Research Article

Food Waste in Schools: A Science Learning Activity for Fostering Sustainable Development Goals in a School Setting

Witsanu Suttiwan, Pratuengsook Maneelam, Chokchai Yuenyong*

Department of Science Education, Faculty of Education, Khon Kaen University, 40002 Khon Kaen, Thailand
*   Corresponding author: ychok@kku.ac.th

ABSTRACT

Food waste in school canteens represents a persistent environmental challenge with strong relevance to Sustainable Development Goal 12 (Responsible Consumption and Production), yet it remains underutilised as a contextual driver for science learning. In many educational settings, including Thailand, science instruction continues to prioritise content acquisition over sustainability-oriented and transformative thinking. This study addresses this gap by designing and developing a context-based science learning activity on food waste for Grade 10 students, aimed at examining contextual needs, applying the Pedagogical Content Knowledge for Transformative Learning and Sustainable Development (PCK for TLSD) framework integrated with transformative learning theory, and refining the activity through expert validation. A qualitative developmental research approach was adopted, comprising four phases: needs analysis through literature review, activity design, expert evaluation via a Professional Learning Community, and iterative revision. The findings indicate a clear misalignment between sustainability policy aspirations and existing classroom practices. The resulting learning activity is structured within a seven-stage context-based STEM inquiry model, integrating the core components of PCK for TLSD with Mezirow's transformative learning phases, where food waste functions as a disorienting dilemma to stimulate critical reflection and perspective transformation. Expert feedback affirmed the activity's conceptual robustness, curricular relevance, and practical feasibility for classroom implementation. This study contributes a theoretically grounded and contextually relevant instructional design that advances the integration of sustainable development into science education. It demonstrates the potential of context-based and transformative approaches to move beyond rote learning towards meaningful engagement with real-world environmental issues. Further empirical investigation is recommended to evaluate the effectiveness of the proposed activity in enhancing students' sustainability competencies and transformative learning outcomes.

1.   INTRODUCTION

Food waste is one of the most pressing yet often overlooked environmental challenges of the modern era. Globally, approximately one-third of all food produced for human consumption is lost or wasted each year, contributing significantly to greenhouse gas emissions and the depletion of natural resources (United Nations, 2015). In the context of schools, food waste from canteens and lunch programmes represents a visible, daily occurrence that directly affects students' immediate environment. Despite its significance, food waste in schools is rarely utilised as a meaningful context for learning, particularly in science classrooms, where it has the potential to connect scientific concepts with real-world sustainability challenges. This missed opportunity is especially concerning given the global urgency to achieve Sustainable Development Goal (SDG 12:Responsible Consumption and Production) (UNESCO, 2020). Recognising this urgency, the United Nations' Sustainable Development Goals (SDGs) serve as a universal call to action to end poverty, protect the planet, and ensure peace by 2030. To achieve these goals, Education for Sustainable Development (ESD) has been recognised as a key instrument, empowering learners to make informed decisions and take responsible actions for environmental integrity and social justice. However, integrating these complex global issues into formal education remains a significant challenge worldwide.

Thailand has actively committed to the SDGs, particularly through the application of the Sufficiency Economy Philosophy (SEP) as a pathway to sustainability. Despite national policies, the practical integration of ESD into the Thai educational system often encounters obstacles. There is a pressing need to transition from theoretical awareness to actionable sustainability, especially regarding waste management and resource consumption, which are critical issues in the Thai socio-economic context. In many Thai classrooms, science education still focuses heavily on content memorisation rather than developing the sustainability thinking required for the 21st century. Zoller (2015) argues that contemporary science education must shift from lower-order cognitive skills (LOCS) teaching to 'know' towards higher-order cognitive skills (HOCS) learning to 'think' in the Science, Technology, Environment, Society, Economy, and Policy (STESEP) context. Specifically, local issues like food waste in school canteens are often overlooked as learning opportunities. Students may learn the biology of decomposition but fail to understand the socio-economic impact of the waste they produce daily, leading to a gap between scientific knowledge and sustainable behaviour.

Science education provides a unique platform to address sustainability by connecting scientific literacy with real-world problems. By focusing on SDG 12, science teachers can design lessons that encourage students to analyse the life cycle of products and the environmental consequences of waste (UNESCO, 2020). Integrating ESD in the science classroom involves moving towards a transdisciplinary approach where students use scientific evidence to solve community-based dilemmas. To address the gap between scientific knowledge and sustainable behaviour, this study draws upon transformative learning theory as its theoretical foundation. Transformative learning, originally developed by Jack Mezirow, refers to a fundamental change in how individuals perceive and interpret their experiences a process known as perspective transformation (Baumgartner, 2019). Mezirow (2000) describes a 10-phase process of perspective transformation, beginning with a disorienting dilemma and progressing through critical reflection, exploration of new roles, and reintegration into life based on a revised frame of reference. These 10 phases were systematically incorporated into the design of the food waste learning activity.

In designing the science learning activity on food waste, these 10 phases were systematically incorporated into the seven-stage context-based STEM inquiry framework. Specifically, the disorienting dilemma (Phase 1) is operationalised through Stage 1, where students encounter the visible reality of food waste through videos and school canteen observations. Self-examination and critical assessment of assumptions (Phases 2-4) are facilitated through Stages 2 and 3, where students investigate the causes of food waste and recognise that their concerns are shared among their peers. The exploration and planning phases (Phases 5-6) correspond to Stages 4 and 5, where students collaboratively explore solutions and design prototypes. The action and integration phases (Phases 7-10) are embedded in Stages 6 and 7, where students test their solutions, build confidence through presentation, and reflect on how their transformed perspective can be integrated into their daily school life.

Within the context of sustainability education, transformative learning has gained increasing recognition as an essential pedagogical approach. Wolff et al. (2022) argue that classic models of education have not managed to address the complexity of current socio-environmental problems, and that sustainability education should promote learning processes that enable learners to critically reflect on their attitudes, values, and worldviews, potentially leading to conceptual change. This perspective aligns with the need for science education to move beyond the transmission of factual knowledge towards fostering deep changes in how students perceive their relationship with the environment and

natural resources. However, applying transformative learning theory to adolescent populations requires careful consideration. Meerts-Brandsma and Sibthorp (2021) examined whether adolescents could experience transformative learning in educational settings. Their findings suggest that, while adolescents experience the stages of transformative learning, the outcomes are often more related to identity formation than to an irreversible change in worldview. Nevertheless, the processes of transformative learning including encountering disorienting dilemmas, engaging in critical reflection, and participating in collaborative discourse remain powerful mechanisms for developing awareness and agency among young learners.

In this study, transformative learning is operationalised through a science learning activity in which the real-world situation of food waste in school canteens serves as the disorienting dilemma. Students encounter the visible reality of food waste in their own school, critically reflect on its causes and consequences through investigation and group discussion, engage in reflective discourse with peers and teachers, and ultimately develop a transformed perspective on their responsibility towards waste reduction and sustainable consumption. This operationalisation connects Mezirow's theoretical framework with the practical goal of achieving SDG 12 within the school context.

