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ORIGINAL

Podcast-based green chemistry learning strengthens student awareness with distinct outcomes across gender and digital literacy dimensions

El aprendizaje de química verde basado en podcasts fortalece la conciencia de los estudiantes con resultados distintos según el género y las dimensiones de alfabetización digital

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ABSTRACT

Contemporary education increasingly demands innovations that integrate sustainability awareness into scientific learning. Green Chemistry offers such an approach by connecting chemical principles with environmental responsibility. This study aimed to examine the effectiveness of podcast-based, culturally responsive Green Chemistry instruction in enhancing students' environmental and cultural awareness, as well as their learning outcomes, while considering gender, digital literacy, and school context. A quasi-experimental mixed-methods non-equivalent control group design was conducted in two East Java high schools (public School X and private School Y) from August to September 2025, involving 120 grade-11 students (60 per school; 40 female, 20 male). The intervention combined podcast-based learning with Culturally Responsive Teaching Theory (CRTT). Data were collected through pre-post tests (normalized gain g), validated questionnaires (CVI = 0,94; Cronbach's α = 0,87), classroom observations, and semi-structured interviews. Quantitative data were analyzed using descriptive statistics and ANOVA, while qualitative data were thematically coded and triangulated. Results indicated medium normalized gains overall (female g = 0,640; male g = 0,523), with female students consistently outperforming males. Students with higher digital literacy and culturally supportive environments showed deeper reflection and sustained engagement. Thematic analysis revealed that family engagement, community influence, technology use, and ethical or religious values shaped awareness development. In conclusion, podcast-based Green Chemistry learning effectively enhances both cognitive and affective learning dimensions, with gender and digital literacy emerging as significant moderating factors. These findings suggest the importance of integrating gender-responsive pedagogy and digital literacy reinforcement to optimize sustainability-oriented learning through digital media.

Keywords: Podcast; Green Chemistry; CRTT; Gender; Digital Literacy; Environmental and Cultural Awareness.

RESUMEN

La educación contemporánea demanda cada vez más innovaciones que integren la conciencia sobre la

sostenibilidad en el aprendizaje científico. La Química Verde ofrece un enfoque de este tipo al vincular los principios químicos con la responsabilidad ambiental. Este estudio tuvo como objetivo examinar la efectividad de la instrucción en Química Verde basada en podcasts y culturalmente sensible para mejorar la conciencia ambiental y cultural de los estudiantes, así como sus resultados de aprendizaje, considerando además el género, la alfabetización digital y el contexto escolar. Se llevó a cabo un diseño cuasi-experimental de métodos mixtos con grupo de control no equivalente en dos escuelas secundarias de Java Oriental (la escuela pública X y la escuela privada Y) entre agosto y septiembre de 2025, con la participación de 120 estudiantes de 11.º grado (60 por escuela; 40 mujeres y 20 hombres). La intervención combinó el aprendizaje basado en podcasts con la Teoría de la Enseñanza Culturalmente Sensible (CRTT). Se recopilaron datos mediante pruebas previas y posteriores (ganancia normalizada g), cuestionarios validados (CVI = 0,94; α de Cronbach = 0,87), observaciones en el aula y entrevistas semiestructuradas. Los datos cuantitativos se analizaron utilizando estadística descriptiva y ANOVA, mientras que los datos cualitativos se codificaron temáticamente y se sometieron a triangulación. Los resultados indicaron ganancias normalizadas medias en general (femenino g = 0,640; masculino g = 0,523), con las estudiantes superando consistentemente a los estudiantes varones. Los estudiantes con mayor alfabetización digital y entornos culturalmente favorables mostraron una reflexión más profunda y un compromiso sostenido. El análisis temático reveló que la participación familiar, la influencia comunitaria, el uso de la tecnología y los valores éticos o religiosos influyeron en el desarrollo de la conciencia. En conclusión, el aprendizaje de Química Verde basado en podcasts mejora de manera efectiva tanto las dimensiones cognitivas como afectivas del aprendizaje, emergiendo el género y la alfabetización digital como factores moderadores significativos. Estos hallazgos sugieren la importancia de integrar una pedagogía sensible al género y el refuerzo de la alfabetización digital para optimizar el aprendizaje orientado a la sostenibilidad a través de los medios digitales.

