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Integration of TPACK and Education for Sustainable Development in Digital Green Chemistry Worksheets: Efforts to Enhance Student Creativity through Contextual Learning

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Abstract: This research investigates the development and effectiveness of a digitally delivered worksheet designed to enhance students' creative thinking in green chemistry through the integration of Technological Pedagogical Content Knowledge (TPACK) and Education for Sustainable Development (ESD). Grounded in both constructivist learning theory and the framework of sustainability education, the study utilizes digital technology to facilitate contextual learning by engaging students in a real-world project: transforming used cooking oil into aromatherapy candles. The worksheet was implemented in a quasi-experimental one-group pretest-posttest design involving 34 tenth-grade students. A two-tiered test was used to assess the impact on creative thinking, measuring four indicators: fluency, flexibility, originality, and elaboration. Statistical analyses demonstrated significant improvement across all indicators, with flexibility showing the highest normalized gain (N-Gain = 0.72) and a large effect size (Cohen's *d* = 1.24). These outcomes align with prior studies emphasizing TPACK's capacity to foster higher-order thinking skills and ESD's role in improving sustainability literacy. The findings underscore the promise of TPACK-ESD-integrated digital resources as effective tools for cultivating creativity and sustainability-oriented competencies in chemistry education. This study also highlights broader implications for curriculum reform, teacher professional development, and the institutional adoption of digital, sustainability-focused learning materials.

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INTRODUCTION

Chemistry education faces critical challenges in helping students connect theoretical knowledge to real-life applications. The Programme for International Student Assessment (PISA) 2022 results reveal that many students struggle to comprehend complex chemistry concepts, particularly when such content is abstract or not grounded in meaningful context. Traditional instruction methods that rely heavily on rote memorization and textbook-centered delivery have proven insufficient in preparing students to confront the multifaceted sustainability challenges of the 21st century, including environmental pollution, resource depletion, and climate change. Responding to these challenges requires a transformative shift in teaching approaches that integrates contextual, interdisciplinary, and technology-supported learning. This study attempts to address these gaps by incorporating TPACK, as proposed by Koehler and Mishra (2009), and ESD, as advocated by UNESCO (2017), into a digital chemistry worksheet. By doing so, the study aligns with recent calls in the literature for innovative, student-centered, and technology-enhanced pedagogical strategies that empower learners to think critically and act responsibly in a sustainable society.

The integration of TPACK and ESD serves as the theoretical foundation for this study. The TPACK framework emphasizes the need for teachers to blend technological knowledge, pedagogical strategies, and subject matter expertise to design effective and engaging instruction. In the context of chemistry education, TPACK supports the use of simulations, animations, and interactive platforms to clarify abstract scientific concepts such as molecular interactions and reaction mechanisms. These digital tools not only facilitate comprehension but also foster deeper student engagement and participation, as noted by Lachner et al. (2021). On the other hand, ESD promotes learning experiences that are contextually relevant and focused on sustainability. It encourages students to understand the environmental, economic, and social dimensions of scientific phenomena and to act accordingly. Through the lens of green chemistry, ESD links science education with real-world applications such as waste reduction and renewable resource use. The digital worksheet developed in this study is anchored in these principles, featuring a hands-on project that requires students to upcycle used cooking oil into aromatherapy candles. This activity illustrates the practical value of chemistry and reflects Larsen et al.'s (2020) emphasis on project-based learning that cultivates environmental stewardship and responsible citizenship.

Although numerous studies have examined the effectiveness of the TPACK framework in STEM education and highlighted ESD's contribution to sustainability literacy, limited research has explored the combined impact of these two approaches on fostering students' creative thinking in chemistry. Existing literature tends to treat TPACK and ESD as separate domains, leaving a critical gap in understanding how their integration might contribute to higher-order cognitive development, particularly in the context of green chemistry education. Moreover, while project-based learning (PjBL) is increasingly recognized for its ability to promote creativity, few studies explicitly measure creativity outcomes using established indicators. This research seeks to fill that void by designing and testing a digital worksheet that integrates TPACK and ESD through a PjBL approach, with student creativity assessed based on Munandar's (2012) four indicators of creative thinking: fluency, flexibility, originality, and elaboration. By addressing this gap, the study contributes to the growing body of knowledge on innovative chemistry teaching practices that enhance content mastery and nurture the competencies required for sustainable living.