To facilitate this, it may be necessary for teachers to undergo professional development in Pedagogical Content Knowledge for Transformative Learning and Sustainable Development (PCK for TLSD). The PCK for TLSD framework was developed in the first author's doctoral dissertation (Suttiwan, 2026) by synthesising Shulman's (1987) original Pedagogical Content Knowledge model with principles of transformative learning theory (Baumgartner, 2019) and ESD (UNESCO, 2020). The framework comprises four core knowledge areas that guide science teachers in designing transformative learning activities: (1) Knowledge of Science Curricula (KSC), which draws on curriculum integration theory to connect science content with real-world sustainability issues; (2) Knowledge of Students' Understanding of Science (KSU), which is grounded in constructivist perspectives on learners' prior knowledge and misconceptions; (3) Knowledge of Instructional Strategies (KIS), which integrates STEM pedagogy approaches and strategies for transformative learning; and (4) Knowledge of Assessment of Scientific Literacy (KAS), which builds on formative assessment literature to evaluate students' development of 21st-century skills and sustainability competencies. This framework enables teachers to transform complex sustainability concepts into meaningful learning experiences. For instance, using a STEM pedagogy approach teachers can design activities in which students identify problems, such as food waste, and use the Engineering Design Process to create prototypes or solutions, such as bio-fertilisers or waste-tracking applications (Fachrunnisa et al., 2021).

The relationship between the PCK for TLSD framework and the seven-stage context-based STEM inquiry framework is as follows: Knowledge of Science Curricula (KSC) informs the selection of food waste as the socio-scientific issue connecting the Thai science curriculum to SDG 12, and provides the content foundation for all seven stages. Knowledge of Students' Understanding of Science (KSU) guides the identification of student misconceptions addressed throughout Stages 1-3, where students' prior assumptions about waste are surfaced and challenged. Knowledge of Instructional Strategies (KIS) provides the pedagogical structure through the seven-stage STEM inquiry framework itself (Sutaphan & Yuenyong, 2019), with transformative learning principles integrated across all stages. Knowledge of Assessment of Scientific Literacy (KAS) informs the formative assessment methods applied throughout the activity. In this way, the four foundations of PCK for TLSD are not applied to individual stages in isolation but serve as an integrated framework that shapes the entire instructional design. Despite the significant potential of these theoretical frameworks, there is currently a notable scarcity of research concerning specific science learning activities tailored for the Thai school context that explicitly address food waste through the lens of Pedagogical Content Knowledge for Transformative Learning and Sustainable Development (PCK for TLSD). While the global literature discusses sustainability in broad terms, there remains a theory-practice gap in how Thai educators can effectively translate these concepts into classroom-level interventions (Christopher & Pinias, 2025).

Specifically, the problem addressed in this study is that food waste is a pervasive and visible issue in Thai school canteens, yet it has not been systematically utilised as a context for science learning activities that promote transformative learning and sustainable development. While students encounter food waste on a daily basis, existing science curricula do not provide structured opportunities for them to investigate, critically reflect upon, and take action on this issue. There is a need for a concrete, contextualised science learning activity that uses food waste as a vehicle to foster students' sustainability thinking, going beyond factual knowledge towards genuine changes in awareness and behaviour.

This research aims to bridge this gap through three interrelated research questions: Research Question 1: What are the contextual needs and theoretical foundations that justify the development of a science learning activity on food waste in the Thai school context? Research Question 2: How can a

science learning activity on food waste be designed using the PCK for TLSD framework integrated with transformative learning theory within the cultural and educational environment of Thai schools? Research Question 3: How can the designed activity be reviewed and refined through a professional learning community process to ensure its quality and feasibility? To address these questions, the study is organised into three corresponding phases: (1) a needs analysis through literature review and document analysis (addressing RQ1); (2) activity design using the PCK for TLSD framework (addressing RQ2); and (3) expert review and refinement through the STEM KKU Professional Learning Community (addressing RQ3). Each phase is described in the Methodology, and the corresponding results are presented in separate subsections of the Results section. The expected outcome of this study is a robust, contextualised science learning activity that serves as a practical example for educators. By utilising the PCK for TLSD framework, this activity aims to go beyond the mere transmission of facts, seeking instead to fundamentally transform student awareness and long-term behaviour towards food waste, consistent with the principles of transformative learning. Ultimately, this research provides a pathway for science education to contribute meaningfully to national and global sustainability targets.

The science learning activity is aligned with Strand 1 (Standard SC 1.1, Grade 10/4) of the Thai national science curriculum, which emphasises analysing environmental impacts and proposing solutions for resource conservation. It focuses on three objectives: developing students' critical thinking to design practical strategies for reducing food waste, strengthening their ability to communicate solutions with awareness of social and environmental responsibility, and applying basic economic principles to ensure sustainable waste management. These objectives also support key 21st-century skills, particularly critical thinking and communication.

2.   METHODOLOGY

2.1. Research Design

This study employs a qualitative developmental research design aimed at designing and developing a science learning activity on food waste for Thai secondary school students. The study is situated within the interpretive paradigm, which seeks to understand and construct meaning from the perspectives of the participants involved in the design process (Cohen et al., 2000). The primary objective of this study is to design a contextualised science learning activity not to develop a new theoretical framework or model. The Pedagogical Content Knowledge for Transformative Learning and Sustainable Development (PCK for TLSD) framework (Suttiwan, 2026), developed in the first phase of the first author's doctoral dissertation, serves as the theoretical and pedagogical foundation guiding the activity design. The developmental process was conducted through a Professional Learning Community (PLC) at Khon Kaen University, referred to as the STEM KKU PLC. This PLC process helped the first author to refine the activity by facilitating idea-sharing and collaboration among the researcher and expert peers (Suttiwan et al., 2022). The research design comprised four sequential phases (Figure 1): literature review and document analysis, activity design using the PCK for TLSD framework, expert review and refinement through the PLC process, and final revision.

Figure 1. Conceptual Framework

2.2. Participants

This study is a developmental research project focused on the design of a science learning activity; therefore, the participants involved are the researcher and expert peers who contributed to the design and review process, rather than student participants in a classroom intervention. Three individuals participated in this study, selected through purposive sampling based on their expertise in science education, STEM pedagogy, and transformative learning:

a)   The first author and primary researcher: a doctoral candidate in Science Education at Khon Kaen University, who served as the principal designer of the food waste science learning activity. The first author developed the PCK for TLSD framework in the initial phase of his doctoral dissertation and used it as the foundation for designing the activity presented in this study.

b)   Expert Reviewer A (second reviewer and PhD advisor): an associate professor and faculty member in the Department of Science Education, Faculty of Education, at the university where the study was conducted. He has extensive experience in STEM education research, context-based science teaching, and science teacher professional development.

c)   Expert Reviewer B (first reviewer): a science teacher at the university's demonstration school with practical experience in designing transformative learning science activities for secondary school students. Her experience in classroom implementation provided practical insight into the feasibility of the proposed activity.