Palabras clave: Podcast; Química Verde; CRTT; Género; Alfabetización Digital; Conciencia Ambiental y Cultural.

INTRODUCTION

The challenges of twenty-first-century education are increasingly complex, requiring learning innovations that not only transfer knowledge but also cultivate values and awareness relevant to sustainability. Chemistry is a scientific discipline that focuses on studying the characteristics, structure, and changes in matter and energy. Several concepts in chemistry create difficulties and different perceptions for students because abstract concepts dominate chemistry. In addition, there are several difficulties in learning chemistry based on its characteristics, namely: a) Chemistry simplifies the truth, resulting in a gap between understanding and applying concepts, b) Chemistry has a dynamic and rapidly evolving nature, making the materials studied in chemistry very complex, c) Chemistry can be applied in everyday life.[1]

Green chemistry, as a branch of chemistry that emphasizes environmentally friendly principles, has been positioned as one of the critical approaches in connecting science learning with sustainable development goals.[2] By embedding principles such as waste prevention, energy efficiency, and the use of safer chemicals, green chemistry provides opportunities for students to understand science within the framework of environmental stewardship.[3] The integration of green chemistry into learning is not solely about mastering scientific content but also about developing environmental consciousness and sustainable habits among students.[4,5]

In line with these demands, the use of digital learning media has become an essential strategy in education.[6,7] Podcasts, with their flexibility, accessibility, and ability to integrate narratives, have been widely recognized as effective media for delivering complex content in a contextualized manner.[8] Unlike traditional lectures, podcasts can embed both cognitive and affective aspects of learning, thus aligning with the needs of Generation Z learners who are accustomed to digital content consumption.[9] Podcasts also allow educators to integrate local culture, values, and real-life examples into lessons, making them powerful tools in fostering both scientific literacy and cultural awareness.[8]

Culturally Responsive Transformative Teaching (CRTT) has emerged as a pedagogical model that bridges students' cultural backgrounds with classroom learning.[10] CRTT emphasizes responsiveness to cultural diversity, the use of narratives, and transformative practices that empower students to see the relevance of their learning within their cultural and social realities.[11] Research shows that culturally responsive teaching can enhance student engagement, motivation, and achievement, particularly in diverse school settings.[10,12,13] In this study, CRTT was used as a guiding framework for developing and implementing podcasts that embed green chemistry principles alongside cultural values.

The Indonesian education context provides an interesting case for such an intervention. Public schools often reflect more heterogeneous cultural backgrounds, whereas private schools, such as School Y, tend to have more

homogeneous cultural contexts. These differences may influence how students perceive and engage with cultural and environmental values in learning. Moreover, differences in school type also reflect variations in access to resources, teaching practices, and family involvement, which are critical for shaping students' awareness.[14]

Another critical dimension in STEM education is gender.[15] Global evidence indicates that gender differences often persist in STEM learning outcomes, with female students sometimes outperforming males in certain contexts, especially when affective aspects such as motivation, awareness, and engagement are considered[16] Similarly, as literacy is a hot issue that has been widely discussed recently by education practitioners,[17] digital literacy has become a determining factor in twenty-first-century learning outcomes. Students who are not only exposed to technology but also guided by families and communities that emphasize environmental values are more likely to develop higher levels of awareness compared to those who only consume technology passively.[18]

Despite the growing body of research on digital media and culturally responsive teaching, there remains limited exploration of how podcast-based learning that integrates green chemistry and cultural values can foster both environmental and cultural awareness across gender and digital literacy dimensions. Furthermore, little is known about how public and private school contexts mediate these outcomes. This study aims to fill this gap by implementing podcast-based learning in two different high schools, School X (public) and School Y (private), and examining the differences in student outcomes by gender and digital literacy levels.

The findings are expected to contribute to the literature on STEM education by demonstrating how culturally responsive and sustainability-oriented digital media can foster not only academic achievement but also broader awareness outcomes. By focusing on gender and digital literacy as critical dimensions, this research offers insights into how socio-cultural and individual factors intersect in shaping students' responses to innovative learning interventions.

