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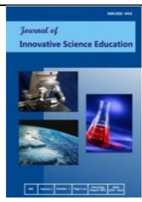

AI-TPACK Integration to Bridge Digital and Environmental Literacy in Science Education for SDGs

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Abstract

The rapid development of Artificial Intelligence (AI) has shifted science education towards reflective, data-driven, and sustainability-oriented learning. Within this context, the AI-Technological Pedagogical Content Knowledge (AI-TPACK) framework positions AI as a scientific thinking partner and a tool for ecological exploration. This study examines AI-TPACK as a bridge between digital and environmental literacy to support Sustainable Development Goals (SDGs). Using a semi-systematic review combining bibliometric analysis and qualitative synthesis of publications from 2015–2025 via the Publish or Perish application—this research outlines trends linking AI-TPACK to these literacies. Results indicate that AI-TPACK transforms 21st-century science education by enabling AI-driven data exploration for social and environmental issues. Digital literacy develops through scientific data analysis, while environmental literacy grows from ecological awareness and sustainability inquiry. Their synergy advances SDG 4 (Quality Education), SDG 13 (Climate Action), and SDG 15 (Life on Land) by enhancing pedagogical competence, analytical skills, and data-based conservation awareness. This study contributes to the conceptual development of AI-TPACK as an integrative framework linking digital and environmental literacy in sustainability-oriented science education.

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INTRODUCTION

The Technological Pedagogical Content Knowledge (TPACK) framework has long provided the foundational conceptual baseline for educators to effectively integrate technology into pedagogical practice. Traditionally, educators who master TPACK harmonize three core dimensions—content, pedagogy, and technology—to construct meaningful, student-centered learning experiences (Dewi et al., 2022). While foundational studies validate that standard TPACK mastery helps educators adapt to digital-native learners by fostering collaborative and problem-based environments, traditional iterations of the framework inherently treat technology as a passive tool. For instance, while Irwandi (2024) demonstrates that TPACK integration in science education elevates critical thinking and scientific literacy, this conventional paradigm often falls short when confronted with autonomous, generative, and adaptive technologies. As digital environments become increasingly complex, a critical gap has emerged in the literature regarding how educators transition from utilizing technology as a mere instructional aid to collaborating with it as an epistemic partner.

The rapid proliferation of Artificial Intelligence (AI) has consequently necessitated an expansion of the traditional TPACK paradigm into Artificial Intelligence-TPACK (AI-TPACK). This evolution introduces AI literacy as a mandatory, distinct competency for modern educators. However, the conceptualization of AI-TPACK in recent literature reveals divergent perspectives. While early exploratory studies often framed AI merely as an efficiency mechanism for grading or content generation, more robust frameworks argue for a paradigm shift. Celik (2023) posits that AI-TPACK requires educators to understand the underlying mechanics of machine learning to prevent algorithmic bias in the classroom. Building upon this, Hava and Babayiğit (2025) argue that true AI-TPACK mastery is not just about technical deployment, but rather the reflective, pedagogical integration of AI while weighing its profound ethical, social, and ecological implications.

In science education specifically, this distinction is vital. AI-TPACK shifts the pedagogical focus from technical mastery to critical data exploration. Intelligent systems are now leveraged to analyze complex environmental datasets, model nonlinear climate change scenarios, predict biodiversity loss, and dynamically assess local air and water quality metrics (Feldman-Maggor et al., 2025). By positioning AI as a scientific thinking partner, educators facilitate scientific inquiries that mirror authentic, real-world research. However, while Blonder et al. (2024) and Mnguni et al. (2024) highlight that these AI-augmented activities dually strengthen digital and environmental literacy, they also inadvertently expose a stark reliance on the educator's capacity to navigate cognitive overload and algorithmic transparency—a challenge traditional TPACK models are ill-equipped to address.

Contextualizing this technological evolution within the current global environmental crisis clarifies the urgency of modernizing science education. The State of the Global Climate 2024 report indicates unprecedented spikes in global average temperatures, greenhouse gas concentrations, and oceanic warming (WMO, 2025). These empirical realities, corroborated by the IPCC Sixth Assessment Report (AR6), confirm that an initial 1.1 °C temperature increase has exponentially catalyzed climate anomalies, from severe droughts to rapid ecosystem degradation (WRI, 2023).

