforts have been made to explore ways in which students' understanding about concepts of green chemistry may be assessed. Taking a test of chemistry achievement and holding interviews, for instance, Karpudewan et al. (2015a) investigated students' motivation to learn green chemistry. Expanding this approach, Karpudewan et al. (2015b) infused green chemistry concepts into the preservice and in-service teacher education programs and administered questionnaires in concert with individual interviews to investigate how green chemistry instruction relates to students' learning motivation, environmental

awareness, and values. Similarly, Mandler et al., (2012) incorporated relevant environmental issues into high school chemistry curricula and employed structured interviews to investigate both cognitive and affective learning outcomes of green chemistry, together with its perceived relevance to students' everyday life. Their findings indicated that this instructional approach enhanced students' interest and willingness to participate in addressing environmental challenges.

The Likert scale has emerged as one of the most widely used assessment instruments in green chemistry education research (Armstrong et al., 2018; Garner et al., 2015). Its appeal lies in its ability to streamline assessment by reducing reliance on lengthy written examinations while enabling the creation of both formative and summative evaluation tools (Gron et al., 2013). Large-scale questionnaire surveys employing Likert-based instruments have shown that many students in China exhibit low awareness of green chemistry (Jia, 2018), possess an incomplete understanding of its concepts (Wang et al., 2017), and struggle to apply green chemistry knowledge in practical contexts (Gu and Wang, 2019). These findings highlight persistent challenges in the effective delivery of green chemistry education. Students often demonstrate limited awareness, insufficient conceptual understanding, and minimal practical engagement (Shan, 2017). Although various assessment tools are available, each is shaped by its specific evaluation focus and pedagogical orientation (Gron et al., 2013). This underscores the urgent need for more comprehensive and systematic assessment instruments that can capture both the conceptual grasp and behavioral application of green chemistry principles. Such tools would enable educators to monitor learning outcomes more accurately, refine teaching strategies, and strengthen the integration of green chemistry within broader sustainability education frameworks (Armstrong et al., 2018; Chen et al., 2020).

3. Methodology

3.1 Research Design and Participants

In Ghana, Integrated Science is a core subject for all senior high school (SHS) students, regardless of their academic programme. The subject incorporates various components of the natural sciences, including chemistry, which introduces learners to foundational concepts relevant to green chemistry principles. This common curriculum exposure ensures that students possess at least a basic understanding of chemistry education and its environmental applications, thereby providing a fair basis for assessing their awareness and understanding of green

chemistry principles. This provided the flexibility for the present study to employ a descriptive cross-sectional survey design to evaluate the level of knowledge of Green Chemistry Principles (GCP) among senior high school students in Winneba due to the common usage and content of the teaching syllabus of Integrated Science.

3.2 Samples and Sampling

The study focused on three senior high schools in the Winneba Municipality. A stratified random sampling was done to ensure that the students selected were proportionally represented in the various schools and levels: SHS 1 = 77, SHS 2 = 109, and SHS 3 = 140. For ethical reasons, the names of the selected SHS were anonymous.

3.3 Data Collection Process

Data were gathered through a structured questionnaire that was adapted from previous validated instruments on green chemistry education (Shamuganathan & Karpudewan., 2017; Mitarlis et al., 2023). The questionnaire consisted of four sections. Section A presented the Demographic Information (age, gender and level), Section B introduced Awareness and Understanding of Green Chemistry Principles – multiple-choice questions assessing students' familiarity with the 12 principles of green chemistry, Section C is about the Sources of Knowledge – items assessing where students acquired information on green chemistry (e.g., classroom instruction, textbooks, media, extracurricular programs), and Attitudes toward Environmentally Sustainable Practices. The instrument underwent content validation by three experts in science education of the University of education, Winneba and environmental chemistry lecturers. A pilot test was conducted with 5 students from a non-participating SHS to check clarity, reliability, and internal consistency.

3.4 Ethical Issues

Prior to data collection, informed consent and introduction letter were obtained from the relevant institutional authorities. The necessary permission was sought from the authorities of the schools. The researcher visited the selected schools and administered the questionnaires during normal class hours. The purpose of the study was explained to participants, and informed consent was obtained from all respondents. Anonymity and confidentiality were assured; participation was voluntary, and students had the right to withdraw at any time. On average, the questionnaires were completed in 5-7 minutes.

