



# The Role of TPACK in Strengthening Geometrical Thinking and Numeracy Literacy through Contextual Manipulative Media: A Qualitative Study Integrating Climate Literacy

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## KEYWORDS

TPACK, Contextual Manipulative Media, Geometry Thinking, Numeracy Literacy, Climate Literacy, SDG 4

**ABSTRACT** The need to improve the quality of education (SDG 4) urges the integration of global sustainability issues, such as climate literacy, into the core curriculum, particularly mathematics. This study stems from the urgency of improving students' geometric thinking and numeracy literacy, which remains a challenge, while emphasizing the importance of teachers' roles as learning designers. Objective: This study aims to explore in-depth the role of teachers' TPACK (Technological Pedagogical Content Knowledge) in planning, implementing, and reflecting on the use of contextual manipulative media that integrates climate literacy to strengthen students' conceptual understanding of geometry and numeracy. This study uses a qualitative approach with a case study design. Data were collected through in-depth classroom observations, semi-structured interviews with teachers and students, and analysis of learning documents (Lesson Implementation Plans and student artifacts) from teachers who implemented the TPACK framework. The findings indicate that the TPACK framework significantly guides teachers in selecting mathematically relevant climate content (PCK), designing effective and adaptive manipulative media (TCK/TPK), and facilitating critical discussions (PK) that link mathematical calculations (numeracy) to climate-based solutions. The role of TPACK enables a shift from passive learning to active and meaningful learning. Conclusion: The integration of climate literacy through contextual manipulative media, facilitated by strong TPACK mastery, not only successfully strengthens understanding of geometry and numeracy but also increases students' awareness and ability to apply mathematical knowledge to sustainability issues. These results provide important implications for teacher professional development in the digital and sustainability era.

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## INTRODUCTION

Achieving Sustainable Development Goal (SDG) 4 on Quality Education (Dash, 2024) requires education systems to not only provide access but also ensure the relevance and depth of learning. In the mathematics domain, improved geometric thinking

and numeracy literacy are key indicators of success (Ma, 2022; Tang, 2021). Both are foundational to the quantitative analysis and spatial reasoning required in the 21st century. Unfortunately, global and national data often indicate that students' ability to

use geometric and numeracy concepts in contextual problem-solving still requires significant pedagogical intervention (Otun & Njoku, 2020). Education must integrate pressing global issues. Climate literacy is now a vital cross-curricular competency, requiring students to use mathematical skills (numeracy and geometry) to understand and analyze the impacts of climate change (Udhma & Sari, 2017). To achieve this meaningful integration, the use of contextual manipulative media offers a solution. These media allow students to physically model climate phenomena (for example, calculating the volume of melting ice or modeling the area of land affected), making abstract concepts of geometry and numeracy tangible and functional (Atsara, 2021). The success of this complex integration between mathematical content, manipulative media, and the climate literacy context depends on the expertise of the teacher (Lai, 2022). TPACK (Technological Pedagogical Content Knowledge) serves as a highly relevant theoretical framework (Irwanto, 2021; Rakes, 2022). TPACK guides teachers to (Hava, 2025; Zou, 2022) (1) identify intersections between Geometry/Numeracy and Climate Literacy (PCK) content, (2) select or design effective contextual manipulative media (TPK), and (3) manage active learning processes that engage higher-order reasoning (PK). Exploring teacher practices within the TPACK framework is key to understanding how complex content can be delivered effectively. While each component (TPACK, Manipulative Media, Climate Literacy) has been extensively researched, a substantial research gap lies in qualitative studies examining the dynamic interaction of the three (Schmid, 2020). Existing research tends to be quantitative, measuring impact on scores without explaining how and why such integration is successful. No in-depth qualitative studies have explicitly investigated the role of teachers' TPACK in navigating the complexities of designing and implementing contextual manipulative media that simultaneously aim to strengthen geometric thinking, numeracy literacy, and climate literacy (Falloon, 2020; Verlie, 2021). This gap limits our understanding of teachers' pedagogical decision-making processes in sustainability teaching. This study offers significant novelty and original contributions to the educational literature: (1) Qualitative Tripartite Synergy: This is a comprehensive qualitative study that maps the synergy between TPACK (Hava, 2025), Contextual Manipulative Media, and Climate Literacy within a single learning intervention framework (Ahmed, Kent, & Keller-Margulis, 2023; Chamorro, 2024). (2)