Analytically, these ecological metrics represent more than a global crisis; they signify a profound pedagogical imperative. Traditional, theoretical science education is no longer sufficient to address human-driven environmental degradation (e.g., deforestation, fossil fuel reliance). The academic consensus insists that modern education must transition from knowledge transfer to active ecological stewardship, shaping a scientifically literate generation capable of sustainable problem-solving (Purnamasari & Hanifah, 2021). Therefore, modern science education must be critically evaluated not just by test scores, but by its capacity to foster actionable environmental literacy.

This urgency aligns directly with the United Nations' Sustainable Development Goals (SDGs) agenda. As an interconnected framework, the SDGs position Quality Education (SDG 4) as the essential catalyst for realizing Climate Action (SDG 13) and Life on Land (SDG 15) (Ainiyah et al., 2024). Science education operates as the strategic locus for this intersection. However, a critical review of Education for Sustainable Development (ESD) literature suggests that fostering environmental literacy—the cognitive and affective capacity to understand human-nature symbiosis and enact sustainability-based decisions—requires highly contextualized, data-driven learning (Burmeister & Eilks, 2017). While UNESCO (2017) and Purnamasari and Hanifah (2021) argue that contextualizing local issues (e.g., urban air pollution, extreme weather) strengthens ecological awareness, traditional instructional methods often lack the capacity to process these massive environmental variables. This is where the synergy of digital literacy and environmental literacy becomes critical. Digital literacy allows students to interact with and process complex data, while environmental literacy provides the ethical and ecological framework to interpret that data meaningfully.

To synthesize these complex conceptual intersections, this study proposes an explicit framework that positions AI-TPACK as the central pedagogical engine driving sustainable science education. The framework begins with the educator's AI-TPACK competency acting as a catalyst, wherein the teacher utilizes AI not merely as a pedagogical substitute, but as an advanced instrument for ecological modeling and scientific inquiry. This application of AI-TPACK then serves as a mediating bridge that simultaneously cultivates two interconnected literacies in students. First, digital literacy is developed through critical interaction with AI tools, prompting students to analyze, visualize, and question large-scale environmental data. Concurrently, environmental literacy is cultivated through the context of the data itself, fostering deep ecological awareness, systems thinking, and empathy for local and global biosystems. Ultimately, the synergy of these two literacies directly contributes to the macro-outcomes of the global agenda; by enhancing pedagogical competence through AI (SDG 4), students develop the analytical skills required for systemic climate intervention (SDG 13) and design data-based conservation strategies for terrestrial ecosystems (SDG 15).

Despite the theoretical promise of this conceptual framework, current literature highlights a severe practical bottleneck: educator readiness. Recent findings by Yunita and Harimurti (2024) critically expose that pre-service and in-service science teachers struggle profoundly to operationalize the nexus of AI technology, pedagogy, and science content. Unlike earlier barriers to Ed-Tech adoption—which primarily involved a lack of hardware access or basic software fluency—the current gap is highly epistemic. Educators find it difficult to transition to activity-based, AI-driven learning because it requires a relinquishment of traditional control and an embrace of complex, dynamic datasets. This condition underscores a critical misalignment between the theoretical demands of modern sustainability education and the practical competencies of today's teachers. Educators require targeted interventions that transcend basic software training, focusing instead on the ethical, pedagogical, and ecological affordances of AI. Therefore, exploring and strengthening AI-TPACK competencies represents a vital, under-researched strategy. It serves as the necessary bridge connecting digital and environmental literacies, ultimately positioning science education as a pragmatic, transformative force in achieving SDGs 4, 13, and 15.

RESULTS

Data collection was conducted systematically by adapting the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) reporting guidelines (Figure 1). The literature identification process utilized the Publish or Perish (PoP) software to extract articles from the Scopus and Google Scholar databases. The search was conducted on August 5, 2025, limiting the publication year to the 2015–2025 period to cover the emergence and development of the AI-TPACK concept. The search keywords utilized a combination of English and Indonesian terms, including "AI-TPACK" or "Artificial Intelligence and TPACK"; "Digital Literacy and Science Education"; "Environmental Literacy and SDGs".