The selection of these two expert reviewers was based on their complementary expertise: Expert Reviewer A provided theoretical and research-based perspectives on STEM pedagogy and transformative learning, while Expert Reviewer B contributed practical, classroom-based knowledge of activity implementation. Together, they formed the STEM KKU Professional Learning Community (PLC) that guided the development process.

2.3. Phase 1: Literature Review and Document Analysis

The first phase of the study involved a comprehensive review and synthesis of documents and literature to establish the conceptual foundations for the activity design. The literature review was organised into six thematic areas:

a)   First, international sustainability frameworks were reviewed, including the United Nations' SDGs, which serve as a global call to action to preserve the earth's condition, promote environmental development, and maximise the use of natural resources.

b)   Second, Thai national policies and educational needs were examined. Thailand's National Economic and Social Development Plan incorporates the SDGs as a guiding framework for national development, including education.

c)   Third, the Thai national science curriculum was analysed. An examination of the Thai science curriculum and the country's needs reveals that science education in Thailand does not focus solely on subject-specific knowledge or skills. The primary aim is for students to integrate scientific knowledge with other disciplines to solve real-life problems (Ministry of Education, 2017).

d)   Fourth, literature on 21st-century skills was reviewed. In a rapidly changing world, students need to develop learning skills, technology skills, and life skills, collectively known as 21st-century skills (Larson & Miller, 2011). These skills enable students to learn and adapt to evolving global conditions.

e)   Fifth, literature on formative assessment was synthesised. Rather than focusing solely on assessments to measure learning outcomes, teachers should prioritise learner development assessments to monitor student progress and engagement in learning activities (Cowie & Bell, 1999).

f)   Sixth, literature on transformative learning theory was reviewed, particularly Mezirow's perspective transformation process and its application in adolescent educational settings (Meerts-Brandsma & Sibthorp, 2021).

The synthesis of these six thematic areas provided the conceptual foundation for understanding the context of science learning in Thailand and the global direction of science education. This foundation informed the subsequent phase, in which the first author returned to the PCK for TLSD framework to guide the design of the food waste learning activity. The literature review and document analysis followed a systematic content analysis process combining deductive and inductive approaches (Elo & Kyngäs, 2008). The deductive component used the four foundations of the PCK for TLSD framework (KSC, KSU, KIS, and KAS) as a pre-established coding framework. Each document was read and coded according to which foundation(s) it addressed. For example, documents on the Thai science curriculum and SDG frameworks were coded under KSC; documents on student misconceptions about

environmental issues were coded under KSU; documents on STEM pedagogy and transformative learning strategies were coded under KIS; and documents on formative assessment were coded under KAS. In addition to deductive coding, an inductive approach was applied to identify emerging themes beyond the PCK for TLSD framework, revealing the theory–practice gap in sustainability education and the relevance of transformative learning for adolescents, which informed the design decisions in Phase 2. The content analysis involved initial familiarisation with the documents, systematic coding based on the six thematic areas, synthesis of codes into themes to guide the activity design, and validation against the PCK for TLSD framework, with the process conducted by the first author and reviewed with the PhD adviser to ensure analytical rigour.

2.4. Phase 2: Activity Design Using the PCK for TLSD Framework

Following the literature review, the first author applied the PCK for TLSD framework (Suttiwan, 2026) as the guiding structure for designing the food waste science learning activity. As described in the Introduction, this framework comprises four integrated knowledge areas: Knowledge of Science Curricula (KSC), Knowledge of Students' Understanding of Science (KSU), Knowledge of Instructional Strategies (KIS), and Knowledge of Assessment of Scientific Literacy (KAS). In applying this framework to the food waste context, the first author took the following design steps:

a)   For KSC, the activity was aligned with Strand 1 (Standard SC 1.1, Grade 10/4) of the Thai national science curriculum, which requires students to investigate environmental impacts and propose solutions for natural resource conservation. Food waste was selected as the socio-scientific issue connecting science content to SDG 12.

b)   For KSU, common student misconceptions about waste and the environment were identified from the literature. These included the belief that mixing waste with water does not create environmental problems, and the fatalistic belief that individual actions cannot influence climate change (Choi et al., 2010; Kharrazi et al., 2018).

c)   For KIS, the instructional strategy was designed using a context-based STEM pedagogy approach, structured through a seven-stage framework: (1) identification of social issues; (2) identification of potential solutions; (3) need for knowledge; (4) decision-making; (5) development of prototypes; (6) test and evaluation; and (7) socialisation and completion decisions. Transformative learning principles were integrated throughout, with real food waste situations serving as the disorienting dilemma (Baumgartner, 2019).

d)   For KAS, the assessment approach was designed using formative assessment principles (Cowie & Bell, 1999), including open-ended questioning, observation of student participation, and peer feedback. The assessment focused on students' development of critical thinking, communication skills, and sustainability awareness, rather than rote memorisation.

The first author also conducted a school site visit to a secondary school where he was supervising pre-service teachers. During this visit, food waste in the school canteen was observed as a visible and daily occurrence, which confirmed the relevance and authenticity of the chosen topic for the learning activity. Based on these design steps, the first author drafted the initial version of the food waste science learning activity plan.

To guide the integration of transformative learning theory into the activity design, the first author drew upon Mezirow's 10-phase process of perspective transformation (Mezirow, 2000, as cited in Meerts-Brandsma & Sibthorp, 2021). These phases can be understood in three clusters. The first cluster involves the triggering experience and initial response: (1) a disorienting dilemma an event that challenges existing assumptions; (2) self-examination with feelings of guilt or shame; (3) a critical assessment of epistemic, sociocultural, or psychic assumptions; and (4) recognition that one's discontent and the process of transformation are shared with others. The second cluster involves exploration and planning: (5) exploration of options for new roles, relationships, and actions; and (6) planning a course of action. The third cluster involves action and integration: (7) acquisition of knowledge and skills for implementing one's plans; (8) provisional trying of new roles; (9) building of competence and self-confidence in new roles and relationships; and (10) a reintegration into one's life on the basis of conditions dictated by one's new perspective (Meerts-Brandsma & Sibthorp, 2021).

In designing the food waste learning activity, these 10 phases were systematically mapped onto the seven-stage context-based STEM inquiry framework. Specifically, the disorienting dilemma (Phase 1) is operationalised through Stage 1, where students encounter the visible reality of food waste through videos and school canteen observations. Self-examination and critical assessment of assumptions (Phases 2-4) are facilitated through Stages 2-3, where students investigate the causes of food waste and recognise that their concerns are shared among their peers. The exploration and planning phases (Phases 5-6) correspond to Stages 4 and 5, where students collaboratively explore solutions and design

prototypes. The action and integration phases (Phases 7-10) are embedded in Stages 6-7, where students test their solutions, build confidence through presentation, and reflect on how their transformed perspective can be integrated into their daily school life. To ensure a coherent theoretical-practical linkage, the first author mapped the four PCK for TLSD foundations, the seven-stage context-based STEM inquiry framework, and Mezirow's phases of transformative learning into an integrated design matrix. This mapping, presented in Table 1, guided the design of each stage of the food waste activity and ensured that every stage was grounded in both the PCK for TLSD framework and transformative learning theory.