Focus on Cognitive and Pedagogical Processes: This study focuses not solely on learning outcomes, but rather on a qualitative process exploration namely, how TPACK influences teachers' teaching practices and how it is internalized into students' geometric and numeracy thinking (Megawati & Sutarto, 2021). (3) Dual Contextualization: Using climate context to support the simultaneous enhancement of two distinct core mathematics competencies offers a replicable pedagogical model.

Based on these backgrounds, gaps, and novelties, this study focuses on a qualitative exploration of the role of teachers' TPACK in strengthening students' geometric and numeracy thinking through the use of contextual manipulative media that integrates climate literacy, with the hope of providing important insights for curriculum development and teacher professional training in the context of SDG 4.

## METHOD

### 2.1. Research Design

This research adopts a Qualitative Design with a Case Study approach (Phelps, 2021). The case study was chosen because it allows researchers to conduct an in-depth and holistic investigation of contemporary phenomena in a real-life context, namely how teachers' TPACK influences the process of teaching Geometry and Numeracy through Contextual Manipulative Media that integrates Climate Literacy. This qualitative approach aims to:

- a. Exploring teachers' understanding and perspectives on TPACK, media, and climate literacy.
- b. Analyze the media implementation process in detail in class (observation).
- c. Understand students' experiences in building their geometric and numeracy thinking from the use of contextual media.

### 2.2. Location and Subject of Research

The research will be conducted at Universitas PGRI Wiranegara Pasuruan, which was selected based on the criteria that the school has a commitment to learning innovation and supports the integration of sustainability issues. The main subjects of the research are:

- a. Mathematics Teachers is 2 mathematics teachers selected using purposive sampling. The teacher selection criteria include: (1) experience in teaching Geometry and Numeracy, (2) active involvement in developing learning media, and (3) having an initial understanding or willingness to implement TPACK and integrate climate issues.
- b. Students is 6 students from the class taught by the subject teacher. Key students will be

selected based on varying levels of understanding (high, medium, low) to gain diverse perspectives on the impact of media.

Qualitative data was collected using triangulation to ensure the validity and reliability of the findings. The techniques used include:

### 2.3. Data Collection Procedures and Techniques

Data collection technique	Purpose of Use	Focus of the Data Obtained
Semi-Structured Interview	Exploring the role and understanding of teachers' TPACK (TPK, PCK, TCK) in designing climate-based contextual manipulative media, as well as their views on the effectiveness of the media.	Conceptual understanding, teachers' pedagogical decision-making, and post-implementation reflection.
Participant Observation (Class)	Analyzing the implementation process and interactions in the classroom directly. Observations focused on: (1) how teachers apply TPACK when using media, (2) student engagement with media, and (3) the quality of discussions linking Geometry, Numeracy, and Climate Literacy.	Concrete evidence of TPACK implementation, student behavior, and the quality of contextual learning.
Document Analysis	Review planning documents and student work. Documents include TPACK-based Lesson Plans (RPP), contextual manipulative media designs, and student worksheets/projects demonstrating the application of Geometry and Numeracy to climate issues.	Consistency between teacher planning (TPACK) and implementation, as well as evidence of strengthening students' geometric and numeracy thinking.

### 2.4. Data Analysis Techniques

Data analysis was conducted inductively and continuously throughout the data collection process, referring to qualitative data analysis models (Triwahyuningtyas & Sesanti, 2023). The analysis stages include:

- a. Data Reduction: Summarizing, selecting the main points, focusing on data relevant to the research question (the role of TPACK, manipulative media, climate literacy, geometry/numeracy).
- b. Data Display: Presenting reduced data in the form of a matrix, narrative, or organized chart to facilitate understanding and drawing conclusions.
- c. Conclusion Drawing and Verification: Drawing temporary conclusions and verifying them through triangulation of data sources (interviews, observations, and documents) to ensure the final findings are strong and trustworthy.
- d. Coding and Categorization: Conducting open, axial, and selective coding of interview transcripts and field notes, which were then categorized to develop themes that explain in detail the role of TPACK in the context of this research.