METHOD

Type of Study, Period, and Location

This research employed a quasi-experimental mixed methods design using a non-equivalent control group model to comprehensively explore the impact of podcast-based Green Chemistry learning on students' awareness across gender and digital literacy dimensions. The quantitative component focused on learning gains through pre- and post-test analysis, while the qualitative component examined students' environmental and cultural awareness through interviews and open-ended reflections.

The study was conducted over a two-month period, from August to September 2025, during the first semester of the 2025/2026 academic year. Two senior high schools were selected as research sites: School X, a public school with a heterogeneous cultural background and socio-economically diverse students, and School Y, a private school with a relatively homogeneous socio-cultural context. Both schools are located in East Java, Indonesia, representing contrasting institutional and cultural profiles relevant to the aims of the study.

Population, Sample, and Sampling Criteria

The target population comprised senior high school students enrolled in Grade XI science classes. A total of 120 students participated in the study. 60 students from each school (40 females and 20 males).

Sampling was conducted using a purposive sampling technique, selecting schools and participants based on accessibility, willingness to participate, and suitability for the Green Chemistry intervention.

Inclusion criteria included: 1) Active enrollment in Grade XI during the 2025/2026 academic year. 2) Completion of prior chemistry instruction on chemical reactions and global environmental issues. 3) No prior exposure to Green Chemistry content. 4) Willingness to participate in two full podcast-based learning sessions. 5) Submission of written informed consent.

Exclusion criteria included: 1) Absence from either of the two learning sessions or post-test. 2) Incomplete submission of questionnaires or tests. 3) Inconsistent participation or disruption of group learning. 4) Refusal to provide data after consent explanation.

Exit criteria were applied to participants who did not complete both podcast sessions or failed to take the post-test; such participants were excluded from the final analysis, as they were considered not fully exposed to the intervention.

Variables Analyzed

The study analyzed five major variables: 1) Learning Achievement, measured through pre- and post-tests on Green Chemistry concepts. 2) Gender, categorized as male or female. 3) Digital Literacy, covering aspects such as access to technology, digital usage frequency, ability to evaluate information, and collaborative online engagement. 4) Environmental Awareness, defined as students' knowledge, attitudes, and behaviors toward ecological sustainability. 5) Cultural Awareness, conceptualized through the Culturally Responsive Transformative Teaching (CRTT) lens.

A distinct variable introduced in this study was CRTT-based Cultural Awareness, defined as "The ability of

students to connect Green Chemistry concepts with local cultural practices, values, and lived experiences, allowing them to reflect on sustainability through their sociocultural context." This variable reflects the transformative dimension of CRTT in linking scientific learning with cultural meaning and environmental responsibility.

Instruments, Techniques, and Procedures

Instruments

Four main instruments were used: 1) Achievement Test, 30-items combination of multiple-choice assessing conceptual understanding of Green Chemistry. 2) Environmental and Cultural Awareness Questionnaire, designed to capture students' reflections and attitudes using both closed and open-ended items. 3) Semi-structured Interview Guide, exploring deeper insights into students' awareness, family and community influence, and reflections on podcast experiences.

All instruments were validated by three expert validators in chemistry education and educational technology. The validation process covered content relevance, construct alignment, and language clarity, yielding an overall validity index of 0,94 (very valid). The internal consistency reliability (Cronbach's α) for the questionnaire instruments was 0,87, indicating high reliability.

Learning Procedure

The podcast-based intervention was implemented over two 90-minute sessions. Each episode presented Green Chemistry concepts contextualized with local cultural narratives and sustainability ethics.

Students listened to the podcasts individually through their devices, teacher also provide devices to students who don't have any, and then followed by small-group discussions and guided reflection activities using learning worksheets. Teachers acted as facilitators, while researchers observed and recorded engagement indicators.

Data Collection Process

Data collection occurred in three sequential stages: 1) Pre-Intervention Stage: Administration of pre-test and baseline questionnaires on digital literacy and awareness. 2) Intervention Stage: Implementation of podcast-based learning sessions, classroom observation, and collection of reflective worksheets. 3) Post-Intervention Stage: Administration of post-test and post-questionnaires, followed by semi-structured interviews with 20 representative students (10 from each school; 5 males and 5 females) selected based on diverse awareness and achievement test score levels.

