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Preparing Modern Mathematics Teachers Through the Integration of TPACK, Abstraction, and Environment in Digital Era Learning

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Abstract
Limited access to professional development and digital learning innovation remains a challenge for teachers in post-disaster coastal areas, affecting the quality of mathematics instruction. This community service program aimed to strengthen the competence of mathematics teachers and school principals in Sumur District, Pandeglang Regency, through the integration of Technological Pedagogical Content Knowledge (TPACK), the theory of abstraction, and environment-based learning. The program employed a Participatory Action Research (PAR) approach through workshops, mentoring, lesson study, collaborative learning, and technology-assisted mathematics instruction. The results showed improvements in teachers' pedagogical competence, digital literacy, and ability to design contextual mathematics learning integrated with environmental awareness. Teachers were able to utilize Augmented Reality (AR) technology and implement learning resources aligned with the Merdeka Curriculum. The program also strengthened professional learning communities and contributed to improving educational quality, educational resilience, and sustainable learning practices in post-disaster coastal communities, and supported long-term educational transformation for sustainable community development outcomes.

Keywords: *abstraction theory, environmental-based learning, mathematics learning, teacher empowerment, TPACK.*

Introduction

Pandeglang Regency is located at the western tip of Java Island and consists of several coastal districts vulnerable to natural disasters, including Sumur District. In 2018, the eruption and partial collapse of Mount Anak

Krakatau triggered a tsunami in the Sunda Strait that caused severe destruction to educational infrastructure, including school buildings, textbooks, teaching facilities, and community learning environments (Radiarta et al., 2012). The tsunami also affected tourism activities, coastal economic stability, and social conditions in local communities (Wulung & Abdullah, 2020). Educational recovery, therefore, became an important component in post-disaster community reconstruction because education functions not only as a means of knowledge transfer but also as a social instrument for rebuilding community resilience.

The impact of the disaster on the education sector was multidimensional. Many schools experienced damaged classrooms, reduced availability of teaching media, and interruptions in learning activities. Teachers and students also experienced psychological pressure caused by post-disaster trauma, which indirectly affected the learning process. In addition, the geographical conditions of coastal areas made access to educational support and professional development programs more difficult compared to urban regions. These conditions contributed to educational disparities between coastal communities and other regions with better infrastructure.

Although reconstruction efforts have gradually restored physical infrastructure, educational quality in coastal communities remains relatively low compared to urban areas. Teachers in remote coastal schools still experience limited access to digital learning innovation, professional development training, and educational technology integration. This condition affects the implementation of modern learning approaches and limits teachers' opportunities to improve instructional quality (Lega & Hartanto, 2023; Sihaloho et al., 2024). Furthermore, educational inequality in disadvantaged and frontier areas continues to become a national challenge requiring sustainable empowerment programs (Rosmana et al., 2022).

The transformation of education in the digital era requires teachers not only to master subject content but also to integrate pedagogical strategies and technology effectively. Rapid technological advancement has changed students' learning characteristics, requiring teachers to develop adaptive and innovative instructional approaches. In mathematics education, this challenge becomes more complex because mathematical concepts are often abstract and difficult for students to visualize. Students frequently experience difficulties understanding geometry, algebraic relationships, and spatial reasoning because these concepts require high levels of abstraction.

Therefore, teachers need innovative approaches that transform abstract concepts into meaningful learning experiences. The integration of digital technology can support visualization, interaction, and conceptual understanding in mathematics learning. Technology-assisted learning environments also enable teachers to create interactive and contextual learning experiences that increase students' engagement and motivation.

One important framework supporting this transformation is Technological Pedagogical Content Knowledge (TPACK), which integrates technological knowledge, pedagogical knowledge, and content knowledge into comprehensive learning practices (Rafi & Sabrina, 2019). TPACK emphasizes that effective technology integration requires more than just technical skills. Teachers must understand how technology can reshape pedagogical strategies and content representation so that learning activities become more meaningful and student-centered.

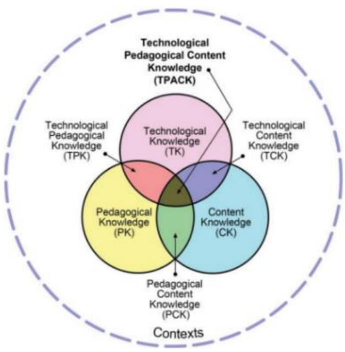

Figure 1. Technological Pedagogical Content Knowledge (TPACK) Framework.