3.5 Data Analysis

Data collected were coded and entered onto SPSS (v26) for analysis. Demographic data, levels of awareness, understanding of GCP, and attitudes toward environmentally sustainable practices. Data were summarized using descriptive statistics, including frequencies, percentages, means, and standard deviations. Independent tests were applied to examine associations between the demographic variables of the students and knowledge of GCP. Pearson's correlation analysis was employed to investigate students' knowledge of GCP regarding their attitude towards environmentally sustainable practices.

4. Results and Discussion

Table 1 presents the demographic characteristics of the 326 participants. The study reveals that 73.6% were male and 26.4% were female. Most respondents (66.3%) were aged between 16 and 18 years, while 20.2% were aged 13–15 years and 13.5% were 19 years and above. In terms of academic level, 23.6% were in SHS 1, 33.4% in SHS 2, and 42.9% in SHS 3.

Table 1: Respondents background information

Variable	Category	Frequency	Percent (100%)
Gender	Male	240	73.6
	Female	86	26.4
Age	13-15 years	66	20.2
	16-18 years	216	66.3
	19 years and above	44	13.5
Level	SHS 1	77	23.6
	SHS 2	109	33.4
	SHS 3	140	42.9

Total participants = 326

4.1 Descriptive statistics of GCP knowledge across SHS levels

Table 2 indicates that students' knowledge of Green Chemistry Principles (GCP) increases with academic level. SHS 1 students recorded the lowest mean score ($M = 31.72$, $SD = 2.77$), followed by SHS 2 students ($M = 33.89$, $SD = 3.27$), while SHS 3 students achieved the highest mean score ($M = 35.14$, $SD = 4.01$). The range of scores shows that SHS 1 students scored between 28 and 36, SHS 2 students between 27 and 40, and SHS 3 students between 27 and 39. The relatively smaller standard errors across all groups (0.27–0.46) suggest that the sample means are stable and representative of their respective populations. The results reflect a positive relationship between grade level and GCP knowledge, with higher academic levels associated with better understanding of green chemistry concepts.

Table 2: GCP knowledge across SHS levels

Level	N	Mean	Std. Deviation	Std. Error	Minimum	Maximum
SHS 1	77	31.7248	2.77179	.26549	28.00	36.00
SHS 2	109	33.8857	3.27204	.27654	27.00	40.00
SHS 3	140	35.1429	4.00564	.45648	27.00	39.00
Total	326	33.4601	3.55570	.19693	27.00	40.00

This difference in GCP knowledge across SHS levels was statistically significant according to the one-way ANOVA from Table 3, $F_{(2,323)} = 26.10$, $p < .001$ $F_{(2, 323)} = 26.10$, $p < .001$ $F_{(2,323)} = 26.10$, $p < .001$. While post-hoc comparisons are necessary to indicate exactly which levels differ, the overall indication is that the higher the academic level, the significantly greater the knowledge about green chemistry principles.

Table 3: ANOVA results

GCP	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	571.638	2	285.819	26.099	.000
Within Groups	3537.343	323	10.952		
Total	4108.982	325			

Table 4 presents the post-hoc analysis using Tukey's Honestly Significant Difference (HSD) test, revealing statistically significant differences in Green Chemistry Principles (GCP) knowledge scores across the three senior high school levels. SHS 1 students scored significantly lower than both SHS 2 students, $M = -3.42$, $SE = 0.49$, $p < .001$, and SHS 3 students, $M = -2.16$, $SE = 0.42$, $p < .001$.

Similarly, SHS 2 students scored significantly lower than SHS 3 students, $M = -2.16$, $SE = 0.42$, $p < .001$, but significantly higher than SHS 1 students, $M = 1.26$, $SE = 0.47$, $p = .021$. Conversely, SHS 3 students achieved the highest GCP scores, outperforming both SHS 1 ($M = 3.42$, $SE = 0.49$, $p < .001$) and SHS 2 ($M = 1.26$, $SE = 0.47$, $p = .021$) students. These results indicate a consistent upward

trend in GCP knowledge from SHS 1 to SHS 3, suggesting that higher grade levels are associated with greater understanding of green chemistry concepts.