All interviews were conducted face-to-face in Indonesian, recorded with participants' consent, and transcribed verbatim for thematic analysis. Each session lasted approximately 15–20 minutes.

Data Analysis Process

Quantitative data from pre- and post-tests were analyzed using normalized gain (g) to categorize improvement as low ($g < 0,3$), medium ($0,3 \leq g < 0,7$), or high ($g \geq 0,7$). Descriptive statistics were used to summarize mean scores, while inferential analyses (normality test, homogeneity test, and ANOVA) were conducted to examine quantitative data.

Qualitative data from interviews and open-ended responses were analyzed through thematic coding. Coding categories were developed inductively, focusing on recurring patterns related to environmental and cultural awareness.

Integration of quantitative and qualitative results was achieved through methodological triangulation, using a joint display matrix to connect learning gains with qualitative insights. This approach ensured a comprehensive understanding of how podcast-based learning fostered both cognitive and affective outcomes.

Ethical Aspects of the Research

This study adhered to research ethics approved by the Ethics Committee of Universitas Negeri Malang. Written informed consent was obtained from students and their guardians prior to participation.

To maintain confidentiality, all personal identifiers were removed, and schools were anonymized as "School X" and "School Y." Participation was voluntary, and students were informed that their involvement would not affect academic grades.

Potential risks such as fatigue or digital discomfort were mitigated by: 1) Limiting each session to 45 minutes with interactive breaks. 2) Providing orientation for students with lower digital literacy. 3) Ensuring psychological comfort during interviews through supportive facilitation.

No adverse events were reported during the study.

RESULTS

Student Demographics

Student demographics can be seen at table 1.

Table 1. Student Demographics				
Aspect	**School X**		**School Y**	
	Female	**Male**	**Female**	**Male**
Character	more culturally homogeneous, diverse socio-economic backgrounds		culturally heterogeneous, mostly middle to upper class	
Technology access	varied, some students limited to basic smartphones		nearly all students own laptops and advanced smartphones	
Total students	40	20	40	20
Total	60		60	

Table 1 presents the demographic characteristics of the students who participated in the study from both research sites. It compares the gender distribution, socio-cultural background, and level of technology access between School X (public) and School Y (private). As shown in the table, each school involved 60 students, comprising 40 females and 20 males. School X represents a more socio-economically diverse and culturally homogeneous setting, whereas School Y reflects a predominantly middle-to-upper-class background with higher technological accessibility. These contextual differences provide an essential foundation for interpreting students' responses to podcast-based Green Chemistry learning.

Learning Outcomes (Normalized Gain, g)

Learning outcomes can be seen at table 2.

Table 2. Learning Outcomes (Normalized Gain, g)				
School	**Female Gain**	**Male Gain**	**Category Female**	**Category Male**
School X (Public)	0,610	0,453	Medium	Medium
School Y (Private)	0,672	0,589	Medium	Medium
Overall Average	0,640	0,523	Medium	Medium
Source: Authors' own work, according to the classification (0–0,3 = low, 0,3–0,7 = medium, 0,7–1,0 = high) from Hake, 1998[19]				

Table 2 presents the comparison of normalized gain (g) scores representing students' learning outcomes across two schools. The table distinguishes between female and male students, showing both the numerical gain values and their categorical interpretation (medium level). The data indicate that students from School Y (Private) achieved slightly higher gains than those from School X (Public), with female students showing higher gains than male students overall.Female students achieved higher gains (0,640) than male students (0,523)., all gains fall in the medium category, with female students consistently outperforming males across both schools.

Awareness Outcomes

Themes emerging from interviews include in table 3.

Table 3. Awareness outcomes in various themes		
No	**Themes**	**Context**
1	Family engagement	Students with families practicing eco-friendly habits reported stronger awareness
2	Community influence	Students involved in local community clean-ups or cultural events showed higher cultural awareness
3	School climate	Public school students reported stronger cultural awareness due to exposure to diverse peers
4	Technology use	Students who actively explored digital resources beyond podcasts deepened their understanding
5	Religious/ethical values	Several students connected environmental responsibility to religious teachings or moral obligations
6	Peer influence	Students were motivated when friends discussed podcast content outside class
7	Personal experiences	Some linked awareness to personal observations of pollution or waste in their neighborhoods

Table 3 summarizes the themes that emerged from interview data related to students' awareness outcomes. Each theme highlights different contextual factors influencing awareness development, such as

family engagement, community influence, school climate, technology use, religious and ethical values, peer influence, and personal experiences. The table provides insights into how these factors contributed to variations in students' cultural and environmental awareness.

