UNIVERSAL EDUCATION
JOURNAL OF TEACHING AND LEARNING
UEJTL: Universal Education Journal of Teaching and Learning
E-ISSN: 3047-8235
2025, Vol. 2, No. 3, pp. 97~104
DOI: https://doi.org/10.63081/uejtl.v2i3.83

Original Research

Developing Sustainable Technological Pedagogical Content Knowledge (S-TPACK) in Teaching Science

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Article Info

Article history:

Received 08 08, 2025
Revised 09 11, 2025
Accepted 09 13, 2025

Keywords:

Sustainable TPACK
Science education
Eco-friendly technology integration
Professional development
Environmental Stewardship

ABSTRACT

This mixed-methods study introduces the concept of Sustainable Technological Pedagogical Content Knowledge (Sustainable TPACK), extending the TPACK framework with a focus on eco-friendly technology integration in science education. The research aimed to operationalize the Sustainable TPACK framework and explore its application in science teaching contexts. A survey was administered to assess in-service science teachers' self-reported Sustainable TPACK levels, followed by in-depth case studies involving classroom observations, interviews, and document analysis. The findings demonstrated that science teachers generally possessed moderate to high levels of Sustainable TPACK and faced challenges in implementing eco-friendly technology, which could be overcome through collaboration and professional development opportunities. The study highlights the need for targeted initiatives supporting science educators in developing Sustainable TPACK, fostering environmental stewardship among students, and addressing domain-specific challenges. Future research may examine the impact of Sustainable TPACK on student learning outcomes and the effectiveness of various professional development strategies in promoting this framework among science educators.

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1. INTRODUCTION

In recent years, the urgency to address environmental challenges and promote sustainable practices has become increasingly apparent. The integration of technology in education can play a pivotal role in fostering a generation of environmentally-conscious citizens. Building upon the established Technological Pedagogical Content Knowledge (TPACK) framework, Sustainable TPACK highlights the importance of incorporating eco-friendly technology in teaching practices to cultivate environmental stewardship among students.

The TPACK framework has been widely used to understand and develop teachers' knowledge and skills in effectively integrating technology into their pedagogy. However, there is a need to expand the scope of TPACK to address environmental sustainability, given the critical role education plays in shaping future generations' attitudes and behaviors towards the environment. This introduction to Sustainable TPACK serves as a starting point for exploring how teachers can integrate eco-friendly technology in their teaching practices, ultimately contributing to a more sustainable future.

By examining the interplay between technological, pedagogical, and content knowledge in the context of environmental sustainability, this study emphasizes the importance of fostering a comprehensive understanding of Sustainable TPACK among educators. In doing so, the current study aims to empower teachers to design and implement innovative learning experiences that not only leverage technology effectively (Roozafzai, 2024a; Roozafzai, 2024b) but also encourage environmental stewardship among their students.

The Technological Pedagogical Content Knowledge (TPACK) framework has been widely recognized as a valuable tool for understanding the complex interplay between technology, pedagogy, and content knowledge in educational contexts (Koehler & Mishra, 2009). However, recent studies have highlighted the need to expand TPACK to address contemporary challenges, such as environmental sustainability (Fahrurozi et al., 2019; Purwianingsih et al., 2022; Latip et al., 2023).

Research on education for sustainable development (ESD) emphasizes the importance of integrating environmental concerns into teaching practices (Lotz-Sisitka et al., 2015). Moreover, scholars have identified technology as a potential catalyst for promoting sustainable behaviors and raising awareness about environmental issues (Midden et al., 2007; Ballew et al,. 2015). However, limited research has explored the intersection of TPACK and ESD, particularly in terms of eco-friendly technology integration.

The concept of Sustainable TPACK emerged in response to this gap in the literature, aiming to bridge the worlds of technology integration and environmental sustainability in education (Matherson et al., 2014; Cherner & Smith, 2017). By considering the ecological impact of technology use in teaching practices (studies such as Roozafzai & Zaeri, 2024a; Roozafzai & Zaeri, 2024b; Roozafzai, 2024c), Sustainable TPACK can guide educators in designing and implementing environmentally-conscious pedagogical strategies (Koehler et al., 2013; Purwianingsih et al., 2022).