Figure 1 illustrates the relationship between technological knowledge, pedagogical knowledge, and content knowledge within the TPACK framework. This framework emphasizes that effective digital learning occurs when teachers are able to integrate technology, pedagogy, and subject matter simultaneously in classroom instruction. In mathematics learning, TPACK helps teachers design interactive learning environments capable of improving conceptual understanding, critical thinking, communication skills, and students' problem-solving abilities.

Several studies have demonstrated that technology-enhanced mathematics learning can improve conceptual understanding, learning motivation, and spatial visualization abilities (Ng et al., 2020; Saeed et al., 2017). The use of digital visualization technology, such as Augmented Reality (AR), provides students with opportunities to understand geometry concepts more interactively and contextually. AR-based learning media are particularly effective in helping students visualize three-dimensional mathematical objects and improving their abstraction processes. Through AR applications, students can manipulate virtual objects, observe shapes from different perspectives, and connect abstract mathematical representations with concrete experiences.

In addition to technological competence, mathematics learning also requires strong abstraction ability. According to Hershkowitz et al. (2007), abstraction involves three important cognitive processes: recognition, building-with, and construction (RBC). These cognitive processes support students in gradually developing mathematical understanding from concrete experiences toward abstract reasoning. Mathematical abstraction is strongly influenced by visualization and cognitive reconstruction processes during learning activities (Sümen, 2019; Yilmaz & Argun, 2018). The RBC model provides teachers with a framework for designing learning sequences that facilitate conceptual development systematically.

Another important aspect is the integration of environmental contexts into mathematics learning. Environmental-based learning enables students to connect mathematical concepts with real-life situations and strengthen ecological awareness. This approach is particularly relevant for coastal communities surrounding Ujung Kulon National Park, where environmental conservation and disaster mitigation are closely related to daily life (Firmansyah et al., 2023; Leksono et al., 2023). Mathematics learning can therefore become more meaningful when students use mathematical concepts to analyze environmental issues such as coastal erosion, tsunami mitigation, biodiversity, and waste management.

Previous studies have examined TPACK implementation, abstraction theory in geometry, and environmental education separately. However, few studies have integrated all three components within teacher empowerment programs in post-disaster coastal communities. Most previous studies focused only on improving technological competence or conceptual understanding without considering environmental contexts and disaster-affected educational conditions. Therefore, the novelty of this program lies in integrating TPACK, abstraction theory, environmental education, and Augmented Reality technology within mathematics teacher empowerment in post-disaster coastal communities.

Based on these conditions, this community service program aimed to prepare modern mathematics teachers through the integration of TPACK, abstraction theory, and environmental-based learning in the digital era. The program was expected to strengthen teachers' pedagogical competence, digital literacy, collaborative learning culture, and ability to design contextual mathematics learning suitable for students in coastal areas.

Literature Review

TPACK in Mathematics Education

TPACK was developed by Mishra and Koehler as an extension of Shulman's Pedagogical Content Knowledge (PCK). The framework consists of seven domains: Technological Knowledge (TK), Pedagogical Knowledge (PK), Content Knowledge (CK), Technological Pedagogical Knowledge (TPK), Technological Content Knowledge (TCK), Pedagogical Content Knowledge (PCK), and TPACK itself. In mathematics education, TPACK enables teachers to select appropriate digital tools for representing complex concepts like functions, geometry, and statistics.

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Technological Knowledge refers to teachers' understanding of digital tools, software, and technological systems. Pedagogical Knowledge involves knowledge about teaching methods, classroom management, learning theories, and instructional strategies. Content Knowledge refers to mastery of subject matter concepts. Effective learning occurs when these three domains are integrated meaningfully.

In mathematics education, TPACK enables teachers to select appropriate digital tools for representing complex concepts such as geometry, functions, statistics, and algebraic relationships. Teachers who possess strong TPACK competence can integrate technology not merely as an additional learning medium but as a pedagogical instrument that transforms students' learning experiences.

Research by Rafi and Sabrina (2019) found that teachers with strong TPACK are more capable of designing inquiry-based learning activities using digital simulations and interactive visualization. Technology integration also improves students' participation and supports collaborative learning environments. However, in the Indonesian context, TPACK implementation remains limited in rural and coastal areas due to infrastructure limitations, internet access constraints, and limited opportunities for professional training.

The development of TPACK competence is particularly important in the digital era because students are increasingly familiar with technology in their daily lives. Teachers are expected to create learning environments that align with students' digital experiences while maintaining pedagogical effectiveness. Therefore, strengthening TPACK competence among teachers is essential for improving educational quality and reducing digital disparities between regions.