Interview Data

The following section presents selected excerpts from student interviews conducted in both School X and School Y. The quotes represent diverse reflections from male and female participants, highlighting variations in perception, engagement, and contextual understanding of green chemistry topics introduced through the podcast. These responses illustrate gender-based differences, where female students tend to connect the content to cultural, familial, or ethical dimensions, while male students often focus on technical or practical aspects. They also reflect differing levels of digital literacy, as some students extended their learning beyond the podcast through online exploration and peer discussion.

Female, School X: *"The podcast reminded me of my grandmother's habit of reusing water bottles. I now see it as part of green chemistry."*

Male, School X: *"I enjoyed the science part, but I did not really connect it to my daily life unless the teacher explained more."*

Female, School Y: *"At home we already separate trash, so the podcast made me realize why it matters scientifically."*

Male, School Y: *"My family doesn't talk much about the environment, but the podcast pushed me to think about electricity use at home."*

Female, School X: *"I shared the podcast with my friends in the neighborhood, and we talked about reducing plastic."*

Male, School X: *"It was interesting but sometimes I just listened once. My female classmates discussed it more seriously."*

Female, School Y: *"I liked how the podcast mixed science with culture; it made me proud of local traditions in saving resources."*

Male, School Y: *"I usually play games online. After the podcast, I tried searching for videos about eco-friendly technology."*

Female, School X: *"For me, it connected with my faith—protecting the earth is also a religious duty."*

Male, School X: *"I think it would be better if my peers talked more about it. I learn faster when I discuss with friends."*

The quotes illustrate gender differences (females more reflective and culturally connected, males more focused on technical aspects) and digital literacy differences (some extend learning beyond podcasts, others do not).

Summary of Key Differences

Table 4 below summarizes the key differences identified across major research dimensions, including learning outcomes, environmental awareness, cultural awareness, gender patterns, and digital literacy. The table integrates both quantitative and qualitative findings to highlight how gender, school context, and digital access shaped students' engagement with podcast-based learning. It emphasizes that while overall learning gains were moderate, female students tended to show deeper reflective awareness, and students with greater digital literacy demonstrated extended learning behaviors beyond the classroom.

Table 4. Summary of Key Differences

No	Dimension	Key Findings
1	Learning Outcomes	Female students achieved consistently higher normalized gains (0,640) compared to males (0,523), though all results fall within the medium category.
2	Environmental Awareness	Stronger among students with supportive families, religious grounding, or personal experiences of environmental issues. Technology alone was not sufficient.
3	Cultural Awareness	Public school students demonstrated higher cultural awareness due to heterogeneous peer interactions, while private school students showed steadier reinforcement from family practices.
4	Gender Patterns	Female students were more reflective, engaged, and connected podcasts to family, culture, and values. Male students were more content-focused and less likely to extend discussions outside the classroom.
5	Digital Literacy	Students with higher digital literacy deepened learning by seeking additional resources and engaging in peer or family discussions, while lower literacy limited awareness development.

DISCUSSION

Gender Differences in Learning Outcomes

The findings indicate that female students consistently achieved higher normalized gains than their male peers in both schools. In School X, female students recorded a gain of 0,610 compared to 0,453 for males, while in School Y, the gap was even larger with females achieving 0,672 versus 0,589 for males. When combined, the overall average for female students reached 0,640 compared to 0,523 for males. Although all values fall into the medium category, the pattern shows that females benefitted more strongly from the podcast-based intervention.

This difference can be explained through several dimensions. From a cognitive standpoint, female students are often more responsive to narrative and reflective learning models, which aligns with the podcast format designed around CRTT principles. The integration of cultural narratives and values into science content may have resonated more strongly with females, allowing them to connect personal experiences with abstract green chemistry concepts.