The escalating climate crisis and the urgent global imperative for sustainability (IPCC, 2022) underscore a critical gap in educational frameworks: while technology integration (TPACK) and Education for Sustainable Development (ESD) are well-researched, they largely exist in separate silos. Previous research has effectively outlined the components of TPACK (Koehler & Mishra, 2009) and championed the importance of ESD (Lotz-Sisitka et al., 2015). Scholars have also called for a reconceptualization of TPACK for modern challenges (Cherner & Smith, 2017) and noted the potential of technology to foster sustainable behaviors (Ballew et al., 2015). However, the specific integration of these fields into a unified framework for teachers to explicitly link pedagogical technology use with ecological responsibility remains novel and urgently needed.

This study directly addresses this gap by introducing and operationalizing the Sustainable TPACK framework. The novelty of this research lies in its deliberate fusion of these two critical domains, moving beyond theoretical calls to action by providing an empirical investigation into its practical application in science classrooms. Unlike previous studies that may touch on aspects of sustainability or technology, this research uniquely positions itself by defining a concrete Sustainable TPACK construct with measurable components, thereby moving from a theoretical concept to an empirically investigable framework. It then quantifies in-service science teachers' knowledge levels within this new framework, providing a crucial baseline understanding of the current landscape. Finally, the study moves beyond mere measurement to identify the specific, practical barriers and facilitators that impact its implementation, offering actionable insights for teacher development and educational policy.

So by investigating the application of Sustainable TPACK in educational settings and examining its implications for eco-friendly technology integration, this study aims to address the following: understand Sustainable TPACK as a critical component of teacher knowledge in the 21st century and identify effective strategies to support educators in fostering environmental stewardship among their students. So one research question for the study on Sustainable TPACK in science teaching could be:

What challenges do science teachers face in integrating eco-friendly technology into their teaching practices, and how can targeted professional development opportunities help overcome these challenges to enhance their Sustainable TPACK?

This research question addresses both the obstacles teachers encounter in implementing Sustainable TPACK and the potential solutions in the form of professional development to improve their knowledge and skills in eco-friendly technology integration.

2. METHOD

To explore the concept of Sustainable TPACK and its application in educational contexts, a mixed-methods approach was employed. This methodology would allow for a comprehensive understanding of the phenomenon by integrating both quantitative and qualitative data.

3.1. Participants

The participants in this study consisted of 100 in-service teachers from various public and private schools teaching science across different regions. The sample included teachers from diverse subjects in science, grade levels, and years of teaching experience. All participants had prior experience with technology integration in their teaching practices and were familiar with the concept of flipped classrooms. Summary of participant demographics as shown in Table 1.

By including a diverse range of participants in terms of their backgrounds and teaching contexts in science, this study aimed to provide a comprehensive understanding of the application of Sustainable TPACK in various educational settings.

3.2. Research Implementation Stage

3.2.1. Phase 1: quantitative survey

A survey was administered to a sample of in-service teachers to assess their self-reported Sustainable TPACK levels. The survey instrument was developed based on the existing TPACK survey (Schmidt et al., 2009) and adapted to include items related to eco-friendly technology integration. Descriptive statistics will be used to analyze the survey data, providing an overview of teachers' Sustainable TPACK levels.

Table 1. Participant Demographics (N = 100)

Demographic Characteristic	Description	Percentage
Subjects Taught	Science	100%
School Type	Public	65%
	Private	35%
Grade Levels	Elementary	20%
	Middle School	35%
	High School	45%
Years of Teaching Experience	0-5 years	25%
	6-10 years	30%
	11-15 years	25%
	16-20 years	15%
	Over 20 years	5%
Prior Technology Integration Experience	Low	10%
	Moderate	45%
	High	45%
Familiarity with Flipped Classrooms	Low	5%
	Moderate	30%
	High	65%

3.2.2. Phase 2: qualitative case studies

In-depth case studies were conducted with a subset of teachers who have demonstrated high levels of Sustainable TPACK in the survey. Data collection methods included classroom observations, interviews, and document analysis. Observations focused on teachers' integration of eco-friendly technology in their teaching practices, while interviews provided insights into their pedagogical decision-making and perceived challenges and opportunities. Document analysis involved examining lesson plans, teaching materials, and student work samples to further understand how Sustainable TPACK manifests in the classroom.

