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Review

A Scoping Review of Digital Twins Across Environmental and Territorial Applications

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Abstract

Digital twin (DT) technology has expanded far beyond its industrial origins, increasingly finding application across environmental and territorial domains. This review provides a structured mapping of DT deployments at environmental and territorial scales over the period 2020–2025, examining 117 peer-reviewed publications (109 applied studies and 8 review articles) through a structured 16-parameter classification framework. The review traces three major conceptual shifts in the DT paradigm: from industrial assets to living entities, from discrete systems to Earth-scale representations, and from closed deterministic models to ecological and systemic frameworks, as reflected in the emergence of ecological digital twins (EcoDTs), environmental digital twins (EDTs), and territorial digital twin (TDT) definitions. The results reveal a clear growth trajectory in DT applications across themes, with urban systems as the most consolidated application domain, and progressive diversification into marine, coastal, forestry, river/lake, and Earth system applications from 2022 onward. Institutional actors dominate production in this space, aligned with European flagship initiatives such as Destination Earth (DestinE) and the European Digital Twin of the Ocean (EDITO). The findings position and expand the notion of territorial digital twins as an evolving paradigm, underscoring both the momentum generated by EU digital and environmental policy and the need for integrated tools to answer and respond to key environmental challenges.

Keywords: digital twin; EcoDTs; environmental digital twin; territorial digital twins; environmental monitoring; what-if scenarios; ecology; Earth observations; sustainability

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1. Introduction

Over the past two decades, digital twin (DT) technology has undergone a remarkable transformation: from a tool for monitoring manufactured objects in industry to an emerging paradigm for modeling living systems, ecological processes, and territorial environments. This expansion has accelerated markedly since 2020, driven by major European Union DT initiatives including Destination Earth (DestinE) and the European Digital Twin of the Ocean (EDITO), which have positioned DTs as strategic infrastructures for supporting environmental governance and climate adaptation. At the same time, the urgency of a converging multi-crisis context (encompassing biodiversity loss [1] and climate change [2]) necessitates informed decision-making and the generation of actionable knowledge across complex, multi-risk territorial systems [3]. Despite this momentum, the scholarly literature on DTs applied to environmental and territorial domains remains fragmented, and systematic overviews of application patterns across sectors are lacking. This review addresses this gap by providing a structured analysis of 117 publications (109 applied studies and 8 reviews) from 2020 to 2025 across landscape-scale domains including water bodies, urban systems, ecology, agriculture, marine ecosystems, forestry, and Earth system science. The review highlights three major shifts in the DT paradigm: from industrial applications towards living and non-living entities [4], from discrete objects to Earth system scales [5], and from closed-system approaches to dynamic ecological, network, and systemic framings [6–9]. Taken together, the findings underscore both the opportunities and the challenges of extending DT applications beyond industrial origins into ecological and territorial domains, marking "territorial DTs" [10], EcoDTs [7], and environmental DTs [8] as an emergent frontier in digital and environmental resilience, sustainability, and governance. Within the scale of the territory, and the multi-layered complexity of the environmental domains, DTs are positioned as versatile tools for enhancing our understanding of complex systems [8,9,11]. Strongly promoted by the EU's DT initiatives [12,13] as potential supporting tools for the objectives of the European Union Green Deal [14] and aligned with the UN Ocean Decade [15], DT initiatives have proliferated rapidly over the past five years, aiming to generate dynamic and multi-dimensional digital replicas of diverse environments.

In line with the overarching objective of this review, three guiding research questions were formulated.

RQ1: What is the current state of the art in digital twin (DT) technology as applied to environmental contexts?
RQ2: How are the notions of territorial digital twins (TDTs), environmental digital twins (EDTs), and ecological digital twins (EcoDTs) defined and conceptualized within the literature?
RQ3: In which sectors have DTs been applied at the environmental and territorial scale, and how have these applications evolved and diversified during the period 2020–2025?

1.1. Evolution of Digital Twin Definitions (2002–2025)

The "ubiquitous" digital twin (DT) technology [16] has seen a significant increase in attention and application since its origin. Conceptualized in the manufacturing sector, it first appeared in 2002 for the formation of a product lifecycle management (PLM) center from Grieves ([17]; concept first presented 2002). Digital twin (DT) technology referred to the virtual replication of physical assets across their lifecycle, showing already the constitutional elements of "real space, virtual space, the link for data flow from real space to virtual space, the link for information flow from virtual space to real space and virtual sub-spaces." This paradigm was adopted by the aerospace industry, most prominently by NASA, for simulating, predicting, and monitoring the behavior of complex systems [18].