Socio-cultural expectations may also play a role.[20] Female students reported in interviews that they felt a sense of responsibility toward environmental and cultural preservation, reflecting gendered patterns of socialization in Indonesian families and communities. Male students, by contrast, tended to focus more on technical or factual aspects of the podcasts, showing less evidence of reflective integration. This suggests that gender does not simply influence cognitive performance but shapes how students interpret and engage with sustainability-oriented content.[21]

Importantly, the gender differences were present in both the public and private school settings, indicating that the effect was consistent across socio-cultural contexts. This reinforces the idea that gender-sensitive approaches are necessary when designing STEM education interventions aimed at fostering awareness and values, not just academic mastery.

School Context and Cultural Awareness

The comparative setting between School X (public, more culturally homogeneous with diverse socio-economic backgrounds) and School Y (private, culturally heterogeneous, middle to upper class) provides unique insights into how school context mediates awareness outcomes.

Students at School X reported greater exposure to peers from varied socio-economic conditions but shared more homogeneous cultural traditions. Interviews suggested that this context encouraged students to frame environmental responsibility through socio-economic struggles, such as saving electricity or reducing waste to cut costs. Cultural awareness was expressed more narrowly, tied to local practices familiar to most students.

In contrast, School Y students operated in a culturally heterogeneous environment with classmates from diverse regions and traditions. This diversity encouraged broader discussions of cultural awareness, with students recognizing variations in environmental practices across different family backgrounds. For example, some students noted differences in waste management or water conservation practices between their households and those of their peers. The more stable middle-to-upper class background also provided resources that allowed students to more easily act on their environmental awareness, such as installing water filters or practicing recycling with better infrastructure.

The school climate thus shapes how awareness is expressed.[22] Public school students framed green chemistry values as pragmatic strategies for daily living, while private school students contextualized them as cultural and lifestyle choices. These differences underline the importance of considering institutional and cultural settings when designing learning interventions.

Digital Literacy as a Mediator of Awareness

Digital literacy could be a mediator[23] as emerged as a decisive factor in shaping environmental and cultural awareness. Students with high digital literacy did not only consume the podcasts more effectively but also extended their learning by searching for related resources, sharing content with peers, or discussing insights with family members. For example, a male student from School Y reported that after listening to the podcast, he searched online for eco-friendly technologies. Similarly, female students from both schools described sharing podcast lessons with peers and communities, amplifying their impact.

Conversely, students with lower digital literacy often treated the podcasts as a one-time experience. They lacked strategies for revisiting or expanding upon the material, and without strong family or peer support, their awareness gains remained shallow. This demonstrates that digital literacy should not be understood purely as technical skill but rather as the ability to engage critically, socially, and culturally with digital content.[24]

The interviews also revealed that digital literacy interacted with other dimensions such as family engagement and religious values. Students with strong digital literacy and environmentally conscious families demonstrated the highest awareness, reinforcing podcast messages through daily practices. Others connected the podcasts with religious or ethical values, framing sustainability as a moral duty. Peer influence was another factor,

students reported greater motivation when their classmates discussed the podcast outside class, creating a shared learning environment.

Overall, digital literacy acted as a multiplier when combined with supportive social and cultural contexts, it produced stronger awareness outcomes. This suggests that interventions should not only focus on providing access to digital tools but also on cultivating critical and collaborative digital practices.

Multi-dimensional Nature of Awareness Outcomes

Ten representative quotes from students highlight the multi-dimensional nature of awareness outcomes. Several themes emerged as 1) Family engagement 2) Community influence 3) School climate 4) Technology use 5) Religious/ethical values 6) Peer influence and 7) Personal experiences. The explanation of each themes declared by students are described below.