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METHOD

This study employed a quasi-experimental design with a one-group pretest-posttest structure to assess the impact of the digital worksheet intervention. Ethical clearance was obtained prior to data collection. The participants were 34 tenth-grade students (average age = 15.5 years) from a public senior high school in Semarang, Central Java, Indonesia. The intervention consisted of a digital worksheet developed using Liveworksheets.com, incorporating multimedia elements and structured based on project-based learning stages. These stages—formulating essential questions, planning the project, implementing the solution, and evaluating results—are aligned with creative thinking indicators. Students were guided through a real-world chemistry project: converting waste cooking oil into functional aromatherapy candles. This project involved applying stoichiometric calculations and understanding green chemistry principles such as atom economy, renewable feedstocks, and energy efficiency.

Data collection involved a two-tiered multiple-choice test containing 25 items that assessed students' creative thinking across the four indicators. The reliability of the test was confirmed with a Cronbach's alpha of 0.82, indicating good internal consistency. The data were analysed using both descriptive and inferential statistics. The Shapiro-Wilk test confirmed that the data followed a normal distribution ($p > 0.05$), justifying the use of a paired *t*-test to compare pretest and post-test scores. To quantify learning gains, normalized gain (N-Gain) and Cohen's *d* effect size were calculated following the methods described by Hake (1998).

RESULT AND DISCUSSION

Comprehensive Chemistry Curriculum for 21st Century Learners

A comprehensive high school chemistry curriculum is essential for equipping students not only with basic knowledge and scientific process skills but also with a deep understanding of natural phenomena and real-world challenges. Systematic material organization, from fundamental concepts such as atomic structure to complex topics like thermochemistry and electrochemistry, enables students to build a strong conceptual foundation (Latip et al., 2023). Additionally, developing skills such as observation, measurement, and data analysis strengthens their critical thinking abilities. Furthermore, the curriculum must be contextual, linking chemistry concepts to global issues such as renewable energy and climate change to make learning more relevant and meaningful (Sausan et al., 2025; Sujud et al., 2024). The contextual learning approaches significantly improve student engagement and conceptual understanding in chemistry. Their study showed that when chemical concepts are taught through real-world applications, students demonstrate better retention and ability to transfer knowledge to novel situations. This is particularly important in addressing the persistent challenges revealed by international assessments like PISA, where students often struggle to apply chemical knowledge to authentic problems (OECD, 2022).

Integrating the chemistry curriculum with ESD principles is also key to creating transformative learning. Chemistry is studied not only as a pure science but also as a tool to understand and solve environmental, social, and economic sustainability problems. Curriculum reconstruction supporting ESD can be carried out using contextual approaches relevant to real life. For example, the topic of acid-base reactions should cover the Bronsted-Lowry concept and its application in waste management and environmental pollution. Similarly, organic chemistry and polymers can be linked to fossil energy and climate change issues, so students learn not just theory but also understand the social-environmental impact of chemistry and the importance of sustainable solutions through alternative energy. Redox reactions can be taught through case studies of electric vehicle batteries, while acid-base material can be related to industrial waste neutralization. Stoichiometry can be used to calculate the carbon footprint of chemical reactions, and thermochemistry can be used to analyse the energy efficiency of household technologies. This approach makes chemistry learning more applicable, critical, and aligned with global challenges.

The cradle-to-cradle (C2C) concept is an important approach in teaching chemical elements to build awareness of recycling and sustainability (Teo et al., 2024). Students are encouraged to analyse the management of transition metals, rare elements, and carbon materials such as plastics and lithium batteries in the context of recycling and resource efficiency, including hydrogen elements in the green economy, highlighting the importance of clean energy production. By integrating C2C principles, students not only learn the characteristics of elements but also understand sustainable chemical strategies to address resource and environmental crises (Tamoor et al., 2022).