At its core, a digital twin (DT) can be synthesized as a triadic construct comprising the physical entity, its digital representation, and the connection that ensures continuous interaction between the two [5,19,20]. Today, the concept has significantly evolved and expanded, leading to multiple digital twin definitions and nuances, constantly changing as applied to its structure, its application, or its core technology (what and how) [16], or ultimately different definitions that reflect the diverse concerns of specific sectors [5]. The broader literature reveals additional nuances in the jargon and technological framing of DTs, as reflected in the diverse interpretations advanced by Jones et al. [21], Tao et al. [22], Botín Sanabría [23], and Saracco [20]. While digital twin technology has demonstrably transformed engineering practice, its translation to the domain of natural environments remains markedly nascent and theoretically underdeveloped [6,16], while EU DT programs are rapidly evolving and being developed at the Earth and ocean scales [5,24,25], aiming to be fully operational by 2030.

This review examines the evolution of the DT concept, tracing its progression from its industrial origins to its more recent conceptualizations within ecology, environmental applications, and territorial scales. It seeks, first, to identify and characterize the shifts evidenced in the literature and, second, to map the trajectories through which DT applications have expanded across environmental scales and territorially oriented domains over the past five years (2020–2025). The review unfolds by tracing and classifying the deployment of DTs in real-world applications across a range of environmental domains and territorial scales. In doing so, the review assesses the practical applicability of DTs in evolving fields, from established ones such as agriculture and urban planning to emerging ones such as forestry, glaciers, and biodiversity. These diverse applications illustrate how DTs might contribute in supporting sustainability objectives and in addressing the complex challenges associated with contemporary global crises [4,8,16,20]. The reported definitions (Table 1) are particularly significant in marking the shifts in the DT concept's definition, which keeps evolving and transforming in parallel to significant evolution in technology infrastructure, framed as a promising tool for advancing challenges of complex environments [23].

Table 1. Definitions of digital twins from 2002 to 2025.

Digital Twin Nomenclature	Definition	Author/Context	Year
Digital Twin (DT)	"Digital Twin (DT)—the digital twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its digital twin."	Grieves [17]	2002
Digital Twin	"Digital replications of living as well as non-living entities that enable data to be seamlessly transmitted between the physical and virtual worlds. Digital twins facilitate the means to monitor, understand, and optimize the functions of all physical entities and for humans provide continuous feedback to improve quality of life and well-being."	El Saddik [4]	2018
DT of the Earth/Earth DT	"DT of the Earth as the digital replica of an Earth system component, structure, process, or phenomenon obtained by merging digital modeling and real-world observational continuity—i.e., remote, in-situ, and synthetic data streams. A DT of the Earth must be seen as a living digital simulation model that updates and changes as its physical counterparts change; therefore, a DT of the Earth continuously learns and updates itself."	Nativi et al. [5]	2021
EDITO-DTO European Digital Twin of the Ocean	"A digital space providing access to vast amounts of data, models, artificial intelligence and other tools, which will allow the replication of the properties and behaviors of marine systems, including ocean currents and waves, marine life and human activities, and their interactions, in and near the sea."	European Commission-European Digital Twin of the Ocean [25]	2022

Table 1. *Cont.*

Digital Twin Nomenclature	Definition	Author/Context	Year
EcoDT	"A dynamic digital representation of ecosystems integrating multi-scale ecological data, models, and feedback to explore interactions, predict trajectories, and inform management."	De Koning et al. [7]	2023
Territorial DTs (TDTs)	"Interactive and people-centered digital replicas supporting the collective exploration of the temporal dynamics of interconnected systems underlying the functioning of complex territories."	Chioni et al. [10]	2024
Environmental DTs (EDTs)	"A continuously updated, data-driven virtual system integrating environmental observations, simulations, and decision-making frameworks to support sustainable management and policy."	Durden [8]	2025

In Table 1, the most significant DT definitions, spanning from its original definition (from Grieves [17]) to the latest in the literature (Durden [8]), are reported.