Abstraction Theory and the RBC Model

Mathematics is often regarded as an abstract discipline requiring students to understand symbols, patterns, and relationships that are not directly observable. Consequently, abstraction plays a central role in mathematics learning. Hershkowitz et al. (2007) proposed the RBC model of abstraction, which describes how learners construct abstract mathematical knowledge through three epistemic actions: recognition, building-with, and construction.

Recognition refers to identifying previously constructed mathematical structures in new situations. Students recognize similarities between prior experiences and new mathematical problems. Building involves combining existing constructs to address new problems or situations. In this stage, students use prior knowledge flexibly to solve mathematical tasks. Construction refers to creating new mathematical constructs that were not previously available, enabling students to achieve deeper conceptual understanding.

The RBC model aligns with constructivist learning theory because it emphasizes active knowledge construction through interaction and experience. Teachers, therefore, play an important role in facilitating learning environments that support conceptual development gradually from concrete to abstract levels.

Research by Sümen (2019) and Yilmaz and Argun (2018) demonstrated that visualization and conceptual reconstruction significantly influence students' abstraction abilities. Students who are supported with visual learning media and scaffolded instructional activities tend to develop stronger conceptual understanding. Therefore, integrating abstraction theory into mathematics instruction can improve students' reasoning skills and conceptual flexibility.

Augmented Reality in Geometry Learning

Augmented Reality overlays digital objects onto the real world through smartphone or tablet devices. Unlike traditional visualization methods, AR provides interactive experiences that enable users to manipulate virtual objects in real-time. In mathematics learning, AR technology is particularly useful for geometry because it helps students understand spatial relationships and three-dimensional structures.

AR allows students to rotate geometric objects, observe cross-sections, and interact with mathematical representations dynamically. This technology can reduce cognitive barriers caused by abstract visualization and improve students' spatial reasoning abilities.

Studies by Ng et al. (2020) and Saeed et al. (2017) reported significant improvements in students' engagement, conceptual understanding, and spatial reasoning when AR was integrated into geometry instruction. Students showed higher motivation and stronger participation because learning activities became more interactive and enjoyable.

The use of smartphone-based AR applications such as Assembler Edu also increases accessibility because teachers and students can utilize commonly available devices. This becomes especially important in disadvantaged regions where access to advanced technological infrastructure may be limited.

Environmental-Based Mathematics Learning

Environmental-based learning connects mathematical concepts to local ecological and social contexts. This approach emphasizes contextual learning experiences that enable students to apply mathematics in solving real-world problems. For coastal communities, environmental contexts may include tidal analysis, disaster mitigation, biodiversity conservation, waste management, and coastal area measurements.

Environment-based mathematics learning supports meaningful learning because students can directly relate mathematical concepts to their daily lives. This approach also strengthens ecological awareness and sustainability values aligned with Sustainable Development Goals (SDGs), particularly SDG 4 concerning quality education and SDG 15 concerning environmental sustainability.

Several studies indicate that contextual learning improves learning motivation, conceptual understanding, and critical thinking skills. Environmental integration, therefore, provides opportunities for interdisciplinary learning that combines mathematics, science, social awareness, and disaster mitigation education.

Methods

Research Design

This community service program employed a Participatory Action Research (PAR) approach emphasizing collaboration between university academics, teachers, school principals, and local educational communities. The PAR approach was aligned with the empowerment orientation commonly emphasized in community development programs because it encouraged participatory decision-making, collaborative reflection, and sustainable institutional strengthening. PAR was selected because it allows participants to actively identify educational problems, implement solutions, and evaluate outcomes collaboratively (Rizal, 2018). Unlike conventional research approaches that position participants only as research subjects, PAR encourages active involvement and shared decision-making.

The cyclical process of planning, acting, observing, and reflecting ensured that interventions were contextually relevant and sustainable. Through continuous reflection, teachers and researchers collaboratively identified challenges, modified strategies, and improved implementation processes. This participatory approach strengthened participants' ownership of the program and increased the sustainability of educational innovation.

Participants and Setting

The program was conducted in Sumur District, Pandeglang Regency, Banten Province, one of the areas significantly affected by the 2018 Sunda Strait tsunami. The district is characterized by coastal geographical conditions, limited educational infrastructure, and restricted access to professional development opportunities.

The participants consisted of 50 mathematics teachers and school principals within the K3S organization. Participants represented elementary and junior secondary school levels. Before the intervention, most participants still relied on conventional teaching approaches such as lectures and textbook-centered instruction. Teachers had limited experience integrating technology into mathematics learning and rarely utilized digital applications for visualization or interactive learning.