The cradle-to-cradle (C2C) concept, originally developed by Braungart and McDonough, provides an innovative framework for teaching chemical elements and their role in sustainable systems. This approach goes beyond traditional environmental education by emphasizing positive design principles rather than minimizing harm (Braungart et al., 2007). When applied to chemistry education, C2C principles encourage students to analyze the complete life cycles of materials, focusing particularly on transition metals, rare earth elements, and carbon-based materials (Sjöström & Talanquer, 2018). For example, students can investigate the management of lithium in battery technologies, examining both the environmental impacts of extraction and the potential for closed-loop recycling systems. Similarly, the study of plastics can extend beyond polymerization reactions to include circular economy concepts and biodegradable alternatives (Tamoor et al., 2022). The hydrogen economy provides another rich context for applying C2C thinking, allowing students to explore hydrogen production methods (including green hydrogen from renewable sources), storage technologies, and fuel. Recent work by Teo et al. demonstrates how C2C principles can be effectively integrated into secondary chemistry education. Their study showed that students who learned chemistry through this framework developed stronger systems thinking skills and were better able to propose innovative solutions to material sustainability challenges (Teo et al., 2024). Similarly, Tamoor et al. found that C2C-based instruction significantly improved students' understanding of life cycle assessment and sustainable design principles (Tamoor et al., 2022).

Digital Worksheets as a Delivery Mechanism

One effective method for delivering this enhanced curriculum is through carefully designed digital worksheets. In our study, we developed a series of digital worksheets incorporating Project-Based Learning (PjBL) methodologies to support Green Chemistry instruction aligned with Phase E of Indonesia's Merdeka Curriculum for tenth-grade students. These materials package chemical concepts through project activities that emphasize environmental issues and sustainable practices, consistent with ESD principles. One of the worksheets was based on Project-Based Learning (PjBL) and designed to support Green Chemistry material learning in phase E of the Merdeka Curriculum for grade X. The material is packaged through project activities emphasizing environmental issues and sustainable practices, in line with ESD principles. This digital worksheet encourages exploration of chemistry understanding through authentic and contextual activities, such as utilizing used cooking oil waste to make aromatherapy candles.

The main characteristic of this digital worksheet lies in the integration between PjBL syntax structure and creative thinking indicators: fluency, flexibility, originality, and elaboration, as developed by Munandar (U. Munandar, 2012). Each learning stage, from formulating fundamental questions, designing projects, to final evaluation, is designed to stimulate students' abilities to solve problems creatively and reflectively. The creative thinking indicators are clearly stated in the digital worksheet, facilitating teachers in analysing student abilities. Each learning component is designed to strengthen student engagement. For example, in the project planning stage, students are guided to generate diverse ideas reflecting Green Chemistry and ESD principles, aided by video guides and flexible scheduling columns. Project evaluation is packaged through digital reports and multimedia presentations that reinforce the elaboration aspect of creative thinking. Student activities in the worksheet begin with determining fundamental questions (the first PjBL syntax), aimed at training fluency: generating rapid answers to problems or questions and considering alternative responses (Figure 1).