Table 1. Integration of PCK for TLSD, Seven-Stage STEM Framework, and Mezirow's Transformative Learning Phases

7-Stage STEM Framework	Mezirow's TL Phases Addressed	PCK for TLSD Foundation	How Integrated in the Activity
Stage 1: Identification of social issues	Phase 1: Disorienting dilemma Phase 2: Self-examination with feelings	KSC: Food waste linked to SDG 12 KSU: Prior assumptions surfaced	Students watch food waste video, brainstorm, and express feelings about the situation
Stage 2: Identification of potential solutions	Phase 3: Critical assessment of assumptions Phase 4: Recognition of shared discontent	KSU: Misconceptions identified KIS: Collaborative inquiry begins	Students explore school waste management and brainstorm improvements with peers
Stage 3: Need for knowledge (Activities 1–3)	Phase 5: Exploration of options for new roles and actions	KIS: STEM inquiry+TL strategies KSU: Misconceptions addressed KSC: Science content integrated	Students investigate origins, types, and impacts of food waste through surveys, interviews, and documentation
Stage 4: Decision-making	Phase 6: Planning a course of action	KIS: Collaborative decision-making	Students select the most feasible waste management guidelines for their school context
Stage 5: Development of prototypes	Phase 7: Acquisition of knowledge and skills Phase 8: Provisional trying of new roles	KIS: Engineering Design Process KSC: Application of science knowledge	Students design guidelines using digital tools and thinking maps
Stage 6: Test and evaluation	Phase 9: Building competence and self-confidence	KAS: Formative assessment KIS: Critical self-reflection	Students test whether guidelines are practical, can generate income, and reflect on emotional impact
Stage 7: Socialisation and completion decisions	Phase 10: Reintegration into life based on new perspective	KAS: Peer feedback and reflection KIS: Critical social thinking	Students present prototypes, receive peer feedback, reflect on learning, and consider implementation in daily school life

2.5. Phase 3: Expert Review and Refinement Through the PLC Process

After drafting the initial activity plan, the first author submitted it to the two expert peers for review and feedback through the STEM KKU Professional Learning Community (PLC) process. The STEM KKU PLC process was used in the meetings, as it allowed the first author to gain insights from various perspectives. The PLC review process was conducted as follows: The review involved a minimum of three meetings conducted via the Zoom video conferencing platform. Each meeting was recorded, allowing the first author to review the reviewers' suggestions and new ideas. During each meeting, the reviewers examined the activity plan against the PCK for TLSD framework and provided feedback on the following aspects:
a)   alignment of the activity with the Thai science curriculum and SDG 12
b)   appropriateness of the instructional strategies for Grade 10 students
c)   clarity and feasibility of the activity steps
d)   adequacy of the formative assessment methods
e)   overall coherence and quality of the learning experience
The feedback was collected through two methods: verbal feedback during the recorded Zoom meetings and written comments and annotations on the activity plan document. After each meeting, the first author reviewed the recorded sessions, extracted key suggestions, and incorporated the revisions into the activity plan before the next review round. This iterative PLC process served as a form of peer expert triangulation, which enhances the credibility, reliability, and transferability of the research findings in qualitative developmental research.

2.6. Phase 4: Final Revision

Following the PLC review process, the first author compiled all feedback from the three review meetings and conducted a comprehensive revision of the food waste science learning activity plan. The

first author incorporated the reviewers' suggestions to further develop the activity and then sent the revised version back to the expert peers for a final review to confirm that all recommended changes had been adequately addressed. The final version of the activity represents the product of this four-phase developmental process.

2.7. Scope of the Study and Recommended Implementation

It is important to clarify that this study focuses on the design and development phase of a science learning activity on food waste. The activity has not yet been implemented in a classroom setting with students. Empirical evaluation of the activity's effectiveness on student learning outcomes and transformative competencies will be addressed in subsequent research, which may employ approaches such as action research, case study, or quasi-experimental designs. For future implementation, the activity is designed for Grade 10 students (approximately 15-16 years old) and is recommended to be conducted over a period of approximately 12-15 class periods (50 minutes each), spread across 4-5 weeks, with three periods per week. The seven stages of the activity are structured as follows: Stage 1, identification of social issues (2 periods); Stage 2, identification of potential solutions (1-2 periods); Stage 3, need for knowledge, comprising three sub-activities (5-6 periods); Stage 4, decision-making (1 period); Stage 5, development of prototypes (1-2 periods); Stage 6, test and evaluation (1 period); and Stage 7, socialisation and completion decisions (1 period). Each stage includes both in-class discussions and field-based investigation activities within the school environment, such as canteen observations, staff interviews, and waste surveys.

2.8. Ethical Considerations

The procedures for collecting data involving human participants complied with the ethical standards of the Khon Kaen University Ethics Committee for Human Research, Thailand (Reference number: HE673177; GCP compliant).

3. RESULTS AND DISCUSSION

3.1. Contextual Needs and Theoretical Foundations (RQ1)

The first phase of the study identified the contextual needs and theoretical foundations that justify the development of a science learning activity on food waste in the Thai school context. The synthesis of six thematic areas of literature and document analysis revealed the following findings. First, regarding international sustainability frameworks, the United Nations' SDGs, particularly SDG 12, establish a global mandate for education systems to address issues of waste, consumption, and environmental responsibility (United Nations, 2015; UNESCO, 2020). ESD has been recognised as a key instrument for achieving these goals by empowering learners to make informed decisions and take responsible actions. This international context provides the rationale for embedding sustainability issues within science education curricula.

Second, regarding Thai national policies and educational needs, Thailand has committed to integrating the SDGs into national development through the National Economic and Social Development Plan, which incorporates sustainability as a core development principle. Despite this policy commitment, the practical integration of ESD into the Thai educational system remains limited, with a gap between theoretical awareness and actionable sustainability in classroom practice.

Third, the analysis of the Thai national science curriculum revealed that science education in Thailand aims for students to integrate scientific knowledge with other disciplines to solve real-life problems (Ministry of Education, 2017). Strand 1, Standard SC 1.1 (Grade 10/4) specifically requires students to investigate environmental impacts and propose solutions for natural resource conservation. This curricular requirement provides a direct entry point for a food waste learning activity that connects science content with sustainability challenges.