3.3. Tools

The study employed a mixed-methods approach, utilizing both quantitative and qualitative data collection tools. Here is a list of the tools used in the study:

3.3.1. Quantitative data collection tools

Survey: A self-reported survey was adapted from the existing TPACK survey instrument (Schmidt et al., 2009) and modified to include items specific to eco-friendly technology integration. The survey was used to assess teachers' Sustainable TPACK levels.

3.3.2. Qualitative data collection tools

In-depth case studies: Case studies were conducted with a subset of teachers who demonstrated high levels of Sustainable TPACK in the survey. Data collection methods included:

(i) Classroom observations: Researchers observed the selected teachers' classroom practices, focusing on their integration of eco-friendly technology in teaching science.
(ii) Interviews: Researchers conducted interviews with the selected teachers to gain insights into their pedagogical decision-making processes, perceived challenges, and opportunities related to eco-friendly technology integration.

(iii) Document analysis: Researchers examined relevant documents, such as lesson plans, teaching materials, and student work samples, to further understand how Sustainable TPACK manifests in the classroom.

3.4. Data Analysis

Quantitative data from the survey were analyzed using descriptive statistics to provide an overview of teachers' Sustainable TPACK levels. Qualitative data from the case studies were analyzed using thematic analysis to identify common patterns and themes related to eco-friendly technology integration, pedagogical decision-making, and challenges and opportunities faced by teachers.

By employing this mixed-methods approach, the study generated rich insights into the concept of Sustainable TPACK and its application in educational contexts, ultimately informing strategies for promoting eco-friendly technology integration in teacher education and professional development.

3. RESULTS AND DISCUSSION

3.1. Results

3.1.1. Quantitative results

This section presents the quantitative data obtained from the study. Table 2 showcases the data gathered from the survey that assessed the self-reported Sustainable TPACK levels of the participating teachers. The scores are divided into different components of the Sustainable TPACK framework, namely Technological Pedagogical Knowledge (TPK), Technological Content Knowledge (TCK), Technological Pedagogical Content Knowledge (TPACK), Environmental Awareness (EA), Eco-Friendly Technology Integration (ETI), and Sustainable TPACK (STPACK). The table provides an overview of the mean scores and standard deviations for each component, allowing for an analysis of the strengths and areas for improvement in teachers' knowledge and practices related to eco-friendly technology integration.

Table 2. Quantitative Data - Teachers' Self-Reported Sustainable TPACK Levels

Sustainable TPACK Component	Mean Score (out of 5)	Standard Deviation
Technological Pedagogical Knowledge (TPK)	3.8	0.7
Technological Content Knowledge (TCK)	3.5	0.6
Technological Pedagogical Content Knowledge (TPACK)	3.9	0.8
Environmental Awareness (EA)	4.1	0.5
Eco-Friendly Technology Integration (ETI)	3.7	0.6
Sustainable TPACK (STPACK)	3.8	0.6

A closer analysis of these scores reveals a telling discrepancy: while teachers' Environmental Awareness (EA) is high (M=4.1), their ability to select and use domain-specific eco-friendly tools (TCK) is the lowest among all components (M=3.5). This suggests that teachers are highly cognizant of environmental issues and their importance in education, but may lack the practical knowledge of which specific technologies are both effective for teaching science and minimize ecological impact. This gap between theoretical awareness and applied technological knowledge highlights a critical area for targeted professional development, focusing less on the 'why' and more on the 'how' and 'with what' of eco-friendly technology integration.

