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Environmental Digital Twins: A Review of Challenges and Opportunities

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ABSTRACT

Digital Twin (DT) technology has emerged as a transformative paradigm for environmental monitoring, modelling, and sustainability governance, yet its development across ecological and territorial domains remains fragmented and unevenly documented in the literature. This review provides a systematic mapping of Environmental Digital Twin applications published between 2020 and 2025, analysing a corpus of 121 peer-reviewed studies spanning urban environments, agriculture, marine and coastal systems, river and lake networks, forestry, ecology, glaciers, Earth system science, and building sustainability. Drawing on a structured analytical matrix , the review focuses on Technology Readiness Level (TRL), remote sensing integration, data-related challenges, and future development priorities, interrogating Dts technological maturity, sustainability framing, and data readiness in practice. Results reveal a field in active but early-stage development: the TRL distribution is concentrated between levels 2 and 6, with no study in the corpus reaching deployment-ready status, and sustainability framing remains predominantly environmental in orientation, with social and economic co-benefits systematically underrepresented across nearly all application themes. Integration, interoperability, and calibration emerge as the most pervasive and structurally recurring technical constraints. Scaling and deployment, alongside governance and institutional alignment, dominate the stated future priorities of reviewed studies. The review concludes by advocating for the adoption of F.A.I.R., C.A.R.E., and T.R.U.S.T. data governance principles as a foundational framework for advancing EcoDTs and Environmental DTs towards integrated, equitable, and policy-relevant implementation at territorial and ecosystem scales.

Keywords: Digital twin, EcoDTs, Environmental Dts, Data challenges, Sustainability

INTRODUCTION

Digital Twin (DT) technology has experienced marked growth in both scholarly attention and practical application since its inception within the manufacturing sector in 2002 (Grieves & Vickers, 2017), subsequently expanding into aerospace applications (Vickers et al., 2010, in Grieves, 2016) and, more recently, into ecological and environmental governance contexts. In its broadest formulation, a DT may be conceptualised as a triadic system comprising a physical entity, its digital counterpart, and the dynamic bidirectional connection enabling continuous interaction between the two (El Saddik, in Nativi et al., 2018). Since its inception, however, the concept has undergone considerable theoretical evolution, giving rise to a multiplicity of definitions that diverge according to structural configurations

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(Botín-Sanabria et al., 2022; Jones et al., 2020; Nativi et al., 2021; Saracco, 2019), application domains (Ferré-Bigorra et al., 2022; Kritzinger et al., 2018; Pylianidis et al., 2021), and sectoral priorities (Hazeleger et al., 2024; Nativi et al., 2021), an ambiguity that extends complexity in cross-domain comparison and comprehensive knowledge-building.

At the environmental scale, two domain-specific conceptualisations have begun to crystallise. The *Ecological Digital Twin* (EcoDT) is defined as "a dynamic digital representation of ecosystems integrating multi-scale ecological data, models, and feedback to explore interactions, predict trajectories, and inform management" (De Koning, 2025; De Koning et al., 2023). Complementarily, the *Environmental Digital Twin* (Environmental DT) is understood as "a continuously updated, data-driven virtual system integrating environmental observations, simulations, and decision-making frameworks to support sustainable management and policy" (Durden, 2025). Whilst sharing a commitment to data integration and dynamic updating, the two constructs are distinguishable by their primary object of representation: the ecosystem as a living, interacting whole (De Koning et al., 2023) versus the broader environmental and governance context (Durden, 2025); a distinction with material implications for system design, data requirements, and policy uptake. Both constructs are situated within major European and International policy frameworks, including the European Green Deal (European Commission, 2020; 2025) and the EU's Destination Earth initiative (Hoffmann et al., 2023), and are increasingly recognised as transformative socio-technical tools capable of integrating heterogeneous datasets with artificial intelligence, assimilating real-time observations (De Koning et al., 2023; 2024), and supporting responses to anthropogenic pressures including climate change, biodiversity loss, and pollution (Purcell et al., 2023; Tzachor et al., 2023). Their contributions are further associated with circular economy transitions, the SDGs agenda (Ali Z.A. et al., 2025) and social sustainability dimensions (Hu et al., 2023; Omrany et al., 2024).Despite this momentum, DT applications for environmental and ecosystem monitoring remain insufficiently developed and systematically underrepresented in the literature (Blair, 2022; Durden, 2025). The existing body of work is dominated by conceptual frameworks, high-level roadmaps, and proof-of-concept demonstrations, with comparatively few studies achieving operational deployment or rigorous cross-contextual validation (Blair et al., 2019a; De Koning et al., 2023). This gap motivates the present review. Through a structured analysis of 121 peer-reviewed publications published between 2020 and 2025, spanning domains including urban environments, water systems, ecology, agriculture, marine ecosystems, forestry, and Earth system science, this paper interrogates not only *what* DTs are applied to, but *how maturely, how sustainably framed, and how data-ready* these applications are in practice. Two guiding research questions structure the analysis: *(1) what is the definition of EcoDT and Environmental DT technologies and what are their defining characteristics? and (2) what are the principal features of the reviewed corpus in terms of Technology Readiness Levels (TRL) and identified challenges?*