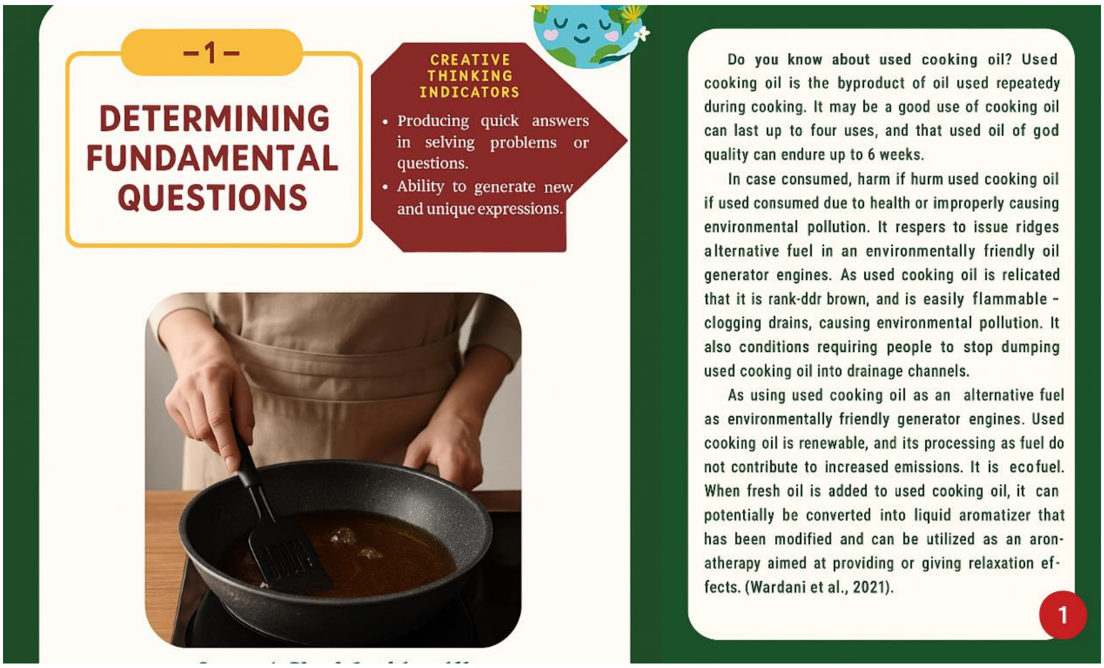

Figure 1. Student activity in the digital worksheet begins with formulating an essential question (syntax 1 of PjBL). This activity is designed to train the fluency indicator: producing answers quickly in response to a problem or question (1), and the ability to consider alternative answers (2).

The creativity indicator consists of four interrelated aspects—fluency, flexibility, originality, and elaboration—each playing a distinct yet complementary role in shaping a person's overall creative thinking ability. Fluency refers to the capacity to generate numerous ideas or responses to a specific problem or question. This aspect not only emphasizes quantity but also reflects the ease and speed with which individuals can produce multiple alternatives. A high level of fluency demonstrates a mind that is open, agile, and able to consider many possibilities, which is a crucial first step in the creative process. Building on this, flexibility highlights the diversity and variety of those responses. Rather than producing many similar ideas, a flexible thinker can shift perspectives, apply different strategies, and adapt to changing conditions. This aspect is essential in problem-solving, as it reflects the ability to think beyond conventional frameworks and embrace multiple viewpoints. Originality, often seen as the core of creativity, pertains to the uniqueness and novelty of the ideas generated. It reflects an individual's capacity to produce uncommon or surprising solutions, or to synthesize unrelated concepts into an innovative whole. This ability to break from the norm and think differently often leads to breakthroughs and discoveries. Lastly, elaboration deals with the richness and detail of an idea. It involves the ability to expand, refine, and develop an initial thought into a more comprehensive and functional concept. Original ideas may remain vague or underdeveloped without elaboration, limiting their practical utility. Together, these four components form a robust framework for evaluating and cultivating creativity, especially in educational contexts (Fahmi & Jumadi, 2023; Purwanti et al., 2024).

In classroom applications—especially in chemistry education integrated with Education for Sustainable Development (ESD)—these indicators can effectively guide teaching and assessment. For instance, in project-based learning (PjBL) settings, every phase of the learning process is designed to nurture and assess students' creative thinking abilities. From the formulation of essential questions to the design, implementation, and final evaluation of a project, students are encouraged to explore multiple pathways, adapt their strategies, and refine their ideas with increasing depth. The digital worksheet developed in this context explicitly incorporates these four creativity indicators. By embedding these elements directly into student tasks and reflections, the worksheet serves as a learning scaffold and provides a transparent framework for teachers to observe and evaluate student progress. Moreover, when students are made aware of these criteria, they become more intentional in how they approach problem-solving and idea development, leading to deeper metacognitive engagement. Teachers can then use this insight to give targeted feedback and differentiate instruction based on individual creative profiles. As a result, the integration of fluency, flexibility, originality, and elaboration into instructional design and assessment promotes a more reflective, student-centered learning environment that aligns with the goals of sustainable and innovative education.

Table 1. Creative Thinking Indicators (U. Munandar, 2012)

Creativity Indicator	Detailed Aspects
Fluency	1. Producing answers quickly in response to a problem or question. 2. The ability to consider alternative answers.
Flexibility	3. Generating diverse ideas, answers, or statements and being able to view problems from multiple perspectives. 4. Ability to approach or think from different angles.
Originality	5. The ability to produce new and unique expressions. 6. Ability to combine various components or elements.
Elaboration	7. Expanding details of an object or idea to make it more developed.