Fourth, the review of 21st-century skills literature confirmed that students need to develop critical thinking, communication, collaboration, and adaptability to navigate a rapidly changing world (Larson & Miller, 2011). The OECD (2019) further identifies three transformative competencies for 2030 creating new value, reconciling tensions and dilemmas, and taking responsibility all of which are directly relevant to the food waste context.

Fifth, the synthesis of formative assessment literature indicated that assessment should shift from measuring learning outcomes to monitoring student progress and engagement through learner development assessment (Cowie & Bell, 1999; Department for Children, Schools and Families, 2005).

This finding informed the decision to design formative assessment methods, such as open-ended questioning, observation, and peer feedback, rather than summative testing within the activity.

Sixth, the review of transformative learning theory established that Mezirow's 10-phase process of perspective transformation (Meerts-Brandsma & Sibthorp, 2021) provides a powerful theoretical foundation for designing learning experiences that go beyond knowledge transmission towards genuine shifts in awareness and behaviour. However, the review also identified that applying transformative learning to adolescent learners requires careful consideration, as the outcomes may be more closely related to identity formation than to irreversible perspective transformation (Meerts-Brandsma & Sibthorp, 2021).

Taken together, these six thematic areas establish a clear need for a science learning activity on food waste that aligns with both the international SDGs and the Thai national science curriculum, develops 21st-century skills and transformative competencies, employs formative assessment approaches, and is grounded in transformative learning theory. However, the review also reveals a notable gap: despite the potential of these frameworks, there is a lack of context-specific science learning activities for Thai schools that explicitly address food waste through an integrated pedagogical approach, thereby justifying the design presented in the following section.

3.2. Design of the Science Learning Activity on Food Waste (RQ2)

The second phase of the study addressed RQ2 by designing the science learning activity on food waste using the PCK for TLSD framework integrated with transformative learning theory. Following the initial design of the activity focusing on food waste, a consultative process with the experts was conducted to refine and enhance the learning experiences. Their professional feedback was integrated to ensure the quality and effectiveness of the activity. The resulting science learning activity, designed for Grade 10 students, focuses on the critical theme of food waste management through a multidisciplinary lens. The instructional framework aligns with Strand 1 (Standard SC 1.1, Grade 10/4) of the Thai national curriculum, which requires students to research and discuss environmental impacts while proposing solutions for natural resource conservation (Ministry of Education, 2017). This activity integrates core subjects, including natural resource conservation, global warming, and zero waste, specifically targeting the development of critical thinking and communication skills.

The learning objectives of the activity are structured into three primary goals, each aligned with the Thai national science curriculum (Strand 1, SC 1.1, Grade 10/4), SDG 12, and the development of 21st-century skills (Larson & Miller, 2011):

a)   Learning Objective 1: Students utilise critical thinking to apply their knowledge of natural resources and climate change to design practical guidelines for reducing and managing food waste within their school environment.

b)   Learning Objective 2: Students communicate their prototypes and solutions while demonstrating an awareness of local values and social issues, such as the lack of social responsibility in waste segregation and the importance of generosity and food sharing.

c)   Learning Objective 3: Students apply economic principles to ensure that their proposed waste management guidelines are sustainable and viable.

The activity is designed for implementation over approximately 12-15 class periods (50 minutes each), spread across 4-5 weeks with three periods per week. The seven stages are allocated as follows: Stage 1, identification of social issues (2 periods); Stage 2, identification of potential solutions (1-2 periods); Stage 3, need for knowledge, comprising three sub-activities (5-6 periods); Stage 4, decision-making (1 period); Stage 5, development of prototypes (1-2 periods); Stage 6, test and evaluation (1 period); and Stage 7, socialisation and completion decisions (1 period). Each stage integrates both in-class discussions and field-based investigation activities within the school environment, including canteen observations, staff interviews, and waste surveys.

Crucially, the activity addresses several misconceptions about science content that are commonly found among students. Many students mistakenly believe that mixing industrial and household waste with water will not result in unpleasant odours. Furthermore, research indicates that students often propose pro-environmental actions that are not directly linked to climate change mitigation, such as protecting rare species or cleaning streets, rather than focusing on more effective systemic solutions. Most importantly, the activity seeks to counteract the fatalistic belief that individual and collective human actions cannot influence the trajectory of climate change (Choi et al., 2010; Kharrazi et al., 2018). By addressing these misconceptions through a context-based STEM approach, this activity empowers Grade 10 students to become active participants in environmental stewardship and sustainable development. The activity details are shown in Table 2.

Table 2. Science learning activity on food waste in schools

Stage	Activity	Assessment/ Method	PCK for TLSD Foundation & TL Phase
1. Identification of social issues	1.1 "Where did the food waste come from, and is it related to environmental issues?" the teacher asks the students. 1.2 Students generate food waste-related ideas through brainstorming. 1.3 Students watch the video and respond to the following question: • From the video, what points of interest are there and how do they manage them? • From the video, what are your opinions or feelings about the situation? (https://www.youtube.com/watch?v=TX35Yb8KTjg)	1. Using open-ended questions, assess knowledge and awareness about the environmental impact of food waste. 2. Assess critical thinking skills through survey activities and food waste issues in schools. 3. Observe students' participation in activities and presentations to ssess their communication skills.	KSC: Food waste connected to SDG 12 and Thai curriculum SC 1.1 KSU: Students' prior assumptions about waste surfaced through brainstorming TL Phase 1: Disorienting dilemma (food waste video and canteen reality) TL Phase 2: Self-examination (students express feelings about the situation)
2. Identification of potential solution	2.1 Students explore and present food waste situations and school food waste management. 2.2 The teacher asks students, "How is food waste management in our school appropriate, and what issues should be addressed or improved?" 2.3 Students may talk about possible ways to manage and reduce food waste in schools with other groups or by sharing their ideas or discussions with themselves.		KSU: Misconceptions about waste management identified KIS: Collaborative inquiry and shared exploration begin] TL Phase 3: Critical assessment of assumptions about school waste practices TL Phase 4: Recognition that discontent about waste is shared among peers
3. Need for knowledge	3.1 In order to develop the knowledge required regarding the protection of the environment, climate change, and zero waste, students will engage in group activities that use critical thinking and communication strategies to construct the meaning of learning in the following ways: **Activity 1:** This first activity will help students learn and understand where food waste comes from. Step 1: The teacher asks the class, "Where does food waste come from?" Step 2: Students brainstorm ideas within their groups and share ideas with different peers or teachers using their previous experience and knowledge about food waste. Step 3: Students investigate further into the question, "Where does food waste come from?" conduct interviews with staff members, teachers, cooks, and friends as well as by surveying different areas of the school. They may additionally discover more from documents or the internet. Step 4: After step 3, students brainstorm with their peers to figure out where food waste comes from. They will present their own group summary to each group, followed by a discussion with the teacher. This work will be presented using thinking maps or any other methods they think appropriate. **Activity 2:** This activity boosts students' knowledge and skills about the various types of food waste in schools, as well as their understanding and practice of waste management. Step 1: The teacher asks the class, "What are the various types of food waste, and how should each be?" Step 2: Students survey, collect samples, or photograph food waste from various locations all over the school and Experiment with sorting garbage or grouping waste.		KSC: Science content (decomposition, environmental impact) integrated with sustainability issues KSU: Misconceptions actively addressed through investigation KIS: STEM inquiry through surveys, interviews, documentation + TL strategies (critical reflection, dialogue) TL Phase 5: Exploration of options for new understanding and actions