Table 3 displays quantitative data on the challenges faced by teachers when integrating eco-friendly technology in their teaching practices. The table highlights the frequency and percentage of teachers reporting various obstacles, such as limited access to eco-friendly technology, lack of training or professional development opportunities, time constraints, lack of administrative support, and resistance from students or colleagues. By examining the prevalence of these challenges, we can better understand the barriers hindering the effective implementation of Sustainable TPACK and identify potential areas for targeted interventions and support.

Table 3. Quantitative Data - Challenges in Eco-Friendly Technology Integration

Challenge	Frequency	Percent
Limited access to eco-friendly technology	45	45%
Lack of training or professional development	35	35%
Time constraints	25	25%
Lack of administrative support	20	20%
Resistance from students or colleagues	10	10%

The table above presents the frequency and percentage of teachers reporting various challenges in integrating eco-friendly technology into their teaching practices. The most commonly reported challenge was limited access to eco-friendly technology (45%), followed by a lack of training or professional development opportunities (35%). These findings emphasize the need for increased support and resources for teachers to effectively integrate eco-friendly technology in their science classrooms. Overall, the quantitative data gathered from the survey provided valuable insights into the self-reported Sustainable TPACK levels of the participating teachers and the challenges they face in integrating eco-friendly technology.

The overall mean score for Sustainable TPACK (STPACK) was 3.8 out of 5, indicating that teachers possess a moderate to high level of knowledge and skills related to eco-friendly technology integration. Environmental Awareness (EA) emerged as the strongest component, with a mean score of 4.1. This suggests that teachers are cognizant of environmental issues and recognize the importance of addressing them in their teaching practices. Technological Pedagogical Content Knowledge (TPACK) also received a relatively high mean score of 3.9. This demonstrates that teachers are generally capable of effectively integrating eco-friendly technology into their subject-specific pedagogical practices. However, Technological Content Knowledge (TCK) received the lowest mean score of 3.5, indicating that teachers may need additional support in selecting and utilizing domain-specific eco-friendly technology tools. By focusing on improving teachers' TCK, educational stakeholders can enhance the overall effectiveness of Sustainable TPACK in science education.

The quantitative data on challenges faced by teachers revealed several barriers hindering the effective implementation of Sustainable TPACK. Limited access to eco-friendly technology (45%) and lack of training or professional development opportunities (35%) were identified as the most significant challenges. These findings emphasize the importance of providing adequate resources and targeted support to help teachers overcome these obstacles. Time constraints (25%), lack of administrative support (20%), and resistance from students or colleagues (10%) were also mentioned as challenges. Addressing these issues may require systemic changes and increased collaboration among teachers, administrators, and other stakeholders to create a more conducive environment for eco-friendly technology integration. In conclusion, the analysis of quantitative data highlights areas of strength and improvement in teachers' Sustainable TPACK, as well as key challenges that need to be addressed to support the effective integration of eco-friendly technology in science education.

3.1.2. Qualitative results

Qualitative data in this study were collected through case studies involving classroom observations, interviews, and document analysis. Here are the qualitative data for each component of Sustainable TPACK.

1. Technological Pedagogical Knowledge (TPK)
   - Classroom Observation: A teacher effectively used a collaborative online platform to facilitate group discussions on renewable energy sources.
   - Interview: A teacher mentioned, "I find that using digital tools like quizzes and polls helps me assess my students' understanding in real-time."
2. Technological Content Knowledge (TCK)
   - Classroom Observation: A teacher demonstrated the use of a simulation software to teach the carbon cycle.
   - Interview: A teacher shared, "I use various science-specific apps that provide interactive models and virtual experiments to explain complex concepts."
3. Technological Pedagogical Content Knowledge (TPACK)
   - Document Analysis: Lesson plans showed integration of virtual field trips to explore ecosystems and the impact of human activities on the environment.
   - Interview: A teacher explained, "I design my lessons to provide hands-on experiences with eco-friendly technology, which helps students better understand science concepts and their real-world applications."
4. Environmental Awareness (EA)
   - Classroom Observation: A teacher discussed the importance of using energy-efficient devices and encouraged students to adopt sustainable practices.
   - Interview: A teacher stated, "I believe it's crucial to teach students about the environmental impact of technology and how they can make responsible choices."
5. Eco-Friendly Technology Integration (ETI)
   - Classroom Observation: A teacher used recycled materials and programmable robots to teach students about waste management and recycling.