Table 4: Results of least significance test

(I) Level	(J) Level	Mean Difference (I-J)	Std. Error	Sig.
SHS 1	SHS 2	-3.41809*	.49265	.000
	SHS 3	-2.16094*	.42273	.000
SHS2	SHS 1	-1.25714*	.46952	.021
	SHS 3	2.16094*	.42273	.000
SHS 3	SHS 1	3.41809*	.49265	.000
	SHS 2	1.25714*	.46952	.021

*. The mean difference is significant at the 0.05 level.
Dependent Variable: GCP; Model: Tukey HSD

4.2 Students' Performance by GCP Knowledge Category

The analysis of students' performance across the 12 Green Chemistry Principles (GCP) revealed notable variations in their understanding of each principle's concept, definition, and practical application in Table 5. The students demonstrated the strongest knowledge in Principle 1 (Prevent Waste), achieving the highest mean scores for concept (4.61), definition (4.42), and application (4.10).

This suggests that waste prevention is both well understood and easily contextualized within the Integrated Science curriculum. In contrast, Principle 2 (Maximize Atomic Economy) and Principle 9 (Using a Catalyst Instead of a Stoichiometric Reagent) recorded the lowest scores, particularly in application (2.14 and 1.84, respectively), indicating a significant gap in students' ability to transfer theoretical understanding into real-world contexts. Similarly, Principle 11 (Real-Time Analysis to Prevent Pollution) showed weak performance in application (1.69), highlighting limitations in students' exposure to practical analytical techniques.

Table 5: Students' performance by GCP knowledge category

SN	Green Chemistry Principles	Principle	Definition	Application
		Mean	Mean	Mean
X1	Prevent waste	4.61	4.42	4.10
X2	Maximize atomic economy	2.30	2.61	2.14
X3	Designing safe chemicals and chemical products	2.51	2.91	2.61
X4	Design a less dangerous chemical synthesize	3.05	2.84	1.91
X5	Use safe solvents and reaction conditions	2.91	3.18	2.64
X6	Improve energy efficiency	3.23	3.45	3.71
X7	Using renewable raw materials	3.42	3.36	3.01
X8	Avoid chemical derivatives	3.07	3.10	2.65
X9	Using a catalyst instead of a stoichiometric reagent	2.16	2.87	1.84
X10	Design chemicals and products that can decompose after use	3.55	3.24	2.50
X11	Analyze in real-time to prevent pollution:	2.91	2.47	1.69
X12	Minimize the potential accidents	3.80	3.42	3.90

N=326

4.3 Source of Students' Knowledge on Green Chemistry Principles

Table 6 reveals that students' knowledge of Green Chemistry Principles (GCP) is shaped primarily by formal education, with classroom instruction in Integrated Science/Chemistry (76.1%) serving as the dominant

channel. Interestingly, television and radio programmes (64.4%) surpass textbooks (30.1%) as secondary sources, suggesting that mass media may have a stronger penetration and recall effect than traditional print materials. Social media (25.2%) and extracurricular science activities (16.6%) contribute modestly, while peer or family influence (13.8%) remains minimal. The low engagement through informal channels highlights untapped potential for diversifying GCP dissemination.

Table 6: Source of Students' Knowledge on Green Chemistry Principles

Source of Knowledge	Frequency (N)	Percentage (%)
Classroom lessons in Integrated Science/Chemistry	248	76.1
Television or radio programmes	210	64.4
Textbooks or school materials	98	30.1
Social media platforms	82	25.2
Science clubs or extracurricular activities	54	16.6
Friends or family	45	13.8
Other (please specify)	12	3.7
Total respondents	326	100.0

4.4 Comparing GCP Knowledge by Gender and Age

A Mann-Whitney U test was conducted to determine if there were differences in GCP knowledge scores between male and female students. Table 7 revealed that there was no statistically significant difference in GCP scores across gender categories, U = [11, 526.500], z = 1.620, p = .105. The result would, therefore, mean that the gender factor has no effect on students' knowledge in green chemistry principles. Figure 1 shows a graphical dispersion of the mean rank and number of respondents by male and female.