Initial observations indicated that teachers faced several challenges, including limited digital literacy, lack of confidence in using technology, and insufficient understanding of student-centered learning strategies. These conditions highlighted the importance of comprehensive professional development programs that combine technological training with pedagogical support.

Intervention Procedures

The implementation was conducted through five stages over six months.

The first stage involved socialization and needs assessment. Researchers introduced geometry modules integrated with abstraction theory and TPACK (Sahrudin et al., 2024), curriculum adaptation books aligned with Kurikulum Merdeka, and environmental conservation-based learning resources. Pre-test assessments measured teachers' baseline TPACK and digital literacy levels. Interviews and observations were also conducted to identify teachers' instructional challenges and expectations.

The second stage focused on workshops and training. Intensive workshops emphasized TPACK integration, abstraction theory application, digital learning tools, Problem-Based Learning (PBL), and Project-Based Learning (PjBL). Participants learned how to integrate digital applications into mathematics instruction while maintaining alignment with curriculum objectives. Each workshop included hands-on sessions using laptops and smartphones to ensure practical understanding.

The third stage involved technology integration training. Participants were trained to utilize 3D Augmented Reality (AR) technology through the Assembler Edu application. Teachers learned to create QR-code-based materials, upload 3D geometry models, and design AR-enhanced lesson plans. Facilitators guided participants in designing geometry learning activities that combined visualization, exploration, and abstraction processes.

The fourth stage consisted of mentoring and lesson study. Monthly mentoring sessions and lesson study cycles were conducted to support sustainable implementation. Teachers collaboratively planned lessons, observed peer teaching, and reflected on implementation challenges. This strengthened professional learning communities and encouraged collaborative problem-solving.

The final stage involved monitoring and evaluation. Monthly monitoring and reflective discussions ensured program sustainability. Post-test assessments, interviews, and classroom observations measured changes in teacher competence and instructional practice. Evaluation also explored participants' perceptions regarding the benefits and challenges of integrating TPACK, abstraction theory, and environmental learning.

Data Collection and Analysis

Data were collected through observation sheets, semi-structured interviews, documentation, and teacher competency assessments. Observation focused on TPACK implementation indicators, including technology selection, pedagogical adaptation, classroom interaction, and content representation.

Interviews explored teachers' perceptions, challenges, confidence levels, and perceived benefits after participating in the program. Documentation included lesson plans, workshop materials, photographs, reflective journals, and AR-based instructional products developed by participants.

Quantitative data from pre-post tests were analyzed using descriptive statistics and paired t-tests to determine changes in teachers' competence levels. Qualitative data were analyzed thematically through data reduction, categorization, interpretation, and triangulation to ensure credibility and consistency.

Result

Improvement in Digital Literacy and Technological Competence

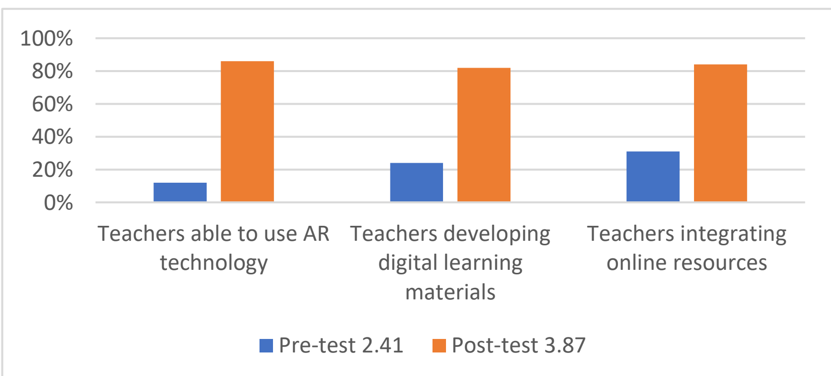
Initial observations and pre-test results indicated that participants had limited experience in utilizing digital technology for mathematics instruction. Approximately 68% of teachers only used PowerPoint for presentations and had never employed interactive applications, learning simulations, or augmented reality media. Most participants had limited experience in developing digital teaching materials, integrating online resources, creating QR-code-based activities, and using technology to visualize abstract mathematical concepts. Access to professional development programs and technology-based training was also relatively limited because of geographical constraints and the post-disaster conditions of coastal schools.

Pre-test results showed that the average score of teachers' digital literacy and technological competence was 2.41 on a five-point scale, indicating a moderate-to-low level of competence. The lowest scores were found in the ability to select appropriate digital tools, develop interactive learning media, and integrate technology into pedagogical practices.