METHODOLOGY

This review follows a systematic literature review (SLR) protocol adapted from PRISMA guidelines to ensure transparency, reproducibility, and rigour in study identification and selection. A structured database search was conducted across Scopus and Google Scholar using Boolean strings centred on *"digital twin"* AND (*"environment*"* OR *"sustainability"* OR *"urban"* OR *"ecology"* OR *"climate"* OR *"earth"*), temporally bound to 2020–2025. The identification phase yielded 312 records. Following deduplication, 247 were retained for title and abstract screening; 69 were excluded for thematic irrelevance, yielding 178 papers for full-text assessment. A further 57 were excluded due to absent or insufficiently defined DT frameworks, producing a final corpus of 121 peer-reviewed publications (Figure 1). Each retained paper was coded against a structured analytical matrix (Excel Sheet) encompassing nine dimensions. Compound classifications were retained where dimensions were reported in combination; ambiguous entries were excluded from dimension-specific counts. Quantitative synthesis generated frequency distributions, cross-tabulations, and temporal trend analyses. Given the heterogeneity of included studies in methodology, scale, and disciplinary origin, results are presented as descriptive and comparative mappings aimed at identifying structural patterns and research gaps, with application themes serving as the primary contextual grouping variable.

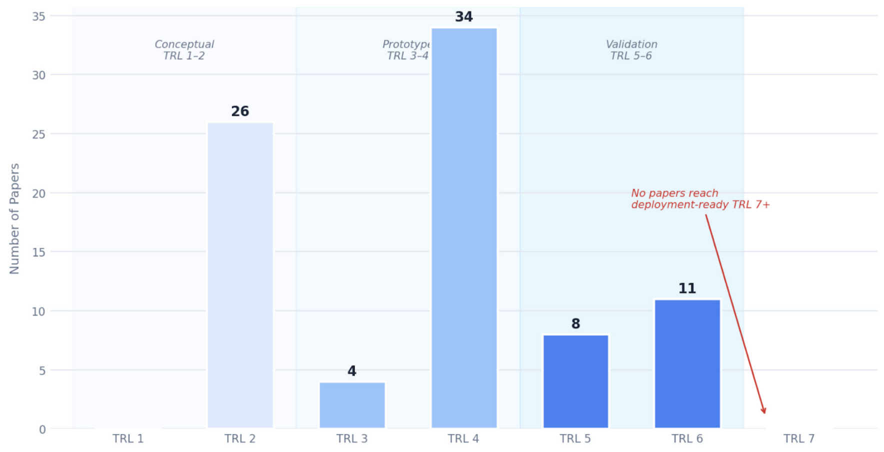

Figure 1: Technology Readiness Level (TRL) distribution across the corpus.

DISCUSSION

TRL Distribution, Data Challenges and Future Development Priorities

Technological maturity and the deployment gap. The TRL distribution across the reviewed corpus reveals a field in active but early development, structurally concentrated between TRL 2 and TRL 6 (Figure 1). The modal range spanning conceptual formulation through validated prototype indicates that the dominant mode of contribution in the environmental DT literature remains theoretical elaboration and small-scale demonstration, rather than operational deployment. Critically, no paper in the corpus reaches TRL 7 or above, the threshold at which a system is considered demonstrated in an operational environment. This finding carries significant implications for policy uptake: whilst the volume of DT-related publications has grown substantially since 2021, this growth has not been accompanied by a commensurate advance in implementation readiness. The concentration at TRL 3–4 (validated proof-of-concept) suggests that the field is producing a considerable volume of methodologically sound but practically premature outputs, a pattern consistent with the early phase of an emerging technology (Rotolo et al., 2015), characterised by high conceptual output and limited systemic diffusion. The absence of deployment-ready studies is particularly consequential in environmental governance contexts, where the translation of monitoring tools into actionable, institutionally embedded systems is a prerequisite for meaningful impact.