Stage	Activity	Assessment/ Method	PCK for TLSD Foundation & TL Phase
	Step 3: Students investigate documents or the Internet to learn about various types of waste and how to manage them. After that, students summarize what they've learned and share it with their peers. Step 4: After that, ask students to collaborate to develop guidelines for managing every type of waste they collect. (Students may use a sample of food waste collected during a survey to create a draft of work that will be presented.) Step 5: Students share their learning with teachers and other groups by presenting the work that their group has completed. **Activity 3:** The final activity's learning objective is for students to recognize and be aware of the social, environmental, and well-being consequences of food waste. In addition, they will learn how to add value to food waste or process waste for profit. Step 1: The teacher asks the class, "Does food waste have an impact on society, the environment, or people's well-being? Let the students explain." And "In your minds, what is the littering culture among students like? Does it impact the increased amount of food waste? Step 2: The findings of the survey on the impact of food waste and littering culture among students and individuals in schools will be shared with peers and teachers. Step 3: Students brainstorm ideas for a survey that will collect data on the impact of food waste and the littering culture among students and individuals in schools. They then memorized and collected the data as planned before synthesizing and summarizing it. Step 4: Every student in the room discusses the similarities and differences between the results of different groups and summarizes the classroom results. Step 5: "Is it possible to process, value, or profit from food waste that is discovered in schools?" The teacher asks the class. Step 6: Students attempt to find more information in documents or on the Internet, and they interview teachers or experts about the process, value, or profit from food waste. Step 7: Students share more information about the process, value, and profit from food waste with their friends and other groups.		
4. Decision-making	4.1 Each student group draws their own conclusions about how to Manage and Reduce Food Waste in School. • Students should be able to draw clear conclusions and show consistency between waste types, waste management practices, and output or outcomes. 4.2 Students and teachers discuss how to manage and reduce food waste in school once more. 4.3 Students choose guidelines to managing and reducing food waste in school that is appropriate for the school context and highly feasible.		KIS: Collaborative decision-making and shared control TL Phase 6: Planning a course of action (selecting feasible waste management guidelines)
5. Development of prototype or product	5.1 Using a computer program, each group of students create guidelines for managing and reducing food waste in school. • The guidelines should be based on the group consensus (clause 4.3). • Students should create an understandable presentation, such as Thinking Maps. • Students should create work that is visually appealing and easy to understand. 5.2 Students can use a variety of tools to develop guidelines for managing and reducing food waste at school. These tools are dependent on the student's aptitude and availability.		KIS: Engineering Design Process applied KSC: Science knowledge applied to practical solution design TL Phase 7: Acquisition of knowledge and skills for implementation TL Phase 8: Provisional trying of new roles (designer, problem-solver)
6. Test and evaluation	6.1 Students will be asked to develop some ideas about "how guidelines for managing and reducing food waste in school". They need to test for following issues: • Do the student-created guidelines fit the actual context of the school?		KAS: Formative assessment of feasibility, impact, and emotional response KIS: Critical self-reflection on own solutions

Stage	Activity	Assessment/ Method	PCK for TLSD Foundation & TL Phase
	• Is it possible that student-created guidelines will reduce food waste in schools? How? • In addition to reducing food waste in schools, can food waste generate income for schools or students? How? • If the student-created guidelines are followed in school, what emotions or thoughts will students have? (e.g. I'm glad it works well and can help reduce waste; I'm proud that at least I'm helping to save the planet; the school's garbage pile is much smaller than it was before, I'm happy and want to do this all the time; and I want to share the idea with other schools because all students will help with food waste.)		TL Phase 9: Building competence and self-confidence in new roles
7. Socialization and completion decision	7.1 Present ideas to design and build guidelines for managing and reducing food waste in school. 7.2 Present how the test and evaluation of the solution. 7.3 Present and explain how the prototype can be implemented. 7.4 Share what they learn from the comment and what they will revise for the completion solutions. *Note: Activities 7.1-7.4 should promote discussion and information sharing among students or between students and teachers. Following that, students should reflect on what they have learned about food waste.*		KAS: Peer feedback and qualitative observation of presentation and reflection KIS: Critical social thinking through peer discussion TL Phase 10: Reintegration into life based on new perspective toward food waste

Table 2 presents the science learning activity on food waste for Grade 10 students, which is structured through a seven-stage context-based STEM inquiry framework designed to foster sustainable development. The process begins with the identification of social issues, where students engage with real-world situations, such as videos of food waste, to trigger critical thinking and awareness regarding environmental impacts. This leads to the identification of potential solutions, during which students explore their own school's waste management practices and brainstorm areas for improvement. The core of the learning occurs during the need for knowledge stage. Students participate in three distinct activities: Activity 1: investigating the origins of food waste through surveys and interviews with school staff and peers; Activity 2: learning to categorise different types of waste and developing initial management guidelines based on scientific documentation and hands-on sorting; and Activity 3: analysing the broader consequences of waste on social well-being and the environment, while exploring ways to add economic value to waste products.

Once sufficient knowledge is gathered, students move into the decision-making phase. Here, they collaborate to select the most feasible and appropriate guidelines for their specific school context, ensuring consistency between waste types and management practices. This is followed by the development of prototypes, where students use digital tools and creative methods, such as thinking maps, to design visually appealing and understandable management plans. The final stages focus on rigour and dissemination. In the test and evaluation stage, students critically assess whether their guidelines are practical for their school, their potential to generate income, and the emotional impact of their environmental stewardship. The process concludes with socialisation and completion decisions, where groups present their prototypes and evaluation results to the class. This final stage emphasises peer feedback and reflection, allowing students to refine their solutions and internalise the complexities of managing food waste at the source.

3.3. *Expert Review and Refinement Through the PLC Process (RQ3)*

The third phase of the study addressed RQ3 by reviewing and refining the food waste learning activity through the STEM KKU Professional Learning Community (PLC) process. The expert review was conducted through a minimum of three Zoom meetings with two reviewers: Expert Reviewer A (PhD adviser with expertise in STEM pedagogy) and Expert Reviewer B (science teacher with experience in transformative learning activities). The key findings from the review process are summarised below.