Table 1. Improvement in Teachers' Digital Literacy and Technological Competence

Indicator	**Pre-test**	**Post-test**
Average digital literacy score (1–5 scale)	2.41	3.87
Teachers able to use AR technology	12%	86%
Teachers developing digital learning materials	24%	82%
Teachers integrating online resources	31%	84%

Table 1 presents the comparison between pre-test and post-test results of teachers' digital literacy and technological competence. The average competence score increased from 2.41 to 3.87, while the proportion of



teachers able to utilize AR technology increased from 12% to 86%. Similar improvements were observed in teachers' ability to develop digital learning materials and integrate online resources into mathematics instruction. These findings demonstrate the effectiveness of the workshops and mentoring activities in improving teachers' readiness to implement technology-enhanced mathematics learning.

Figure 1. Improvement in Teachers' Digital Literacy and Technological Competence Before and After the Program

Figure 1 further illustrates the improvement in teachers' digital literacy and technological competence before and after the intervention. Significant gains were observed across all indicators, confirming the effectiveness of the training and mentoring activities in enhancing teachers' technological readiness and confidence in integrating digital tools into mathematics instruction.

Following workshops and mentoring activities, participants demonstrated greater confidence in integrating technology into mathematics instruction. Approximately 86% of participants were able to independently operate the Assembler Edu application, develop QR-code-based learning materials, and integrate three-dimensional Augmented Reality (AR) into geometry instruction. Teachers also became more confident in utilizing smartphones and laptops as instructional tools rather than merely communication devices.

The improvement was further reflected in teachers' ability to design multimedia-based lesson plans, integrate online learning resources, and facilitate collaborative digital learning activities. Participants also explored educational videos, simulation platforms, and online assessment tools to enrich mathematics learning activities. Teachers also reported that technology-assisted learning increased students' enthusiasm and engagement during mathematics lessons because learning activities became more interactive and visually meaningful. These findings indicate that the program successfully strengthened teachers' digital literacy and technological competence, enabling them to implement more interactive, contextual, and technology-enhanced mathematics instruction. The program also contributed to fostering sustainable professional development, strengthening collaborative learning practices among teachers, and supporting the establishment of professional learning communities in post-disaster coastal schools.

Application of Abstraction Theory in Lesson Design

The implementation of geometry modules integrated with TPACK and abstraction theory improved teachers' understanding of students' cognitive development stages. By applying the RBC model, teachers designed activities that moved students from concrete manipulation of physical models to abstract reasoning about geometric properties.

For example, teachers introduced three-dimensional objects using real physical models before transitioning to AR visualization and symbolic mathematical representation. Students first observed concrete objects, identified patterns, manipulated virtual models, and finally constructed mathematical formulas and conceptual relationships.

Classroom observations showed increased use of questioning techniques that prompted students to recognize patterns, build connections, and construct new understandings. Teachers encouraged students to explain reasoning processes, compare multiple solution strategies, and reflect on conceptual relationships.

Student engagement during geometry lessons increased noticeably based on teacher reports and observer notes. Students showed higher participation, curiosity, and willingness to explore mathematical concepts independently. Visualization activities also reduced students' anxiety toward geometry topics that were previously considered difficult.

Development and Use of Integrated Learning Modules

Figure 2. Geometry Module Integrated with TPACK, Abstraction Theory, and Augmented Reality Technology.

Figure 2 shows the geometry learning module integrated with TPACK and abstraction theory, the Intellectual Property Rights (HKI) certificate, and the implementation of AR technology in mathematics learning. The module contains modern instructional approaches, including problem-solving activities, contextual learning tasks, reflective questions, and interactive visualization through smartphone-based applications.

The learning modules were designed to align with Kurikulum Merdeka principles emphasizing student-centered learning, flexibility, and contextual understanding. Environmental issues such as coastal conservation and disaster mitigation were integrated into mathematical problems to increase relevance and ecological awareness.

The use of AR technology enabled students to visualize three-dimensional geometric objects more concretely and interactively, thereby improving students' spatial reasoning and conceptual understanding (Ng et al., 2020). Students could rotate objects, examine cross-sections, and connect geometric properties with mathematical formulas.

Teachers reported that students became more motivated because they experienced mathematics as a dynamic and interactive subject rather than a collection of abstract formulas. AR technology also facilitated collaborative learning because students often worked in groups to explore virtual objects and discuss findings.

Strengthening Professional Learning Communities

Lesson study activities fostered a culture of collaborative learning among teachers. Teachers actively discussed lesson plans, reflected on classroom implementation, and shared innovative instructional practices. The collaborative process enabled teachers to learn from one another and develop collective problem-solving strategies.