### 2.5. Data Validity (Trustworthiness)

The validity of data (validity and reliability) in qualitative research is guaranteed through:

- a. Source Triangulation: Comparing information from teachers, students, and documents.

- b. Triangulation Method: Using interviews, observation, and document analysis.
- c. Member Check: Asking research subjects (teachers) to verify and confirm the researcher's interpretation of their interview data.
- d. Thick Description: Presents findings with a very detailed description of the context and process, allowing readers to assess the extent to which the findings can be transferred to other contexts.

## RESULT AND DISCUSSION

### RESEARCH RESULT

The results of this qualitative study present key findings regarding the role of mathematics teachers' TPACK as an orchestration framework in designing and implementing learning that integrates contextual manipulative media based on climate literacy. These findings are organized based on three main dimensions: the role of TPACK in design, the effectiveness of implementation, and its impact on student competency.

#### 3.1. The Role of Teachers' TPACK in Integrated Learning Design

Interview and document analysis (TPACK-based lesson plans) revealed that the TPACK framework is the main foundation for teachers in making complex pedagogical decisions:

**TPACK Conceptual Mapping:** Findings indicate that TPACK serves as an integrative framework, ensuring that content (Geometry/Numeracy and Climate Literacy), pedagogy (Learning Strategies),

and technology (Contextual Manipulative Media) are mutually supportive. This role is crucial for balancing curriculum demands with the relevance

of global issues. A visualization of this interrelationship is presented in Figure 1.

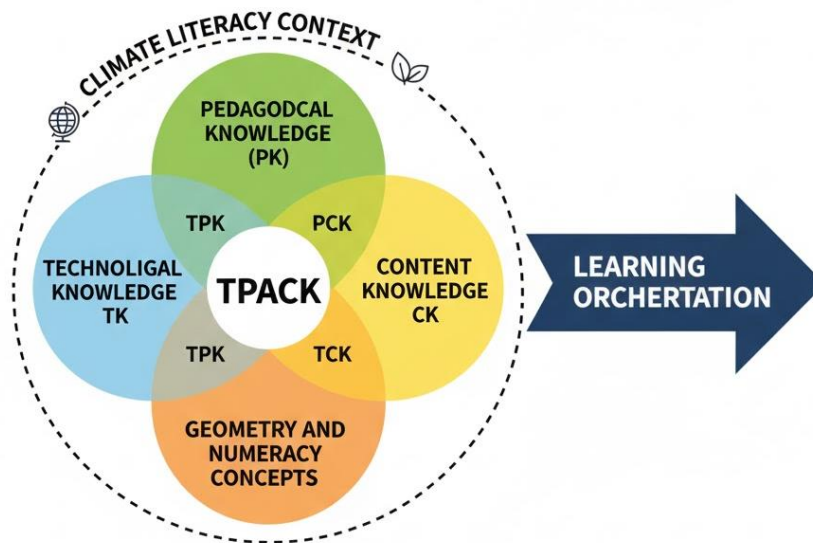


Diagram 1. TPACK Conceptual Framework as an Integrated Geometry and Numeracy Learning Orchestrator for Climate Literacy.

**Pedagogical Content Knowledge (PCK)** The Curriculum and Climate Issues Bridge: Effective teachers demonstrate strong PCK skills in drawing precise connections between core mathematical concepts (such as area, volume, and scale) and relevant climate literacy issues (e.g., carbon footprint calculations, ice melt modeling, or flood extent). TPACK enables teachers to prioritize the most applicable mathematical concepts for analyzing climate data, making mathematics a functional tool for environmental understanding.

**Technology Content Knowledge (TCK)** Contextual

**Media Design (Hyun, 2020) and Validation:** The TCK domain involves not only digital tools, but also knowledge of how technology (such as spreadsheets or simple modeling applications) can support physical media. For example, teachers design prototypes of manipulative media (such as scale models of forests or water catchment systems) and use technology to analyze data generated from the physical manipulation of these media. TCK influences teachers' ability to select manipulative media that are contextually valid and appropriate to real-world scenarios.