- Interview: A teacher mentioned, "I constantly look for new eco-friendly tools that can improve student engagement and learning outcomes."

6. Sustainable TPACK (STPACK)
   - Document Analysis: Teachers' reflective journals revealed their commitment to professional development in Sustainable TPACK and their efforts to enhance eco-friendly technology integration in their teaching practices.
   - Interview: A teacher said, "I strive to create a learning environment that fosters environmental stewardship through the effective use of technology."

These qualitative data examples provide rich insights into teachers' knowledge, practices, and experiences related to eco-friendly technology integration, complementing the quantitative survey findings. So the analysis of the qualitative data revealed several themes related to eco-friendly technology integration and Sustainable TPACK. These themes provide a deeper understanding of the challenges, opportunities, and experiences of teachers in this domain.

1. Teachers' Motivation for Eco-Friendly Technology Integration: Many teachers expressed their commitment to environmental sustainability and saw the potential of technology in fostering eco-friendly practices among students.
2. Teachers' Competence in Integrating Eco-Friendly Technology: While some teachers demonstrated confidence in their ability to select and utilize eco-friendly technology tools, others expressed a need for more training and support.
3. Challenges in Implementing Sustainable TPACK: Limited access to eco-friendly technology, lack of professional development opportunities, and time constraints emerged as key challenges faced by teachers.
4. Benefits of Eco-Friendly Technology Integration: Teachers reported positive impacts on student engagement, motivation, and understanding of science concepts, as well as enhanced environmental awareness among students.
5. Importance of Collaboration and Support: Teachers emphasized the value of working with colleagues, administrators, and external experts to overcome challenges and improve their Sustainable TPACK.
6. Teachers' Commitment to Professional Growth: Many teachers showed a willingness to continuously learn and improve their knowledge and skills in eco-friendly technology integration.

Further analysis of these themes reveals their interconnected nature and helps to explain the quantitative findings. For example, the frequent expression of Teachers' Motivation for Eco-Friendly Technology Integration (Theme 1) directly contrasts with the challenges expressed in Implementing Sustainable TPACK (Theme 3, e.g., lack of access, training). This tension illustrates that will and motivation are present but are often thwarted by external barriers.

Furthermore, these qualitative findings provide crucial context for the quantitative results. The lowest quantitative score was in Technological Content Knowledge (TCK), and this is directly reflected in the qualitative data. While teachers expressed high motivation (Theme 1) and saw clear benefits (Theme 4), many simultaneously voiced a need for more training and support within the Teachers' Competence theme (Theme 2), specifically asking for guidance on which tools to use for specific science topics. For instance, one teacher's comment, 'I constantly look for new eco-friendly tools...' (Theme 5), exemplifies high motivation but also implies a struggle to find relevant resources, thereby illustrating the TCK gap identified in the survey. This synergy between datasets strengthens the conclusion that supporting teachers' TCK is a paramount need.

So these analyses highlight the significance of providing teachers with the necessary resources, training, and support to develop their Sustainable TPACK and effectively integrate eco-friendly technology in their teaching practices. It also underscores the importance of fostering a collaborative school environment that values and promotes environmental sustainability through innovative pedagogical approaches.

3.2. Discussion

The mixed-methods findings of this study reveal both the promise and the challenges of implementing Sustainable TPACK in science education, offering insights that resonate with, yet also extend, the existing literature. The most significant barriers teachers reported, which are limited access to eco-friendly technology (45%) and a lack of training or professional development opportunities (35%), are welldocumented within general TPACK research as common obstacles to technology integration (Schmidt et al., 2009). However, our study crucially identifies that these challenges are amplified in the niche context of eco-friendly technology, where specialized tools and pedagogical knowledge are less established and accessible. This finding aligns with concerns raised by Matherson et al. (2014) about the need for sustained and specific support to realize new educational frameworks.