- Family engagement. Responses indicated that female students benefited more from family practices that modelled eco-friendly behaviours. Female students reported greater recall of home-based examples presented in the podcasts and were more likely to describe family conversations that reinforced podcast messages. This alignment appeared to amplify their post-test gains. Male students also referenced family routines, but less frequently tied those practices to conceptual understanding. Family engagement for males tended to support behavioural intentions more than conceptual integration, producing smaller incremental gains.
- Community influence. Participation in community clean-ups and cultural events correlated with higher cultural awareness for both genders, but females more often described emotional and relational links between community activities and podcast narratives (e.g., "this reminded me of…," "I felt responsible for…"). These affective connections helped females transfer local examples into broader sustainability concepts, supporting higher normalized gains. Males tended to report community involvement in pragmatic terms (task, role), which bolstered motivation but less consistently translated into conceptual gains measured by the tests.
- School climate. The comparative setting showed that public school students reported stronger cultural awareness due to peer diversity, within that context, female students leveraged peer discussions to deepen meaning-making about podcast content, whereas male students engaged in peer talk more for problem-solving or factual clarification. Consequently, female students in mixed-peer environments showed larger gains in items assessing contextual application, while males improved on procedural or recall items to a lesser extent.
- Technology use. Students who actively explored digital resources beyond the podcasts deepened their understanding. This effect was gender-differentiated. Female students who demonstrated higher digital literacy often used social and collaborative tools (discussion threads, shared notes) to elaborate podcast ideas, which reinforced learning and awareness. Male students with similar digital literacy tended to use technical search strategies (quick lookups, fact checks) that improved factual accuracy but produced smaller increases in integrative awareness. Thus, digital practices mediated gender differences in whether technology amplified conceptual versus factual gains.
- Religious/ethical values. Several female students explicitly framed environmental responsibility through relational and duty-based religious language, linking podcast themes to moral obligations and everyday choices, such framing supported sustained behavioural intentions and deeper reflective answers in interviews, aligning with higher post-test performance on application items. Male students also invoked ethical or religious justifications, but more often in abstract or principle-based terms that correlated less strongly with changes in daily practices or with the test items oriented to applied understanding.
- Peer influence. Peers discussing podcast content outside class motivated students of both genders, but females reported more frequent and sustained peer conversations (e.g., study groups, sharing examples), which reinforced internalization of messages and supported higher gains. Male peer influence often manifested as short, competitive exchanges (quizzes, correctness checks) that increased engagement but less reliably enhanced deeper awareness measured qualitatively.
- Personal experiences. Students who had direct exposure to pollution or waste in their neighborhoods connected podcast content to lived consequences. Female narratives tended to emphasize caregiving and stewardship roles, linking observations to concrete behaviour change and reflective insight, which paralleled stronger normalized gains. Male narratives emphasized observation and problem identification, sometimes proposing technical fixes; these responses increased problem-solving orientation but less often reflected the integrated awareness captured in interview themes and some post-test items.

Overall, these theme-level patterns suggested that female students more frequently integrated socio-cultural narratives, relational meanings, and collaborative digital practices stimulated by the podcasts into both awareness and measurable learning gains. Male students showed gains as well, but their pathways were

relatively more oriented to pragmatic, factual, or instrumental routes (task-oriented peer talk, technical digital searches, problem identification), which resulted in smaller but still meaningful normalized gains. These gendered tendencies did not imply deterministic differences but rather highlighted how gender interacted with family, community, school, technology, religion, peers, and lived experience to shape the depth and form of awareness produced by the podcast intervention.

Podcasts acted as a catalyst, but students' ability to translate messages into awareness depended heavily on their socio-cultural and personal environments. This finding is consistent with CRTT principles, which emphasize connecting academic content to students' cultural realities. By embedding green chemistry values into culturally responsive narratives, the podcasts provided multiple entry points for students to engage meaningfully. Yet, the depth of engagement was contingent upon how well these narratives resonated with each student's context.

Synthesis Findings

The synthesis of findings demonstrates that podcast-based Green Chemistry learning strengthened student awareness, yet the pathways and depth of impact differed across gender and digital literacy dimensions. The podcasts, designed through the CRTT framework, functioned not only as instructional tools but as cultural mediators that connected sustainability concepts with students' lived realities. Through narrative-driven and contextually grounded episodes, students developed multidimensional awareness encompassing environmental, cultural, ethical, and technological aspects.

When gender and digital literacy were analyzed together, a clear interaction effect emerged. Female students with high digital literacy consistently demonstrated the deepest awareness gains, combining relational, reflective, and collaborative modes of engagement. Their digital fluency allowed them to navigate, reinterpret, and share podcast content through social and community-based platforms, transforming passive listening into active meaning-making. Male students with high digital literacy, in contrast, showed greater improvement in factual comprehension and problem-solving orientation but tended to engage less with cultural or ethical layers of the content.