First Review Meeting: Alignment and Scope: During the first meeting, the reviewers examined the initial draft of the food waste activity against the PCK for TLSD framework. The main feedback centred on three areas: (a) Expert Reviewer A recommended strengthening the alignment between the activity and the Thai national science curriculum (Strand 1, SC 1.1, Grade 10/4) by making the learning objectives more explicit and clearly linked to both the curriculum standards and SDG 12; (b) Expert

Reviewer B suggested that the activity steps needed to be more detailed and specific to ensure that teachers unfamiliar with STEM pedagogy could follow and implement them; and (c) both reviewers recommended that the formative assessment methods be embedded within each stage of the activity rather than presented separately. Following this meeting, the first author revised the activity to include three explicit learning objectives and integrated the assessment methods into Table 2.

Second Review Meeting: Instructional Strategies and Feasibility: The second meeting focused on the instructional strategies and practical feasibility of the activity. Key feedback included: (a) Expert Reviewer A recommended that the connection between the seven-stage STEM inquiry framework and transformative learning theory be made more explicit, particularly by identifying which Mezirow phases were addressed in each stage; (b) Expert Reviewer B noted that Stage 3 (need for knowledge) was the most complex stage with three sub-activities, and suggested adding clearer time allocations and step-by-step instructions to guide teachers; and (c) both reviewers discussed the importance of including student misconceptions about waste and the environment to ensure that the activity addressed common barriers to understanding. Following this meeting, the first author added the fourth column to Table 2 and expanded the descriptions of misconceptions.

Third Review Meeting: Final Quality Review: The third meeting served as a final quality review. The reviewers examined the revised activity plan and confirmed that: (a) the learning objectives were clearly stated and aligned with the curriculum; (b) the seven stages were coherent and progressed logically from problem identification to solution development and reflection; (c) the integration of PCK for TLSD foundations and Mezirow's transformative learning phases was explicit and consistent throughout Table 2; (d) the formative assessment methods were appropriate for the activity goals; and (e) the overall activity was feasible for implementation in a Thai secondary school setting within the recommended 12-15 class periods. Minor wording adjustments and formatting improvements were suggested and incorporated into the final version. The iterative PLC review process served as a form of peer-expert triangulation, enhancing the credibility, reliability, and transferability of the activity design (Chummongkol et al., 2023; Cohen et al., 2000). The final version of the activity represents the product of this collaborative developmental process. The reviewers' complementary expertise combining theoretical knowledge of STEM pedagogy and transformative learning with practical classroom experience ensured that the activity was both theoretically grounded and practically feasible.

3.4. The Activity Through the Lens of PCK for TLSD

The integration of Sustainable Development Goals (SDGs) into science education requires a specialized pedagogical framework that transcends traditional content delivery. This discussion analyzes the science learning activity on food waste in schools by applying the framework of Pedagogical Content Knowledge for Transformative Learning and Sustainable Development (PCK for TLSD) (Suttiwan, 2026). By examining the activity's instructional design against the foundations of PCK for TLSD, this section explores the potential of using local school contexts to foster transformative shifts in student worldviews. The following sections will discuss the alignment of the activity with science curricula, student understanding, instructional strategies, and assessment, while highlighting both the strengths and critical tensions identified in the design.

Foundations of Science Curricula and Goals for Transformative Learning and Sustainable Development: The activity demonstrates a strong alignment with the first foundation of PCK for TLSD: the integration of sustainability goals within science curricula. By selecting food waste as a socio-scientific issue, the activity effectively addresses SDG 12 (Responsible Consumption and Production). The activity structure described in Section 3.2 shows that it was designed to help students understand the life cycle of food and the environmental impact of waste. This supports the theoretical shift from 'learning to know' facts about biology to 'learning to think' about systemic impacts (Zoller, 2015). However, a critical observation is the potential tension between these broad sustainability goals and rigid national curriculum standards. While the activity is designed to succeed in fostering 'sustainability thinking' (Zoller, 2015), teachers may face barriers in time allocation, as holistic sustainable development perspectives often clash with discipline-bound traditions (Borg et al., 2012; Chummongkol et al., 2026). In theory, this activity serves as an example of 'transdisciplinary learning,' but in practice, maintaining this depth across all science units remains a significant challenge for educators.

Students' Understanding and Perspective Transformation: A core strength of the food waste activity is its focus on students' prior knowledge and values. According to PCK for TLSD, teachers must understand how students conceptualise their relationship with the world. The activity utilises 'real food waste situations' in the school canteen as a disorienting dilemma (Suttiwan, 2026). In transformative learning theory, a disorienting dilemma is an event or experience that challenges a person's existing frame of reference, triggering critical self-reflection and potentially leading to perspective transformation

(Baumgartner, 2019). In this activity, encountering the visible reality of food waste in their own school environment is intended to serve as this catalytic experience. The activity design indicates that students are guided to identify causes of waste, such as 'unpalatable food' and 'excessive portions'. This design approach supports the constructivist view that learning is most effective when it is personally relevant (Taylor et al., 1997).

The alignment between the seven stages of the activity and Mezirow's transformative learning theory is designed to be progressive and cumulative. Stage 1 introduces the disorienting dilemma (Phase 1) through food waste videos and canteen observations, triggering self-examination (Phase 2) as students express their feelings and opinions about the situation. Stages 2 and 3 facilitate the critical assessment of assumptions (Phase 3) as students investigate school waste practices and discover that their concerns are shared among their peers (Phase 4). This recognition of shared discontent is a crucial social dimension of transformative learning that strengthens students' motivation to pursue change. In Stage 3, the three sub-activities provide structured opportunities for the exploration of options (Phase 5), as students investigate the origins, types, and impacts of food waste from multiple angles scientific, social, economic, and environmental. Stages 4 and 5 correspond to planning a course of action (Phase 6) and acquiring knowledge and skills for implementation (Phase 7), as students collaboratively select feasible guidelines and design prototypes. Stage 6 involves the provisional trying of new roles (Phase 8) and building of competence (Phase 9), as students test and evaluate their solutions. Finally, Stage 7 represents the culmination of the transformative process: through presentation, peer feedback, and reflection, students engage in reintegration (Phase 10) considering how their transformed perspective on food waste can be carried into their daily school life. This progressive alignment ensures that the activity does not merely present transformative learning concepts but structurally embeds the entire 10-phase process within the instructional design. Nevertheless, it is important to acknowledge that achieving a full 'perspective transformation' is complex, particularly with adolescent learners. As noted by Meerts-Brandsma and Sibthorp (2021), adolescents may experience the stages of transformation, but the outcome is often more related to 'identity formation' than to an irreversible change in worldview. Their research found that, while students at semester schools experienced most of Mezirow's 10 stages of transformative learning, the qualitative interviews revealed that students experienced formation more than transformation a process of discovering who they are rather than fundamentally altering their existing frame of reference (Meerts-Brandsma & Sibthorp, 2021). The discussion suggests that, while the activity is designed to spark critical reflection, long-term behavioural change requires a 'relational ontology' where students see themselves as deeply interconnected with the school's ecosystem (Wagle et al., 2023).