Challenges and future development priorities: scaling as the defining frontier. The categorised analysis of stated challenges and future development priorities (Figure 2) identifies Scaling and Deployment as the dominant unresolved concern across the corpus, a finding directly coherent with the TRL distribution: a field concentrated at proof-of-concept and prototype stages will naturally foreground the transition to operational deployment as its primary forward-looking priority. Critically, however, the prominence of Interoperability and Standards and Governance and Policy as the second and third most cited categories reveals that this transition is as much socio-institutional as it is technical. Individual DT implementations exist as largely isolated systems, unable to communicate across institutional and jurisdictional boundaries due to the absence of shared data standards and interoperable platforms, a structural impediment that directly echoes the integration barriers identified in Figure 2. The comparatively lower but analytically significant frequency of Adoption and Capacity challenges introduces a further undertheorised dimension: deployment readiness is not solely determined by technical maturity, but equally by the preparedness of the institutional and professional ecosystems into which DT systems must be embedded.

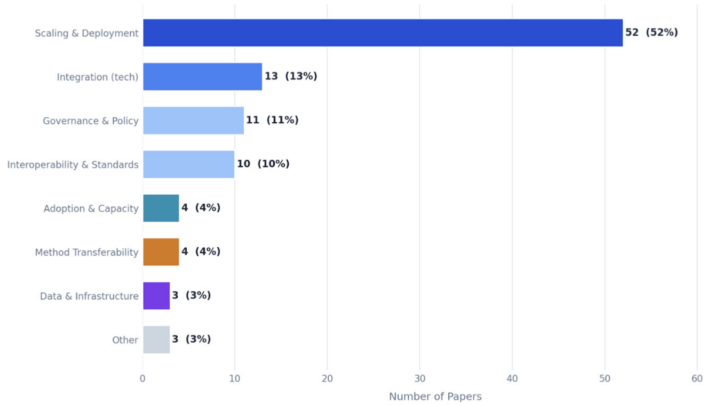

Figure 2: Challenges and future developments, categorised frequency across the corpus.

Data challenges as a systemic constraint. The categorised frequency of data-related challenges (Figure 3) reveals that Integration and Interoperability constitutes the single most prevalent barrier across the corpus, followed by Calibration and Quality, and Scalability and Performance. Taken together, these three categories account for the majority of reported constraints, and their co-occurrence across thematically distinct application domains (from urban systems to marine ecosystems and forestry) suggests that they are not domain-specific limitations but rather structural properties of the current EcoDT and Environmental DT development landscape. The recurrence of integration challenges is particularly revealing: it reflects the fundamental technical difficulty of operationalising the core DT "promise": the fusion of heterogeneous, multi-source, multi-scale data streams into a coherent and continuously updated virtual representation. The prominence of governance and privacy challenges, whilst smaller in absolute frequency, deserves analytical attention disproportionate to its current representation in the literature. As DT systems scale towards operational deployment and begin to interface with institutional data infrastructures, questions of data ownership, access equity, and jurisdictional authority are likely to emerge as binding constraints of a non-technical nature. This finding aligns with Hazeleger et al. (2024) and Blair (2022), both emphasizing that the socio-institutional dimensions of DT governance remain systematically underdeveloped relative to their technical counterparts.