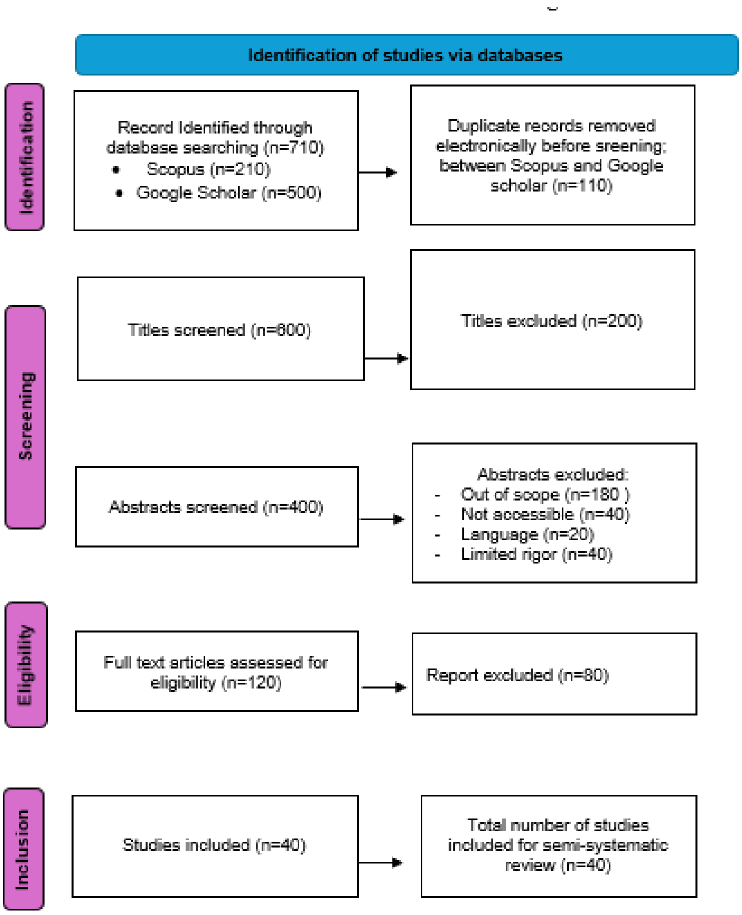

Figure 1. Overview of Prisma Flow

Table 1 presents the inclusion and exclusion criteria used to systematically screen articles for relevance, thematic alignment, and publication quality. These criteria ensured that only high-quality studies directly related to AI, TPACK, digital literacy, environmental literacy, and sustainable science education were included in the review. The inclusion and exclusion criteria were established to ensure that only relevant and high-quality literature aligned with the research objectives was analyzed. Included studies comprised reputable journal articles or conference proceedings indexed in Scopus, DOAJ, or Sinta 1–2, published in English or Indonesian, and explicitly addressing AI, TPACK, digital literacy, environmental literacy, or sustainable science education within educational contexts. Publications that lacked thematic relevance, were published in non-reputable sources, were written in other languages, or were conducted outside educational settings were excluded from the review.

Table 1. Inclusion Criteria and Exclusion Criteria

No	Inclusion Criteria	Exclusion Criteria
1	Reputable journal articles or conference proceedings (Scopus, DOAJ, Sinta 1–2)	Non-reputable publications, theses, opinions, or blogs
2	Written in English or Indonesian	Written in languages other than English or Indonesian
3	Discusses AI, TPACK, digital literacy, environmental literacy, or sustainable science education	Irrelevant to the research themes
4	Focuses on educational contexts	Outside educational contexts