Post-program surveys indicated that 78% of participants continued peer collaboration independently after the formal program ended. Teachers created informal discussion groups through social media platforms to exchange learning resources, discuss instructional challenges, and share classroom experiences.

The mentoring process also strengthened teachers' reflective practice. Teachers became more accustomed to evaluating instructional effectiveness, identifying learning barriers, and modifying strategies based on students' responses. This reflective culture contributed to continuous professional improvement.

Integration of Environmental Contexts

Teachers contextualized mathematics learning using environmental issues surrounding Ujung Kulon National Park, including coastal conservation, biodiversity, disaster mitigation, and waste management. Examples included calculating mangrove planting areas using area formulas, analyzing tsunami wave data using statistics, and measuring coastal erosion rates.

This approach made mathematics learning more meaningful and strengthened students' environmental awareness (Firmansyah et al., 2023). Students realized that mathematics could be applied to solve real-life environmental problems relevant to their communities.

Teachers also reported that environmental integration increased students' participation because learning activities were closely connected to local experiences. Students became more aware of environmental sustainability and disaster preparedness while simultaneously developing mathematical understanding.

Overall Competence Improvement

Evaluation results showed significant improvement in teachers' pedagogical competence, ICT literacy, and ability to integrate environmental contexts into mathematics learning. Average TPACK scores increased from 2.41 to 3.87 on a 5-point scale ($p < 0.01$).

Teachers demonstrated stronger competence in selecting appropriate digital tools, designing contextual learning activities, and facilitating interactive classroom discussions. Participants also showed improved confidence in implementing innovative instructional approaches.

These findings indicate that integrating TPACK, abstraction theory, and environmental learning can effectively empower teachers and improve educational quality in post-disaster coastal communities. The program contributed not only to technological competence but also to pedagogical transformation and collaborative professional development.

Discussion

TPACK as a Catalyst for Pedagogical Transformation

The findings of this study demonstrate that integrating TPACK, abstraction theory, and environmental learning can become an effective strategy for strengthening teacher competence and modernizing mathematics education in post-disaster coastal communities. The success confirms that technology integration involves pedagogical transformation and contextual learning design, not merely device usage (Rafi & Sabrina, 2019).

Teachers who previously relied on conventional instructional approaches gradually adopted more interactive and student-centered learning strategies. Technology was utilized not simply as a presentation medium but as a tool for exploration, visualization, collaboration, and conceptual understanding.

The improvement in teachers' TPACK competence indicates that professional development programs should integrate technological training with pedagogical reflection and content understanding. Teachers require opportunities to explore how technology can reshape learning experiences rather than focusing only on technical operation.

Impact of Augmented Reality on Conceptual Understanding

The use of 3D AR through Assembler Edu provided innovative solutions for visualizing abstract geometry concepts. This supports previous studies showing that technology-enhanced visualization significantly improves conceptual understanding and spatial reasoning (Ng et al., 2020; Saeed et al., 2017).

AR transformed conventional mathematics learning into more interactive and meaningful digital experiences, particularly for visual learners. Students could interact with virtual objects directly, observe transformations dynamically, and connect abstract representations with concrete experiences.

The findings also suggest that AR technology can reduce cognitive barriers in mathematics learning. Students who previously struggled to imagine geometric relationships became more capable of understanding spatial structures through visualization and manipulation.

In addition, smartphone-based AR applications increase accessibility because schools do not require expensive laboratory equipment. Teachers can utilize devices already owned by students, making implementation more feasible in disadvantaged regions.

Role of Abstraction Theory in Scaffolding Learning

Integration of abstraction theory improved teachers' understanding of students' mathematical thinking processes. The RBC model provided a clear framework for sequencing activities from concrete to abstract levels.

Visualization and conceptual reconstruction emerged as critical components supporting students' mathematical abstraction abilities (Yilmaz & Argun, 2018; Sümen, 2019). Students demonstrated stronger conceptual understanding when learning activities included concrete manipulation, guided exploration, and reflective questioning.

The findings indicate that abstraction should not be viewed merely as an individual cognitive process but as a socially mediated learning experience supported by instructional design, visualization tools, and classroom interaction.

Teachers also became more aware of the importance of scaffolding and conceptual progression. Instead of directly introducing formulas and symbolic procedures, teachers guided students through gradual conceptual development processes.

Collaborative Professional Development

The emergence of collaborative learning culture through lesson study aligns with studies emphasizing that participatory mentoring and collaborative professional development significantly improve teacher competence and educational quality (Siswanah, 2017; Rizal, 2018).