Table 1. The Role of TPACK Domains in the Process of Integrating Climate Literacy and Manipulative Media

TPACK Domain	Focus Role in Research	Qualitative Manifestation
PCK	Relate Geometry/Numeracy content to climate context.	Formulation of climate problems that require Volume and Scale analysis (Example: Calculating the volume of water needed to irrigate land affected by drought).
TCK	Utilizing technology to support physical media (Manipulative).	Use of <i>spreadsheets</i> or simple GeoGebra applications to process measurement data obtained from manipulative models (forest scale, water reservoir roof model).
TPK	Strategies for using manipulative media effectively in the classroom.	The teacher's ability to manage the transition from physical manipulation of media to symbolic representation and vice versa; group management when using media.
PK	General teaching strategies and discussions.	Facilitate in-depth discussions that connect the results of numerical calculations back to the implications for environmental ethics and climate solutions.

### 3.2. Effectiveness of Media Implementation Through Technological Pedagogical Knowledge (TPK)

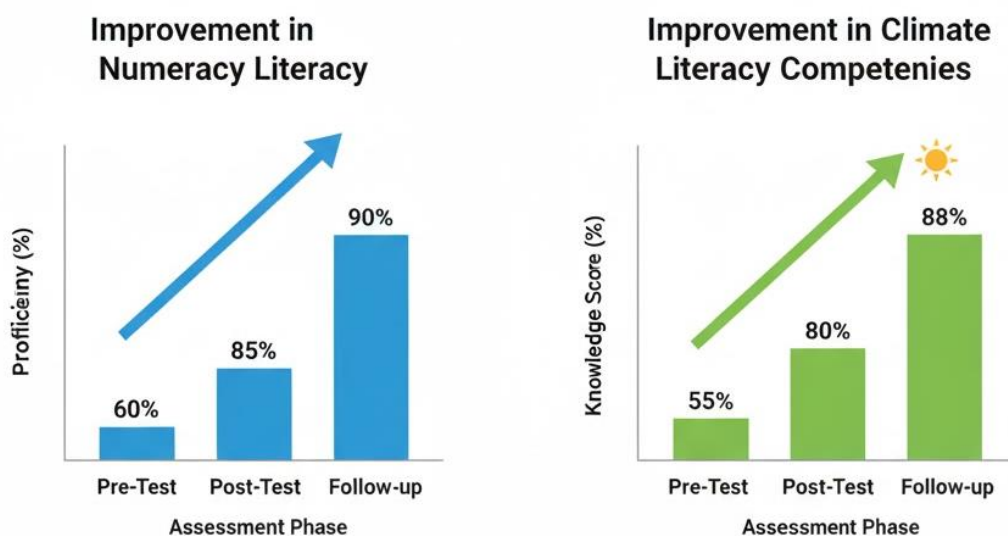
The detailed classroom observation phase shows how the teacher's TPK dimensions are implemented to create a deep learning experience:

- a. **Orchestration of TPK and Facilitation of Critical Discussion:** TPK is evident in the way the teacher manages the learning environment, using manipulative media as a catalyst for the transition of understanding from concrete (physical models) to symbolic abstraction (mathematical formulas). The teacher strategically encourages students to interact with the physical model (e.g., measuring dimensions and performing initial calculations) and then guides the discussion (Pedagogical Knowledge/PK) to connect the results of the numerical calculations (e.g., how much water is lost) back to environmental implications (climate literacy).
- b. **Increased Engagement and Knowledge Transfer:** Student engagement is at a high level because the climate context used is relevant to their lives. Contextual manipulative media changes the learning objectives of Geometry and Numeracy, making them powerful tools for solving environmental problems, rather than just isolated academic tasks.