Technological integration emerges as one of the key strengths of the digital worksheet medium used in this study. Delivered through the Liveworksheets.com platform, the worksheet is complemented by a range of digital tools, including Google Classroom for assignment management, YouTube for visual demonstrations, and references from scientific journals to encourage data-based reasoning. This integrated approach enhances not only the flexibility and accessibility of learning but also cultivates essential digital literacy skills among students in the context of problem-based chemistry education, as funding in another research. By engaging with multimedia content and interactive tools, students are exposed to real-world scientific inquiry processes, making the learning experience more dynamic and relevant (Ulya & Rusmini, 2022). The digital worksheet serves a dual purpose: it encourages students to ask meaningful questions, collaborate effectively, and take ownership of their projects, while providing teachers with an innovative instructional resource that supports curiosity, self-directed learning, and personalized feedback (Susanti et al., 2024). In this way, the worksheet bridges content mastery and 21st-century skills, fostering a creative, contextual, and sustainability-oriented approach to science education. These benefits are supported by prior research, which highlights the positive impact of project-based and interactive digital media on student interest, creativity, and academic achievement (Ayirahma & Muchlis, 2023). As students navigate multiple digital platforms and resources, they also practice evaluating credible information, communicating ideas, and engaging in reflective thinking—skills critical for lifelong learning and global citizenship (Batubara et al., 2024).

To evaluate the effectiveness of this digital worksheet, a limited-scale implementation was conducted involving 34 students from a single class. The central parameter for assessing its impact was students’ conceptual understanding, measured through a designed 25-item two-tier multiple-choice test requiring students to justify their answers through open-ended reasoning. This type of instrument was chosen to assess the correctness of responses and the depth of students’ conceptual thinking. Prior to the learning intervention, students completed a pre-test to establish a baseline of their understanding. Following the use of the digital worksheet, which included interactive exercises, reflective questions, and project-based tasks, a post-test was administered. The comparison between pre- and post-test results enabled researchers to determine how the digital worksheet influenced students’ ability to grasp complex chemistry concepts and apply them in novel contexts. As summarized in Figure 2, students demonstrated notable improvements in their conceptual understanding, reflecting the effectiveness of the worksheet in promoting higher-order thinking and creative problem solving. These outcomes underscore the potential of digitally integrated, project-based learning tools to transform chemistry education into a more engaging, student-centered, and impactful experience. Additionally, the use of open-ended justifications allowed for richer analysis of students’ reasoning patterns, providing valuable insights for future instructional design and assessment refinement.

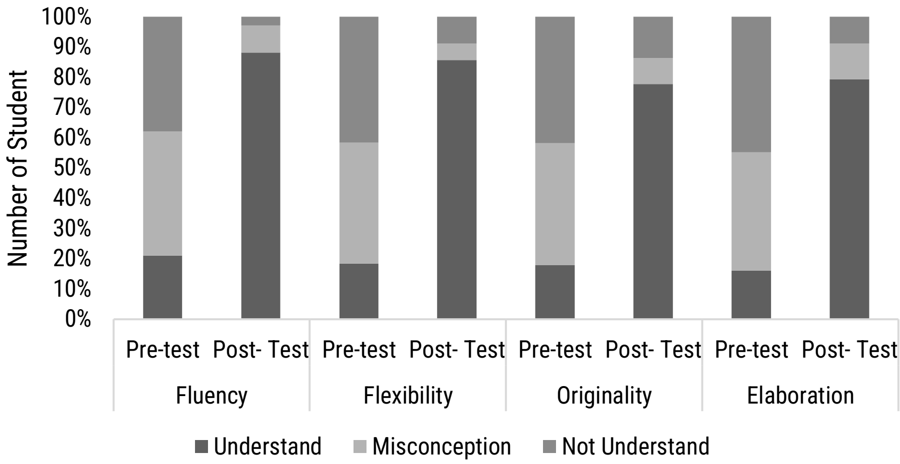

Figure 2. Pre-test and post-test results: overall, there was an increase in students' understanding of green chemistry concepts after implementing the digital worksheet.

The pretest and post-test data analysis showed a significant increase in students’ creative thinking abilities after the learning intervention. All four creative thinking indicators- fluency, flexibility, originality, and elaboration- showed positive shifts in student understanding. In the pretest stage, most students were in the categories of misunderstanding and misconception, especially in the flexibility and elaboration aspects. The post-test results indicated a significant improvement in students’ creative thinking abilities, especially in the flexibility and elaboration indicators. The normalized gain (N-Gain) analysis showed that the flexibility indicator achieved the highest average gain, followed by fluency, originality, and elaboration. This finding suggests that the project-based digital worksheet effectively encourages students to generate diverse ideas and solutions in the context of green chemistry.