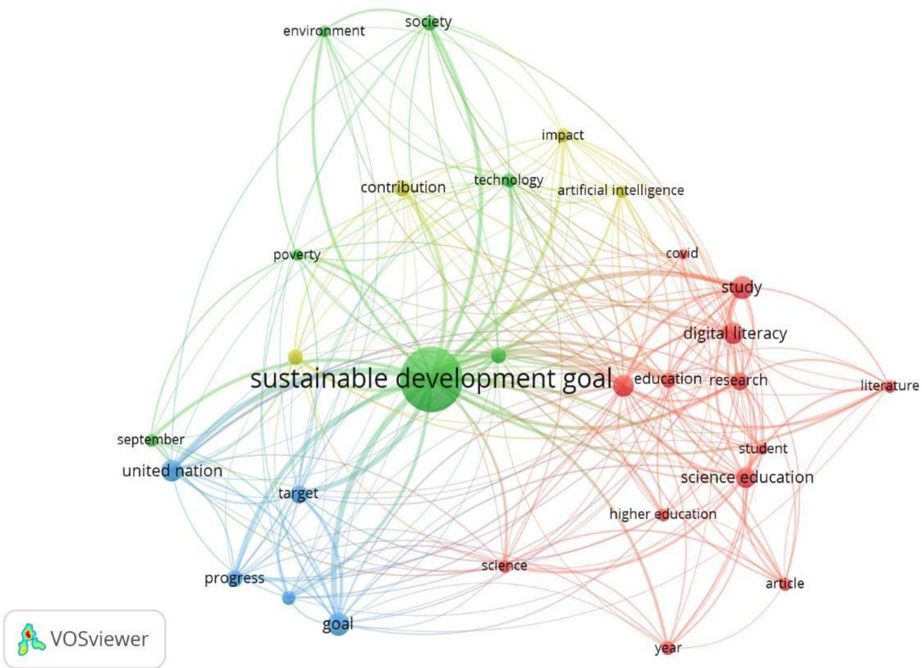

Figure 2. Overview of research related to AI-TPACK, environmental literacy, digital literacy, and SDGs (2015–2025)

The bibliographic data from the selected articles (n=40) were exported in RIS format and analyzed using VOSviewer software. A co-occurrence mapping analysis was employed to visualize the interrelationships between keywords and identify the main thematic clusters within the literature. These visualization results then served as the foundation for qualitative thematic synthesis. The validity of the findings was maintained through source triangulation and reflective interpretation. The final synthesis focused on interpreting the role of AI-TPACK as a bridge between digital literacy and environmental literacy, as well as its contribution to the achievement of SDG 4, SDG 13, and SDG 15.

The VOSviewer analysis (Figure 2) reveals three main conceptual clusters. The first cluster (red) encompasses *digital literacy*, *education research*, and *science education*, highlighting a focus on developing digital competencies and scientific literacy. The second cluster (green) includes *environment*, *society*, *technology*, and *artificial intelligence*, indicating an orientation towards integrating smart technology with socio-ecological awareness. The third cluster (blue) centers on policy dimensions, featuring *United Nations*, *target*, and *goal*. Notably, the concept of sustainable development functions as the largest and most central node, confirming its role as the primary conceptual bridge linking AI integration to educational and environmental outcomes.

Thematic mapping provided the basis for a deeper literature synthesis. Three major themes emerged: (1) the implementation of AI-TPACK in science learning, (2) the development of educator competencies, and (3) the contribution of AI-TPACK to digital and environmental literacies. The foundational articles driving these themes are summarized in Table 2.

Table 2. Selected Articles Published Between 2015–2025

No.	Authors	Title / Focus	Findings and Implications
1	Celik (2023)	Towards Intelligent TPACK	Introduces the AI dimension into TPACK, emphasizing the ethical and reflective use of technology in teaching.
2	Aldemir et al. (2025)	AI Literacy Module for Preservice Teachers	Improves understanding of ethical AI integration; enhances teachers' reflective practices.

No.	Authors	Title / Focus	Findings and Implications
3	An et al. (2025)	Developing the AI- TPACK Scale	Creates a valid instrument to measure the integration of AI- based pedagogy in science education.
4	Feldman-Maggor et al. (2025)	AI Simulations in Environmental Science	AI supports inquiry-based projects and enhances environmental awareness.
5	Wu et al. (2025)	Modeling Climate Change through AI	AI-driven learning boosts student engagement and analytical reasoning in sustainability topics.
6	Mnguni et al. (2024)	Cross-cultural Study on AI-TPACK	Cultural and ethical contexts shape teachers' perceptions of AI integration.
7	Hava & Babayiğit (2025)	AI Competencies in Digital Literacy	AI-TPACK enhances digital collaboration and student inquiry.
8	Dewi et al. (2022)	Project-based TPACK Model	Develops pre-service teachers' design skills; contextual learning promotes sustainability.
9	Oved & Alt (2025)	Teachers' AI Readiness	Identifies structural and affective barriers to AI integration in education.
10	Blonder et al. (2024)	Institutional Support for AI Pedagogy	Highlights policy and infrastructure as key enablers of AI-based learning innovation.
11	Kim (2024)	AI and SDG 4: Quality Education	Demonstrates AI's potential in promoting inclusive, personalized, and equitable learning.