A particularly telling result is the discrepancy between teachers' high self-reported Environmental Awareness (EA; M=4.1) and their lower Technological Content Knowledge (TCK; M=3.5). This suggests that while science teachers are highly motivated by issues of sustainability, which are a core goal of Education for Sustainable Development (ESD) (Lotz-Sisitka et al., 2015), they often lack the specific knowledge of which eco-friendly tools are most effective for teaching particular scientific concepts. This gap between theoretical awareness and practical, domain-specific application is a critical theoretical contribution. It underscores that Sustainable TPACK is not merely an additive model but an integrative one, where the synergy between environmental values (EA) and domain-specific tech tools (TCK) is essential for effective implementation, a nuance that builds upon the foundational TPACK theory (Koehler & Mishra, 2009).

The qualitative data further enriched this understanding, revealing that teachers who successfully navigated these challenges often did so through collaboration, echoing Cherner & Smith's (2017) call for reconceptualizing TPACK through communal knowledge-building. The reported benefits, which enhanced student engagement, deeper conceptual understanding, and heightened environmental awareness, provide empirical support for the theoretical premise that technology can be a potent catalyst for pro-environmental behavior and learning (Midden et al., 2007; Ballew et al., 2015).

The clear need for targeted professional development (PD) to bridge the identified TCK gap calls for programs that move beyond one-off workshops. Effective PD should be immersive, collaborative, and sustained over time. Successful models exist that this work can build upon. For instance, design-based professional learning communities (PLCs), where teachers collaboratively design, implement, and refine lesson sequences integrating eco-friendly technology, have proven highly effective in developing general TPACK (Koehler et al., 2013). Furthermore, PD programs that integrate ESD principles, like those outlined by Purwianingsih et al. (2022), which involve teachers in hands-on, inquiry-based projects focused on local sustainability issues, provide an excellent template. A potential model could involve a hybrid approach: using collaborative online platforms (addressing ETI) for PLC meetings where teachers co-create lesson plans that utilize specific simulation software (addressing TCK) to investigate local environmental data (addressing EA and content knowledge).

Based on the findings of this study, several clear pathways for future research emerge. To build upon this work, subsequent studies should employ longitudinal designs to quantitatively measure the impact of instruction driven by Sustainable TPACK, focusing not only on student achievement in science but also on the development of their long-term environmental attitudes and behaviors. Furthermore, an investigation is needed into the critical institutional factors, such as policies, funding models, and administrative support structures, that most effectively enable the integration of sustainable technologies within schools. Finally, this study underscores the acute need for targeted professional development; future work must therefore focus on designing, implementing, and evaluating evidence-based programs specifically aimed at building teachers' Technological Content Knowledge (TCK) within the Sustainable TPACK framework. Such initiatives could fruitfully draw on established models, such as design-based professional learning communities, that have proven effective in other TPACK contexts.

In conclusion, this study demonstrates that while science teachers are poised to embrace the imperative of Sustainable TPACK, their ability to do so effectively is contingent on systemic support. By providing targeted resources, fostering collaborative environments, and implementing evidence-based professional development, we can empower educators to translate environmental awareness into transformative pedagogical practice.

4. CONCLUSION

In conclusion, this study operationalizes the Sustainable TPACK framework, revealing that science teachers possess moderate to high levels of this knowledge but face significant challenges, primarily limited access to eco-friendly tools and a lack of training. A key finding is the discrepancy between high environmental awareness and lower domain-specific technological knowledge (TCK). Teachers demonstrated a strong commitment to professional growth in this area. Therefore, providing targeted resources, collaborative support, and professional development focused on practical, subject-specific eco-friendly technology integration is crucial. By doing so, educators can be empowered to overcome these barriers, enhance their pedagogy, and effectively foster a new generation of environmentally literate citizens. Future research must now focus on designing such developmental programs and measuring their impact on both teacher practice and student outcomes. So scholars and practitioners should therefore focus on measuring the impact of Sustainable TPACK on learners, understanding the institutional enablers for its implementation, and designing the professional development programs necessary to support it. By incorporating these revised sections, your manuscript will directly address the reviewers' concerns, significantly strengthening its theoretical grounding, analytical depth, and clarity.

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