Table 7: Independent test among gender groups

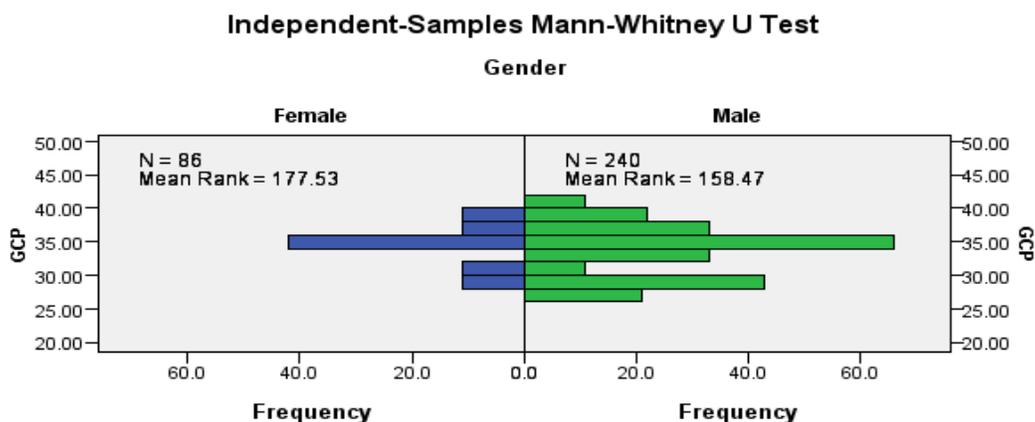| Null Hypothesis	Test	Sig.	Decision
The distribution of GCP is the same across categories of Gender	Independent-Samples Mann–Whitney U Test	.105	Retain the null hypothesis

Fig 1: Boxplot comparison of gender knowledge on GCP

Results of the Kruskal–Wallis test shown in Table 8 indicated that there was no statistically significant difference in the distribution of knowledge about GCP among the age categories, p =.114p = .114, above the .05 level of significance. So the null hypothesis of a similar distribution of GCP knowledge across age categories is retained.

Table 8: Independent test among age groups

Null Hypothesis	Test	Sig.	Decision
The distribution of GCP is the same across categories of Age	Independent-Samples Kruskal–Wallis Test	.114	Retain the null hypothesis

4.5 Students' attitudes towards environmentally sustainable practices in science learning

Table 9 presents the results of students' attitude towards GCP sustainable practices. The study found that majority (59.8%) agreed and 33.4% strongly agreed that it is important to apply green chemistry principles in everyday life, with no respondents disagreeing. Over half (53.1%) agreed and 19.9% strongly agreed that they are motivated to learn more about green chemistry to protect the environment, though 23.6% remained neutral and 3.4% disagreed. Most students (56.4% agree, 36.8% strongly agree) supported the inclusion of more environmental sustainability and green chemistry content in schools, with no disagreement recorded. Similarly, 66.6% agreed and 26.7% strongly agreed that they are willing to adopt sustainable practices in science experiments. The strongest endorsement was observed for the belief that understanding green chemistry will aid future environmental decisions, with 53.4% strongly agreeing and 43.3% agreeing. These results suggest a high level of awareness and willingness to engage with green chemistry concepts, with minimal resistance or disagreement.

Table 9: Students' attitude towards GCP sustainable practices

Question	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
I believe it is important to apply green chemistry principles in everyday life.	0 (0.0%)	0 (0.0%)	22 (6.7%)	195 (59.8%)	109 (33.4%)
I am motivated to learn more about green chemistry to help protect the environment.	0 (0.0%)	11 (3.4%)	77 (23.6%)	173 (53.1%)	65 (19.9%)
Schools should teach more about environmental sustainability and green chemistry.	0 (0.0%)	0 (0.0%)	22 (6.7%)	184 (56.4%)	120 (36.8%)
I am willing to adopt sustainable practices in my science experiments.	0 (0.0%)	0 (0.0%)	22 (6.7%)	217 (66.6%)	87 (26.7%)
Understanding green chemistry will help me make better environmental decisions in the future.	0 (0.0%)	0 (0.0%)	11 (3.4%)	141 (43.3%)	174 (53.4%)

4.6 General Overview

This study's demographic profile, predominantly male (73.6%), largely aged 16–18 years (66.3%), and with increasing representation across SHS levels from SHS 1 to SHS 3, establishes a context where academic progression aligns with developmental maturity, possibly contributing to greater conceptual grasp of environmental topics. The ANOVA and Tukey post-hoc results clearly demonstrate that GCP knowledge significantly increases with students' level, with SHS 3 students outperforming SHS 2 and SHS 1, and SHS 2 outperforming SHS 1. This gradient suggests that curriculum exposure and cognitive growth foster deeper understanding of green chemistry. The GCP knowledge with regards to students' level progression confirms Anhwere et al. (2025) findings on students' performance on year-level basis. In contrast, it contradicts the conclusion of Juanjuan and Shengli (2020) that secondary school students in China had a low understanding of green chemistry-related concepts, possibly due to the difference in study periods.