Sustainable peer discussion encouraged continuous reflection, innovation, and problem-solving. Teachers no longer worked individually but became part of professional learning communities that supported mutual growth.

Collaborative reflection also increased teachers' openness toward feedback and experimentation. Teachers became more willing to modify instructional strategies based on classroom observations and peer suggestions.

These findings highlight the importance of professional learning communities in sustaining educational innovation. Technology integration programs are more effective when combined with mentoring, reflection, and collaborative support.

Environmental Integration and SDG Alignment

Integrating environmental contexts strengthened students' ecological awareness and disaster mitigation understanding. Contextualizing mathematics with local issues supports sustainable education and contributes to SDG 4 and SDG 15 (Firmansyah et al., 2023).

Students learned mathematics not only as an academic subject but also as a practical tool for understanding and solving community problems. This contextual approach increased relevance, engagement, and social awareness.

Environmental integration also reduced educational disparities between coastal and urban communities because learning materials were adapted to local conditions and experiences. Teachers could utilize surrounding environmental issues as authentic learning resources without relying solely on textbooks.

The findings suggest that contextual and environmentally oriented mathematics learning can strengthen both academic competence and community resilience, particularly in disaster-prone regions.

Conclusion and Suggestion

This community empowerment program successfully strengthened the competence of mathematics teachers and school principals in Sumur District through the integration of TPACK, abstraction theory, and environmental-based learning. Workshops, mentoring, lesson study, and collaborative professional learning effectively improved teachers' pedagogical competence, technological literacy, and ability to design contextual mathematics learning aligned with the digital era.

The utilization of AR-based learning media provided innovative opportunities for visualizing abstract geometry concepts. The RBC framework supported teachers in facilitating students' conceptual understanding from concrete experiences toward abstract reasoning. Integrating environmental issues strengthened students' ecological awareness and learning relevance.

The findings demonstrate that educational transformation in coastal and post-disaster communities requires comprehensive approaches integrating technological competence, pedagogical innovation, contextual learning, and collaborative professional development. More importantly, the program highlights that educational empowerment can become an important strategy for strengthening social resilience and community participation in disaster-prone coastal regions. Sustainable empowerment programs are therefore essential for reducing educational disparities and improving learning quality.

Sustainable mentoring programs should be established to maintain teachers' digital competence and support adaptation to evolving educational technology. Local governments are encouraged to strengthen internet access and digital facilities in coastal and disadvantaged schools. Broader collaboration among universities, schools, local governments, and community organizations is also necessary to strengthen environmental education and disaster mitigation awareness.

Future community service programs should focus on evaluating the long-term impact of integrating TPACK, abstraction theory, and environmental learning on students' mathematical reasoning, digital literacy, and learning outcomes. Further empowerment initiatives may also incorporate emerging technologies, such as virtual reality, artificial intelligence, and adaptive learning systems, to support inclusive and sustainable mathematics education.

In conclusion, integrating TPACK, abstraction theory, and environmental learning provides a promising framework for preparing modern mathematics teachers capable of responding to educational challenges in the digital era. By combining technology, pedagogy, abstraction processes, and contextual environmental understanding, mathematics learning can become more interactive, meaningful, and transformative for both teachers and students.

References

Aprilyanto, A., Widana, I. D. K. K., Subiyanto, A., & Rahmat, H. K. (2023). Pemulihan pascabencana tsunami 2018 guna mendukung program pembangunan daerah Kabupaten Pandeglang. *Jagratara: Journal of Disaster Research, 1*(1), 25–32. https://jurnal.unhan.ac.id/index.php/JDR/article/view/2157

Firmansyah, F., Hidayat, S., Leksono, S. M., & Jamaludin, U. (2023). Kearifan lokal dalam menjaga kelestarian lingkungan hidup di cagar alam rawa danau (CARD). *Biosfer: Jurnal Biologi dan Pendidikan Biologi, 8*(1), 1–5.

Hershkowitz, R., Hadas, N., Dreyfus, T., & Schwarz, B. B. (2007). Abstracting processes, from individuals' constructing of knowledge to a group's shared knowledge. *Mathematics Education Research Journal, 19*(2), 41–68. https://link.springer.com/article/10.1007/BF03217455

Leksono, S. M., Marianingsih, P., & Nestiadi, A. (2023). Study of fauna diversity in Ujung Kulon National Park Banten Indonesia. *Indonesian Journal of Biology Education, 6*(1), 1–8.