Discussion

The review employed a semi-systematic approach combining bibliometric mapping through VOSviewer and qualitative thematic synthesis to identify conceptual relationships among AI-TPACK, digital literacy, environmental literacy, and SDGs-oriented science education. The results indicate that integrating AI into science education offers significant opportunities to enrich contextual learning. However, moving beyond mere descriptive findings requires understanding *why* AI-TPACK is effective and *how* it functions pedagogically. Traditional TPACK treats technology as a passive instructional tool. In contrast, AI-TPACK functions effectively because it positions AI as an epistemic partner—a cognitive collaborator capable of processing complex, non-linear environmental datasets that exceed human computational limits. Pedagogically, AI-TPACK shifts the teacher's role from a transmitter of memorized concepts to a designer of data-driven inquiries (Celik, 2023; Karataş & Ataç, 2025). By leveraging AI, educators can facilitate real-time ecosystem simulations, hyper-local air quality analyses, and dynamic climate modelling (Feldman-Maggor et al., 2025; Wu et al., 2025). This functional shift enables students to engage in authentic scientific exploration, thereby making the pedagogy highly effective for modern, complex sustainability issues.

The critical value of AI-TPACK lies in its capacity to simultaneously cultivate two distinct but mutually reinforcing literacies. This theoretical integration is visualized in Figure 3.

AI acts as the central catalyst binding technological, pedagogical, and content knowledge (as illustrated in Figure 3). This integration directly outputs dual literacies. *Digital literacy* is developed practically through the necessity of analyzing scientific data and utilizing machine learning for exploration (Hava & Babayiğit, 2025). Simultaneously, *environmental literacy* is cultivated because this digital exploration is explicitly directed at understanding human-nature relationships and ecosystem degradation (Al Yakin et al., 2024).

The flow detailed in Figure 3 demonstrates that these literacies are not isolated; digital capabilities deepen environmental analysis, while ecological awareness provides the ethical framework for AI usage. Consequently, AI-TPACK operates as the structural foundation for achieving specific SDGs: improving pedagogical quality and innovation (SDG 4), enabling predictive modeling for climate mitigation (SDG 13), and facilitating data-driven local biodiversity conservation (SDG 15).