Instructional Strategies: STEM Pedagogy and Context-Based Inquiry: The instructional strategy employed in the activity moving from identification of issues to finding initial solutions aligns closely with the STEM pedagogy and context-based inquiry models. By working together to find solutions for canteen waste, students are expected to engage in a collaborative learning process (Suttiwan, 2026). This is consistent with social constructivism, which emphasises negotiation and shared control in the classroom (Taylor, 2014). The use of the Engineering Design Process to develop initial ideas for waste reduction provides a practical application of STEM knowledge (Fachrunnisa et al., 2021). From the perspective of transformative learning, the collaborative activities in Stages 1-3 provide opportunities for what Baumgartner (2019) describes as key elements of fostering transformation: individual experience that is personally relevant, critical reflection on assumptions, and meaningful dialogue with peers. The activity's design specifically incorporates group brainstorming, peer discussion, and presentation all of which align with the reflective discourse that Mezirow considers essential for perspective transformation. However, from a critical perspective, the theory practice gap remains evident (Christopher & Pinias, 2025). While the activity provides a structured design for formative assessment in which teachers can notice student interactions (Cowie & Bell, 1999), the leap from initial ideas to transformative action in the community is a considerable hurdle. To move beyond a school project, science education must empower students to challenge the status quo through critical voice (Taylor et al., 1997).

Assessment of Scientific and STESEP Literacy: The final foundation of PCK for TLSD involves assessing not just content, but Science, Technology, Environment, Society, Economy, and Policy (STESEP) literacy. The food waste activity implicitly covers these dimensions by requiring students to consider the economic cost of waste and the social habits of their peers (Suttiwan, 2026). The use of peer feedback and qualitative observation reflects the characteristics of formative assessment (Bell & Cowie, 2001). This approach allows for interactive formative assessment, in which the teacher responds to student learning in real time (Cowie & Bell, 1999). A point of concern, however, is the lack of a standardised rubric to measure transformative competencies. The Organisation for Economic Co-operation and Development (2019) identifies three transformative competencies for 2030 creating new value, reconciling tensions and dilemmas, and taking responsibility all of which are relevant to the food

waste activity. However, without rigorous assessment tools such as the VALUE rubric or Kember's Critical Reflection Questionnaire (Romano, 2014), it is difficult to quantify the level of critical reflection that students may achieve through this activity. This represents an area for future development.

Hence, the science learning activity on food waste in schools serves as a robust example of PCK for TLSD in action. It successfully bridges the gap between scientific theory and sustainable practice by grounding learning in a disorienting, real-world dilemma. The activity excels in fostering personal relevance and collaborative problem-solving. The expert review process confirmed that the activity is coherent, theoretically grounded, and practically feasible. To enhance the transformative potential of such activities, it is recommended that future iterations incorporate futures thinking to help students to envision desirable long-term outcomes (Laherto & Rasa, 2022). Furthermore, addressing the discipline-bound barriers through professional learning communities (Nurhayati et al., 2023) will be essential for teachers to move from occasional activities to systematic transformative science education. Additionally, future research should implement the activity in real classroom settings to gather empirical evidence of its impact on student learning and transformative competencies (Christopher & Pinias, 2025). Ultimately, this study demonstrates that when science teachers possess the right PCK for TLSD, the classroom becomes a 'sandpit' for creating a more sustainable future.

4.   CONCLUSION

This study designed and developed a science learning activity centred on food waste to promote sustainable development within the Thai school context, guided by three research questions. The activity was developed through a four-phase qualitative developmental process: literature review and needs analysis; activity design using the PCK for TLSD framework integrated with transformative learning theory; expert review through a professional learning community; and final revision. Regarding RQ1, the needs analysis identified a clear contextual justification for the activity. The synthesis of international sustainability frameworks, Thai national policies, the science curriculum, 21st-century skills, formative assessment, and transformative learning theory revealed a gap between sustainability goals and classroom practice. Specifically, food waste in school canteens is a pervasive issue that has not been systematically utilised as a context for science learning in Thailand. Regarding RQ2, the study produced a science learning activity structured through a seven-stage context-based STEM inquiry framework, aligned with Strand 1 (SC 1.1, Grade 10/4) of the Thai national science curriculum and designed for 12-15 class periods over 4-5 weeks. The activity integrates the four foundations of PCK for TLSD (KSC, KSU, KIS, and KAS) with Mezirow's 10 phases of transformative learning. Three learning objectives guide the activity: critical thinking for waste reduction; communication of solutions with social awareness; and application of economic principles for sustainability. The design uses food waste as a disorienting dilemma to promote sustainability thinking and multidimensional literacy. Regarding RQ3, the expert review through the STEM KKU Professional Learning Community confirmed the activity's quality and feasibility. Through three iterative review meetings, the reviewers provided feedback that strengthened the alignment with curriculum standards, clarified the integration of transformative learning phases, and improved the practical feasibility of the activity steps. The PLC process served as peer-expert triangulation, enhancing the credibility and transferability of the design.

This study demonstrates that context-based science learning activities grounded in the PCK for TLSD framework are a promising approach for integrating sustainable development into science education. The food waste activity provides a practical example for science teachers seeking to connect scientific content with real-world sustainability challenges. When teachers possess the pedagogical content knowledge to design transformative learning experiences, the science classroom can become a space where students not only acquire knowledge but also develop the awareness and skills needed to contribute to a more sustainable future. However, this study has several limitations. Most importantly, the activity has not yet been implemented in a real classroom setting with students. The conclusions are based on the quality of the design process and expert review, not on empirical evidence of student learning outcomes or behavioural change. In addition, the expert review was conducted by two peers within a single professional learning community, and the current design does not include a standardised rubric for assessing transformative competencies. Furthermore, applying transformative learning theory to adolescent learners requires careful consideration, as the outcomes may be more closely related to identity formation than to permanent perspective transformation. Future research should implement the activity with students in Thai secondary schools and evaluate its effectiveness through empirical approaches, such as action research, case study, or quasi-experimental designs. Developing validated assessment instruments for measuring transformative learning outcomes would further strengthen the contribution. Finally, adapting the activity to different cultural and educational contexts would help to establish the broader applicability of the PCK for TLSD framework.

ACKNOWLEDGEMENT

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTION

Witsanu Suttiwan: Conceptualization, Methodology, Data collection, Data analysis, Writing original draft. Pratuengsook Maneelam: Data collection, Writing original draft, Reviewing and Editing. Chokchai Yuenyong: Data analysis, Writing original draft, Reviewing and Editing, Corresponding author.

DATA AVAILABILITY

All data generated or analyzed during this study are included in this published article.

DECLARATION OF GENERATIVE AI

During the preparation of this work, the author used Gemini (developed by Google), Claude AI, and Grammarly in order to refine the language structure and verify grammatical accuracy. After using these tools, the author reviewed and edited the content as needed and takes full responsibility for the final version of the manuscript.

ETHICS

Human participant procedures were approved by the Khon Kaen University Ethics Committee (HE673177; GCP compliant).

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