### 3.3. Impact on Strengthening Students' Geometric Thinking and Numeracy Literacy

Analysis of student work (artifacts) and interviews with key students underscore the positive impact of using this media, supported by TPACK-based teacher practices:

- a. **Strengthening Geometric Thinking (Relational Understanding):** Students demonstrated significant improvements in their spatial *visualization* and *modeling skills*. When faced with geometric shape optimization problems (e.g., designing an efficient roof for water storage), students not only applied volume formulas, but were also able to provide logical geometric reasoning about the shape's efficiency, demonstrating a shift from instrumental understanding (simply knowing the formula) to relational understanding (why the formula works in this context).
- b. **Improved Numeracy Literacy (Contextual Application):** Improved numeracy competency is seen in students' ability to interpret quantitative data from real-world climate scenarios (e.g., temperature rise or pollutant concentration data). Students are able to convert this data into relevant numerical calculations, project their impacts, and effectively communicate quantitative findings, demonstrating higher numeracy proficiency in an environmental context.



**Figure 2. Improvement in Numeracy Literacy and Climate Literacy Competencies Post-Contextual Manipulative Media Intervention**

Overall, these findings conclude that TPACK serves as a critical orchestration framework in integrating three elements: mathematical content, pedagogical strategies, and climate literacy contexts. Teacher expertise across TPACK domains ensures that contextual manipulatives can effectively serve as a dual tool: reinforcing core competencies of Geometry and Numeracy while simultaneously fostering students' climate awareness and literacy (supporting SDG 4).

## DISCUSSION

### 4.1. TPACK as a Key Orchestrator of Content Integration and Challenge Mitigation

The main findings of this study emphasize the central role of TPACK as an orchestration framework that enables the integration of complex content. TPACK, particularly the intersection of PCK and TCK (Inpeng, 2020; Schmid, 2020; Zou, 2022)s, influences teachers' planning and decision-making in addressing the simultaneous demands of the curriculum and global issues.

- a. Translating Climate Context into PCK: Teachers with strong TPACK (Al-Adwan, 2025; Luo, 2024; Rienties, 2022) are able to translate multidisciplinary climate literacy issues into structured Geometry and Numeracy problems. This aligns with Koehler and Mishra's (2020) view that PCK is the core of effective teaching, which in this context is expanded to include sustainability content. Teachers do not simply add climate issues, but rather use them to provide *conceptual depth* to mathematical formulas.
- b. Optimizing TCK and TPK in Manipulative Media: The use of contextual manipulative media shows that TCK plays a role in ensuring the contextual validity and mathematical accountability of physical media (model prototypes) (Handayani, 2020; Wang, 2022). TPK then ensures a smooth transition from the physical interaction of the media to symbolic representation, which is key to avoiding purely *instrumental understanding* in students.
- c. Mitigating Integration Complexity Challenges: Qualitative studies revealed that teachers' biggest challenges were time allocation and the complexity of curriculum alignment. TPACK serves as an efficiency-guiding tool (Chiu, 2025); teachers can quickly identify the most appropriate pedagogical technology or media for specific climate content, thereby

reducing planning time and addressing the challenges of dual content integration (Geometry/Numeracy/Climate).

### 4.2. Dual Competency Strengthening Mechanism and Triangular Relationships

The results of observations and analysis of student artifacts indicate that contextual manipulative media operated through effective TPACK practices resulted in strengthening two core competencies, as well as a synergistic relationship with climate literacy:

- a. Geometric (Relational) Thinking: Students' physical engagement in modeling climate problems (e.g., comparing the volumes of different water containers) forces them to engage in spatial reasoning and geometric justification (Almheiri, 2020; Tang, 2021; Zheng, 2022). The progression from instrumental to relational understanding is evidence that manipulative-based active learning is highly effective in triggering higher cognitive processes in geometry.
- b. Numeracy Literacy (Functional) and Triangular Relationships (Megawati & Sutarto, 2021; O'Hara, 2022; Purnomo, 2023): The integration of climate literacy positions Numeracy as a functional skill. Students are encouraged to interpret, calculate, and communicate real-world data. A Triangular Relationship was found: Manipulative Media (A) facilitates Geometric Thinking (B), which in turn strengthens students' Numeracy skills (C) in the context of climate data. The climate context provides real-world consequences for numeracy calculations, increasing students' motivation to be accurate in calculations and analysis.