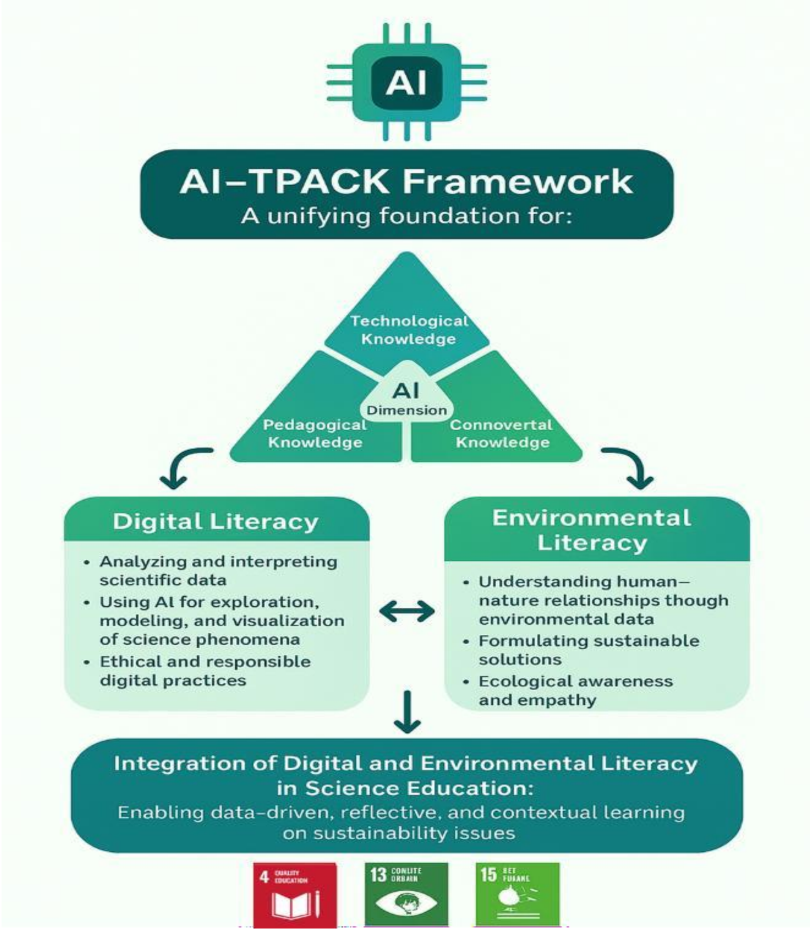

Figure 3. AI-TPACK framework for integrating digital and environmental literacy in science education to support SDGs 4, 13, and 15

Despite its conceptual promise, the successful implementation of AI-TPACK is heavily contested by structural and affective barriers. A critical debate in the current literature reveals a persistent gap between theoretical capability and classroom execution. While pre-service teachers often recognize AI's potential, they frequently lack the pedagogical fluency to integrate it ethically (Aldemir et al., 2025). Furthermore, Shrestha and Yi (2025) note that a primary barrier is epistemic: many educators still view AI strictly as an efficiency tool rather than a cognitive partner. This narrow paradigm hinders pedagogical innovation and reduces the depth of scientific reflection required for environmental education. These affective barriers are compounded by structural deficits, including insufficient AI-specific curriculum policies and weak institutional digital ecosystems (Blonder et al., 2024). Overcoming these challenges requires educational institutions to transition away from basic software training toward collaborative, project-based professional development that balances technical capabilities with ecological values (Wijanarko et al., 2025).

This study extends the traditional TPACK framework by positioning artificial intelligence not merely as a technological support tool, but as an epistemic and cognitive partner within science education. Conceptually, the proposed AI-TPACK framework demonstrates that digital literacy and environmental literacy should not be treated as separate educational outcomes. Instead, both literacies emerge simultaneously through AI-driven inquiry, data interpretation, and sustainability-oriented scientific exploration.

The findings also contribute to sustainability education literature by proposing AI-TPACK as a mediating pedagogical structure that connects technology integration with ecological awareness. This theoretical integration expands prior TPACK studies, which primarily emphasized technological efficiency, by embedding ethical, environmental, and reflective dimensions into science learning. Consequently, AI-TPACK can be understood as a framework-building approach that supports SDGs-oriented science education through the simultaneous development of analytical, ecological, and pedagogical competencies.

Although this study provides a conceptual synthesis of AI-TPACK integration, several areas require further investigation. First, future empirical studies are needed to validate the proposed framework in real classroom contexts, particularly within science education settings. Second, longitudinal research could examine how AI-TPACK competencies influence students' long-term digital literacy, environmental awareness, and sustainability-oriented behavior. Third, cross-cultural studies are necessary to explore how different educational systems, technological infrastructures, and policy environments shape the implementation of AI-TPACK. Finally, future research should investigate ethical dimensions of AI integration in science learning, including algorithmic bias, data privacy, and students' critical awareness toward AI-generated information. These directions are essential for ensuring that AI-TPACK develops not only technologically competent learners, but also socially and environmentally responsible citizens.

CONCLUSION

This literature review demonstrates that integrating artificial intelligence into the TPACK framework transforms science education into a reflective, data-driven, and sustainability-oriented discipline. By positioning AI as a cognitive partner rather than a mere technical tool, AI-TPACK enables educators to design innovative learning experiences that address complex socio-environmental challenges. A key finding is that this framework simultaneously cultivates digital literacy, through the advanced analysis and visualization of scientific data, and environmental literacy, by fostering ecological empathy and sustainability-based problem-solving. Consequently, this pedagogical approach directly advances Sustainable Development Goals 4 (Quality Education), 13 (Climate Action), and 15 (Life on Land), provided there is adequate systemic support through targeted teacher training and adaptive curriculum policies. Ultimately, this study establishes AI-TPACK as a conceptual bridge linking digital and environmental literacy to support sustainability-oriented science education.

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