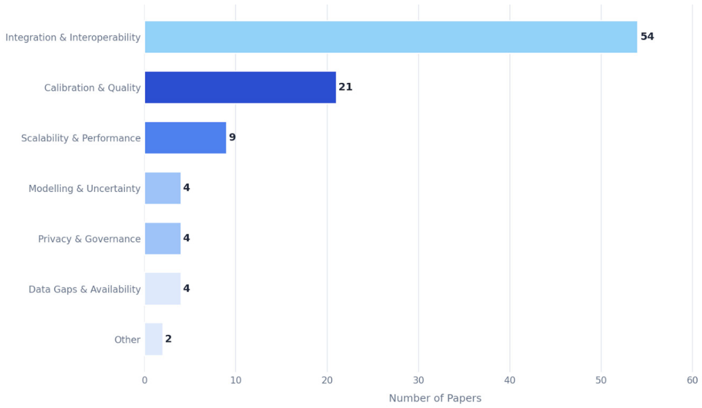

Figure 3: Data-related challenges across the corpus.

Across all three discussion dimensions(TRL maturity, data constraints, and future challenges priorities) the evidence consistently points to the same conclusion: advancing environmental DTs from conceptual promise to operational impact demands a coordinated response across technical, governance, and capacity dimensions simultaneously.

CONCLUSION AND FUTURE DIRECTIONS

This review has provided a systematic mapping of 121 peer-reviewed EcoDT and Environmental Digital Twin applications published between 2020 and 2025 (full corpus listed in the References Section), revealing a field of considerable conceptual vitality but persistent structural immaturity. Four findings emerge consistently across the analytical dimensions examined. First, the TRL distribution: concentrated between levels 2 and 6, with no study reaching operational deployment, confirms that the field is producing methodologically sound but practically premature outputs, whose translation into institutionally embedded systems remains the defining unmet challenge. Second, data-related constraints are not domain-specific but systemic: integration and interoperability, calibration and quality, and scalability recur across all application themes as structural barriers to the operationalisation of the core DT promise. Third, sustainability framing remains overwhelmingly environmental in orientation, with social and economic co-benefits systematically underrepresented, a paradox in a field that explicitly cites SDGs and sustainability transitions as primary objectives and aims. Fourth, scaling and deployment dominate stated future priorities, but the prominence of governance, institutional alignment, and adoption challenges confirms that the path to operational impact is as much socio-institutional as it is technical. Implementation, in environmental governance contexts, is the main challenge at the crossover of political, relational, and ethical dimensions related to data infrastructures. It is in this context that questions of data governance become foundational.

The present review therefore advocates the adoption of the F.A.I.R. (Findable, Accessible, Interoperable, Reusable) (Jacobsen et al., 2020; Wilkinson et al., 2016), C.A.R.E. (Collective Benefit, Authority to Control, Responsibility, Ethics) (Carroll et al., 2021), and T.R.U.S.T. (Transparency, Responsibility, User focus, Sustainability, Technology) (Lin et al., 2020) principles as an integrated governance framework for the next generation of EcoDT and Environmental DT development (Durden, 2025; Islam et al., 2024). These principles represent an evolving ethics of data stewardship that extends beyond accessibility towards epistemic justice, accountability, and relational integrity. The F.A.I.R. principles promote machine-actionable data infrastructures that enhance reproducibility and cross-disciplinary collaboration: directly addressing the integration and interoperability barriers identified in this review. The C.A.R.E. principles reframe openness as a situated practice requiring consent, reciprocity, and respect for collective rights, centring the social contexts in which environmental knowledge is produced and circulated. The T.R.U.S.T. principles further emphasise the institutional dimensions of stewardship, calling for enduring, transparent governance of data repositories that sustain both technical reliability and community confidence.

The relevance of this framework is amplified by the civic dimension of environmental DT data flows. Data in Environmental Dts systems shape governance, inform policy, and mediate participation. Citizens increasingly function as both producers and recipients of DT-generated knowledge, through citizen science initiatives, community monitoring programmes, and territorial co-mapping processes (Carroll et al., 2021; Jacobsen et al., 2020). This dual role carries profound implications: asymmetries in data ownership and governance risk positioning citizens as data subjects rather than data participants, reinforcing structural inequities in visibility, representation, and decision-making (Floridi & Taddeo, 2018). By embedding F.A.I.R., C.A.R.E., and T.R.U.S.T. principles into DT system design from the outset,rather than retrofitting them at the governance stage future implementations can foster a civic data ethic in which transparency is understood not merely as technical openness, but as a practice of justice and mutual responsibility across epistemic, cultural, and technological domains (Han, 2015; Carroll et al., 2021).

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