### 4.3. New Dimension: Formation of Critical Attitudes and Climate Awareness

Qualitative findings also highlight dimensions beyond purely mathematical competency. The use of contextual media based on global issues, orchestrated by a strong TPACK approach, successfully fosters critical thinking and environmental awareness in students:

- a. Increased Critical Thinking and Self-Efficacy: Students not only calculate but also take ethical positions based on data analysis. They begin to see mathematics as a tool for advocacy and sustainable decision-making,

not just as a school subject. This demonstrates the achievement of climate literacy goals at the engagement level.

- b. Climate Literacy as Positive Feedback: Climate literacy built through mathematical calculations (numeracy) becomes a reinforcing feedback (Marsuki, 2020; Shevchenko, 2021) for the importance of their geometric and numeracy accuracy, creating a positive cycle in which mathematical competence triggers social awareness, and vice versa.

#### 4.4. Implications for Achieving SDG 4 and Teacher Professional Development

This research has important implications for curriculum development and teacher training:

- a. Contribution to SDG 4: This study provides qualitative empirical evidence that mathematics education can be a powerful vehicle for achieving SDG 4 (Quality Education) (Colque-Quispe, 2025) and SDG 13 (Climate Action) simultaneously (Ghanem, 2020). Contextual manipulative media integrated with climate literacy is a replicable pedagogical model to ensure relevant and future-oriented quality education.
- b. Focus on TPACK Development: These findings highlight that teacher training (CPD) programs should explicitly include modules on how TPACK can be used to integrate sustainability issues. The focus should not be solely on new digital tools, but on how teachers can connect pedagogy and content to global contexts through various types of technology (including simple technology or physical media).

#### 5. Research Novelties and Future Suggestions

This study successfully fills a research gap by providing a detailed qualitative analysis of the synergy between TPACK, manipulative media, and climate literacy. Its novelty lies in mapping the orchestration *process* undertaken by teachers and *its dual impact* on Geometry/Numeracy and Climate Literacy competencies.

For future research, it is recommended to: (1) Conduct a qualitative comparative study between teachers with high TPACK and low TPACK in the same implementation; (2) Test the transfer of student knowledge from the climate context taught to other sustainability contexts (e.g., circular economy); and (3) Develop a validated TPACK instrument specifically to measure teachers' know

#### CONCLUSION AND RECOMMENDATION

This qualitative research aims to explore in-depth the role of teachers' TPACK (Comprehensive Modeling and Application of Mathematics) in planning and implementing lessons using contextual manipulative media integrated with climate literacy to strengthen students' geometric thinking and numeracy literacy.

The study's key findings confirm that TPACK serves as a crucial and effective orchestration framework for achieving complex curricular integration.

1. TPACK as the Heart of Integration: Teacher expertise across all TPACK domains (especially the intersection of PCK and TPK) is a critical success factor. TPACK guides teachers in precisely selecting mathematical content relevant to climate literacy scenarios (Inpeng, 2020), designing contextually valid manipulative media, and managing the learning transition from physical-manipulative activities to symbolic mathematical representations (Casal-Otero, 2023).

2. Enhancement of Dual Competencies: Effective implementation of TPACK through contextual manipulative media has been shown to simultaneously strengthen two core competencies:

- a. Geometric Thinking: Students demonstrate improvements in relational understanding and spatial reasoning abilities, going beyond simply applying formulas.

- b. Numeracy Literacy: Students demonstrated improvements in functional application as they were able to interpret quantitative data from real-life climate issues and use it for decision-making.

3. Impact of Critical Thinking and SDG 4: This study found that a climate literacy context supported by mathematical analysis fostered environmental awareness and students' ability to take critical and ethical stances on sustainability issues (Okulich-Kazarin, 2024). Thus, this study provides qualitative evidence on how mathematics education can effectively contribute to the achievement of Sustainable Development Goals (SDGs) 4 and 13 (Holst, 2024).

Overall, this study concludes that mastery of TPACK is not merely a technical requirement but an essential competency for teachers to design relevant, meaningful, and future-oriented learning.

The results of this study recommend that teacher professional development (CPD) programs focus more on TPACK training in the context of sustainability issues, so that teachers are prepared to integrate global issues into Geometry and Numeracy learning.

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