The quantitative data revealed significant improvements across all four creative thinking indicators. Normalized gain scores (Hake, 1998) indicated strong growth, with the highest gain in flexibility ($g = 0.72$), followed by fluency ($g = 0.65$), originality ($g = 0.58$), and elaboration ($g = 0.54$). These findings suggest that the project-based approach was particularly effective in helping students approach problems from multiple perspectives and generate diverse solutions. Further analysis using paired t-tests confirmed statistically significant differences between pretest and post-test scores ($p < 0.01$ for all indicators), with large effect sizes (Cohen's d ranging from 1.12 to 1.45), indicating the practical significance of the intervention. These results are consistent with prior research highlighting the effectiveness of project-based learning (PjBL) in science education (Cao et al., 2025; McLaughlin et al., 2024; Prasetya et al., 2021) and the benefits of digital learning tools (Marnita et al., 2024; Schubatzky et al., 2023). Qualitative data from student interviews provided additional context for the quantitative findings. Many students expressed that the cooking oil candle project allowed them to perceive chemistry as "something real and useful," rather than as abstract, textbook-bound knowledge. They also noted that the digital format enhanced their engagement and accessibility, particularly through features like revisitable video tutorials and online collaboration.

These findings carry significant implications for the future of chemistry education. Firstly, curriculum design should intentionally incorporate more Education for Sustainable Development (ESD)-aligned, project-based learning modules to foster student engagement and contextual understanding, as emphasized by Juntunen and Aksela (Juntunen & Aksela, 2014). Such modules encourage students to apply chemistry concepts to real-world sustainability issues. Secondly, teacher education programs must be strengthened by embedding the development of Technological Pedagogical Content Knowledge (TPACK) alongside ESD principles, ensuring that educators are well-equipped to deliver innovative and meaningful instruction (Fabian et al., 2024; Ortega-Sánchez, 2023). Thirdly, there is an urgent need for schools and institutions to invest in high-quality digital learning resources that promote interactive, student-centered, and contextually relevant learning experiences. Finally, assessment systems should be reformed to explicitly evaluate students' creative thinking abilities, including fluency, flexibility, originality, and elaboration, in alignment with the recommendations of Hu and Adey (Hu & Adey, 2002), Hadzigeorgiou (Hadzigeorgiou et al., 2012), and Kange et al. (Kange et al., 2025).

Limitation and Recommendation

Despite its promising results, the study had several limitations. The small sample size (N = 34) limits the generalizability of the findings. The short duration of the intervention (two weeks) also restricts conclusions about long-term retention. Additionally, the study did not include a control group for comparison, and potential teacher effects were not controlled. Future research should address these limitations by employing larger-scale, longitudinal studies with controlled experimental designs. It would also be valuable to explore the transferability of creative thinking skills to other chemistry topics, examine the intervention's impact on underserved student populations, investigate the influence of specific technological features on learning outcomes, and develop similar resources for other science disciplines.

The integration of ESD and TPACK in digital worksheets not only enhances students' conceptual understanding but also fosters their environmental awareness and responsibility. Through project activities, students are trained to identify environmental issues, analyse problems critically, and design innovative environmentally friendly and sustainable solutions. This approach aligns with the demands of 21st-century education, which prioritizes the development of higher-order thinking skills, digital literacy, and sustainable values. The use of digital worksheets also provides flexibility in the learning process, allowing students to access materials and complete assignments independently or collaboratively. The interactive features of the digital platform, such as embedded videos, hyperlinks to scientific articles, and digital reporting, further enrich the learning experience and support the achievement of learning objectives.

CONCLUSION

The development and implementation of a project-based digital worksheet that integrates Education for Sustainable Development (ESD) and Technological Pedagogical Content Knowledge (TPACK) principles have demonstrated significant effectiveness in enhancing students' creative thinking skills, particularly within green chemistry topics. This digital worksheet promotes contextual and meaningful learning experiences while fostering students' environmental awareness and sense of responsibility. The marked improvement across all four creative thinking indicators—especially flexibility—highlights the ability of this approach to encourage diverse, innovative problem-solving strategies rooted in real-world contexts.

These findings affirm that integrating ESD and TPACK into digital learning media design is a powerful strategy for delivering chemistry education that is both content-rich and creativity-driven and sustainability-focused. The project-based format further enables students to apply their knowledge collaboratively, reflectively, and impactfully. For broader application and greater educational impact, further research is encouraged to implement this digital worksheet model across different chemistry topics and education levels, as well as to investigate its long-term influence on students' environmental attitudes, behaviours, and academic growth.

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