Students with limited digital literacy, regardless of gender, exhibited constrained learning trajectories. Without the ability to re-access or critically engage with the digital material, their awareness remained at surface-level and heavily reliant on classroom mediation. In public schools, this limitation was often intertwined with socio-economic factors restricting access and digital exposure. In private schools, lack of family participation or moral reinforcement constrained the translation of knowledge into awareness.

These findings suggest that gender and digital literacy function as intersecting mediators that shape how students internalize sustainability-oriented messages. Female students benefited more affectively and contextually, while male students exhibited strength in analytic and instrumental understanding. Meanwhile, digital literacy amplified the depth and persistence of awareness by enabling students to critically extend podcast learning beyond formal instruction.

In synthesis, podcast-based Green Chemistry learning proved effective in strengthening student awareness, yet the outcomes were distinct and context-dependent. Awareness emerged most robustly when cultural relevance, gender responsiveness, and digital competence converged. Therefore, future STEM education interventions should integrate gender-sensitive approaches with digital literacy development to ensure that digital learning tools not only inform but also transform students' environmental and cultural consciousness.

Limitations and Future Directions

While this study provides valuable insights into the impact of podcast-based Green Chemistry learning across gender and digital literacy dimensions, several limitations should be acknowledged.

First, the sample size was limited to two schools with relatively specific socio-cultural and institutional contexts. This restricts the generalizability of findings to other educational settings, particularly those with different technological access levels or cultural orientations. Future studies could expand to a larger and more diverse sample, including rural or vocational schools, to examine whether similar gendered and digital literacy patterns persist.

Second, although the study employed mixed methods through pre–post testing and qualitative interviews, the design remained primarily descriptive and exploratory. More robust experimental or longitudinal designs could help determine causal relationships between podcast engagement, awareness development, and behavioural changes over time. Incorporating digital learning analytics (e.g., tracking listening duration, content revisits, or interaction logs) would provide a more objective measure of engagement and its correlation with awareness outcomes.

Third, the podcast content itself focused primarily on narrative and reflective aspects of Green Chemistry. While this approach effectively nurtured affective and cultural awareness, it may have limited the development of advanced conceptual or problem-solving skills, particularly for male students who demonstrated stronger instrumental tendencies. Future iterations of the media could integrate more interactive, inquiry-based, or

gamified features, ensuring balanced engagement across learning styles and gender orientations.

Lastly, the study's qualitative findings on digital literacy suggest a broader systemic challenge such as unequal access to digital resources and uneven support from families or schools. Therefore, subsequent research should explore how institutional policies, teacher facilitation, and community partnerships can enhance equitable access and foster collaborative digital practices that sustain awareness beyond classroom boundaries.

Overall, while this study confirmed the transformative potential of podcast-based STEM learning, future work must deepen its scope by scaling across diverse contexts, integrating more interactive digital tools, and adopting longitudinal evaluation to ensure that digital and cultural responsiveness truly converge to shape sustainable scientific citizenship.

CONCLUSIONS

This study demonstrated that podcast-based Green Chemistry learning, grounded in the Culturally Responsive Transformative Teaching (CRTT) framework, effectively strengthened students' environmental and cultural awareness while revealing distinct outcomes across gender and digital literacy dimensions. Female students consistently achieved higher normalized gains and exhibited deeper reflective and affective engagement, particularly when supported by high digital literacy and strong socio-cultural networks such as family and peer collaboration. Male students also benefited from the intervention, showing notable improvement in factual comprehension and problem-solving orientation, though with less integration of cultural and ethical perspectives. Digital literacy emerged as a pivotal mediator that amplified awareness when combined with supportive social contexts, transforming podcast learning from passive listening into critical, collaborative, and contextually grounded practice. Across both public and private school settings, awareness developed most robustly when gender responsiveness, cultural relevance, and digital competence intersected. These findings highlight the transformative potential of podcast-based STEM learning to bridge scientific understanding with socio-cultural meaning, reinforcing the need for educational designs that integrate gender-sensitive and digitally inclusive approaches to foster sustainable scientific awareness among students.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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