Lega, D., & Hartanto. (2023). Tanggungjawab pemerintah dan kesenjangan sosial dalam pendidikan. *Adil Indonesia Journal, 4*(2), 54–67. https://jurnal.unigal.ac.id/index.php/adil/article/view/10255

Nabila, N., & Abdi, A. W. (2024). Sosialisasi kebencanaan sebagai peningkatan pengetahuan mitigasi bencana siswa SMP Negeri 16 Banda Aceh. *Jurnal Pendidikan Geosfer, 16*(2), 132–145.

Ng, O. L., Shi, L., & Ting, F. (2020). Exploring differences in primary students' geometry learning outcomes in two technology-enhanced environments: Dynamic geometry and 3D printing. *International Journal of STEM Education, 7*(1), 1–13. https://stemeducationjournal.springeropen.com/articles/10.1186/s40594-020-00234-x

Radiarta, I. N., Erlania, & Haryadi, J. (2012). Dampak tsunami Selat Sunda di Provinsi Banten dan upaya mitigasinya. *Jurnal Segara, 8*(2), 65–150. https://ejournal-balitbang.kkp.go.id/index.php/segara/article/view/17

Rafi, I., & Sabrina, N. (2019). Pengintegrasian TPACK dalam pembelajaran transformasi geometri SMA untuk mengembangkan profesionalitas guru matematika. *Supremum Journal of Mathematics Education, 3*(1), 47–56. https://journal.unsika.ac.id/index.php/supremum/article/view/1544

Rizal, D. (2018). Pendampingan peningkatan mutu madrasah melalui pembelajaran aktif dan manajemen sekolah. *Dimas: Jurnal Pemikiran Agama untuk Pemberdayaan, 18*(2).

Rosmana, P. S., Iskandar, S., Fadilah, N., Azhar, N., Oktavini, D., & Munte, A. C. (2022). Upaya pemerataan pendidikan berkelanjutan di daerah 3T. *Attadib: Journal of Elementary Education, 6*(2), 405–418. https://jurnal.unma.ac.id/index.php/at/article/view/3525

Saeed, A., Foaud, L., & Fattouh, L. (2017). Techniques used to improve spatial visualization skills of students in engineering graphics course: A survey. *International Journal of Advanced Computer Science and Applications, 8*(3), 91–100. https://theijacsa.com/

Sagiman, S., & Putra, M. M. (2023). Improving teacher competence in managing information technology-based learning materials. *Dimas: Jurnal Pemikiran Agama untuk Pemberdayaan, 23*(1).

Sahrudin, A., Budiarto, M. T., & Manuharawati. (2021). The abstraction of junior high school student in learning geometry. *Journal of Physics: Conference Series, 1918*(4). https://iopscience.iop.org/article/10.1088/1742-6596/1918/4/042095

Sahrudin, A., Pamungkas, A. S., Rosdianwinata, E., Firdaus, R. A. F., Nuraeniyah, A., & Farhan. (2024). *Pembelajaran geometri bangun ruang sisi datar dan lingkaran terintegrasi teori abstraksi dan TPACK*. Banyumas: Pena Persada Kerta Utama.

Sahrudin, A., Setiyowati, S., Pratidiana, D., Rosdianwinata, E., & Rifa'i, R. (2024). *Inovasi adaptasi kurikulum merdeka dalam pembelajaran matematika* (1st ed.). Banyumas: Pena Persada Kerta Utama.

Sihaloho, E. R., Winarti, N., & Putra, A. (2024). Peran dinas pendidikan dalam menangani kesenjangan pendidikan masyarakat pesisir di Desa Mapur Kecamatan Bintan Pesisir Kabupaten Bintan. *Multidisciplinary Indonesia Center Journal, 1*(1), 284–295. https://mic-journal.com/index.php/mic/article/view/28

Siswanah, E. (2017). Penguatan kompetensi guru matematika dalam pengembangan media pembelajaran animasi berbasis komputer. *Dimas: Jurnal Pemikiran Agama untuk Pemberdayaan, 17*(1).

Sümen, Ö. Ö. (2019). Primary school students' abstraction levels of whole-half-quarter concepts according to RBC theory. *Journal of Mathematics Education, 10*(2), 251–264.

Wulung, S. R. P., & Abdullah, C. U. (2020). Upaya mitigasi pasca tsunami di destinasi pariwisata. *Jurnal Media Bina Ilmiah, 14*(7), 2883–2894. http://binapatria.id/index.php/MBI/article/view/303

Yilmaz, R., & Argun, Z. (2018). Role of visualization in mathematical abstraction: The case of congruence concept. *International Journal of Education in Mathematics, Science and Technology, 6*(1), 41–57. https://ijemst.com/index.php/ijemst/article/view/143