Regarding content-specific performance, students demonstrated strongest understanding of the principle "Prevent Waste" across concept, definition, and application. In contrast, understanding and applying advanced principles such as maximizing atomic economy, catalysis substitution, and real-time pollution analysis was notably weaker. This divergence aligns with the broader literature on green chemistry education: simpler, contextually intuitive principles are readily grasped. Amoneit et al. (2024) established that more abstract or technically nuanced ones pose challenges, particularly without hands-on or systems-based pedagogies. Moreover, the study findings highlight that traditional classroom delivery is the primary channel of green chemistry

knowledge (76.1%), followed by television/radio (64.4%), then textbooks (30.1%). The prominence of media over print suggests that accessible and engaging content such as multimedia may reinforce learning more effectively among secondary students. This resonates with pedagogical recommendations advocating multimodal approaches (e.g., student-generated videos, interactive modules) to enhance awareness of GC principles. This supports the work of Suanda 2023 in relevance to everyday and cultural contexts of science. In Akakpo & Ezenwa 2025, the integrated textbook intervention effectively minimized gender disparities in scientific literacy yet still relates to GCP application.

There were no significant differences in GCP knowledge across gender (p = .105) and age categories (p = .114) echoes findings from earlier studies (Mashami & Pahriah, 2025; Ma & Shengli.,2020), reaffirming that such demographic variables exert minimal influence, and that focused instructional strategies are likely the key drivers of student knowledge. In addition, comparable findings emerge that no gender differences in green chemistry awareness among a large of secondary students, reinforcing that curriculum and not demographic variables is central to knowledge acquisition (Juanjuan & Shengli, 2020; Saadon & Abbood, 2022). Additionally, studies examining green chemistry instruction in China highlight that embedding GC principles into lab-based learning and textbooks enhances student comprehension over time, supporting our finding that knowledge accrues with exposure and structured instruction (Gunbatar et al., 2025).

Taken together, the uniformly positive attitudes observed where students overwhelmingly agree on the importance of green chemistry, willingness to adopt sustainable practices, and motivation to learn more suggest strong affective readiness to embrace GC concepts. This mirrors results from studies showing that green chemistry activities can enhance environmental care and attitudes significantly, especially when integrated into authentic learning experiences such as experiments and projects (Amoneit et al., 2024). The research also accentuates calls for curricular reform, aligning with IUPAC-led initiatives to embed sustainability literacy across chemistry education in all second cycle institutions.

5. Conclusion and Recommendations

5.1 Conclusion

This study demonstrates that SHS students possess a generally positive disposition toward green chemistry principles, with high levels of agreement regarding its importance, relevance to daily life, and applicability in future environmental decision-making. Knowledge of green chemistry principles increases significantly with academic level, emphasizing the role of curricular exposure and progressive learning in deepening conceptual understanding. While foundational principles such as "Prevent Waste" are well understood, more advanced principles requiring technical or abstract reasoning remain challenging. Importantly, no significant differences emerged in knowledge based on gender or age, indicating that equitable access to and engagement with green chemistry concepts is possible across demographic groups. The outcomes of this study have significant implications for science education and sustainability literacy among senior high school students in Ghana. The clear association between academic level and knowledge of green chemistry principles suggests that curricular exposure and progressive reinforcement play a critical role in building student competence. This research advocates the need for curriculum developers to integrate green chemistry concepts earlier in secondary education and to provide scaffolding that progressively deepens understanding. Furthermore, the identified gaps in more complex principles, such as maximizing atomic economy or applying catalysts, highlight the necessity for diverse instructional strategies that go beyond traditional lectures, including hands-on laboratory experiences, project-based learning, and multimedia resources.

Although findings are illuminating, the research is far from perfect. Its cross-sectional nature captures attitudes and knowledge at a moment in time, abbreviating the capacity to produce causal connections between learning achievements and academic advancement. Secondly, dependence upon self-report data opens up vulnerability to social desirability bias, as much as anything else, due to the environmental and ethical focus of the subject matter. Geographical location of the sample also restricts the extensiveness of results since the results could not capture the complete diversity of learning environments in various regions.

5.2 Recommendations

Curriculum developers should integrate Green Chemistry into the existing science curriculum and embed relevant green chemistry concepts (e.g., waste minimization, safer chemical design) into chapters of the chemistry syllabus. Curriculum and instructional designers should align activities with Ghana's Science curricula and Sustainable Development Goals (SDG 12: Responsible Consumption and Production).

Teachers should use conceptualized and local examples by employing local case studies (e.g., waste management in Winneba, beach pollution) to make green chemistry relatable and develop problem-based learning (PBL) tasks around environmental issues in the Winneba area.

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