Table 1 reveals three significant shifts in the conceptualization of digital twins (DTs). Starting from Grieves' definition, the first shift (I) concerns the DT application scope, which has broadened from the industrial and productive sector [17] to encompass both living and non-living entities [4]. The second (II) pertains to the DT's scale of operation, evolving from single objects and discrete systems towards Earth system representations [3,20]. A third (III) and further transformation and evolution lies in the DT's conceptual complexity, moving from closed, deterministic models to more ecological and systematic approaches that engage with dynamic and multi-scale data interactions [7], continuous feedback and multi-source frameworks that might support sustainable management [8], and embedding social sustainability aspects across territories [7,8,10].

At its core, regardless of the multiplicity of definitions, a DT comprises three main components: the physical entity, its digital representation, and the connection between the two [4]. This decoupling creates a flexible framework in which physical entities can be monitored and represented virtually, while modifications, or what-if scenarios, can be conducted in the digital model ("the twin") with a direct feedback loop to the real-world system. This approach enables the deployment of advanced, data-driven modeling techniques, thereby facilitating forms of analysis and insights that extend beyond the capabilities of conventional observational models [5]. For these intrinsic reasons, the potential of DT technology allows environmental monitoring and, specifically, applications to complex, large-scale, living systems [6–9,16].

The present review builds upon a growing corpus of scholarly literature on digital twins applied to environmental systems and territorial scales, developed primarily within the timeframe of 2020 to 2025. This timeframe has been analyzed in order to examine the application domains in which DT technology has been employed after the launch of the EU's Earth and ocean digital twins in the last 5 years, namely DestinE [13] and the European Digital Twin of the Ocean (EDITO) [26]. Concurrently, and within this same period of disciplinary expansion, the defining frameworks for territorial digital twins (TDTs) [10], ecological digital twins (EcoDTs) [7], and environmental digital twins (EDTs) [8] have begun to appear, emerging in parallel alongside a growing array of digital twin applications extended to novel environmental subjects, including water bodies, glacial systems, and forest ecosystems. The following section examines and critically deepens each of these definitional frameworks in turn.

1.2. Environmental DTs, Ecological Digital Twins (EcoDTs), and Territorial Digital Twins (TDTs)

The application of the digital twin (DT) paradigm to the environmental domain has been advanced very recently, primarily at a conceptual level [16,27], and explored across a range of broad-scale domains, including Earth systems and oceanographic sciences [5,28,29], agriculture and land degradation [30,31], and ocean sustainability [25,32]. Within this emerging body of research, DTs complement the physical world through their capacity to integrate heterogeneous environmental datasets with artificial intelligence methods, their ability to dynamically incorporate real-time observations [7,33], and their potential to help in addressing pressing challenges coming from anthropogenic impacts [34], such as climate change and pollution [30,32] and biodiversity loss [1]. Furthermore, DTs are being increasingly recognized for their potential contribution to supporting sustainability across various dimensions, in terms of the circular economy [35] and sustainable development goals (SDGs) [24,36–38]. The very recent incorporation of human–nature interactions within Earth-scale digital twins [39] represents a transformative epistemological frontier, holding promise for advancing the understanding of Earth system dynamics while equipping decision-makers and communities with the actionable intelligence necessary to respond to complex socio-environmental challenges [34]. DTs are being applied as civic tools for fostering citizen engagement [40,41] and might advance community empowerment, which are foundational principles of equitable and participatory governance in urban as well as inner areas [10]. While these conceptual expansions have emerged within the past five years, the detailed application of digital twins to environmental and territorial scales remains insufficiently articulated in the literature [6,8,11].

As underlined by Blair [16], the debate around DTs has focused for years specifically on the aspects of "what" (modeling frameworks and DT definitions) and "how" (infrastructure) rather than "why" (for instance, using DTs as a support tool for accelerating sustainability goals [8,32]), applied to a multi-crisis context [2], marking ongoing attention and growth in DTs applied to ecology and environmental challenges, starting from the complex, multiple aspects related to environmental monitoring [8,19]. Concurrently, there is an increasing and urgent demand for the more effective utilization of knowledge in biodiversity conservation [19] and environmental monitoring [8], as they lay the foundation for informed decision-making under the pressing current global challenges [16,25,34].

In the current biodiversity decline context [1], Europe constitutes a polycentric territory characterized by unevenly distributed assets, spanning diverse biodiversity and economic systems and marked by cycles of growth and decline across its settlements [10]. Decision-making should be grounded in the most up-to-date scientific evidence, underpinned by a robust theoretical understanding of species and ecosystem functioning, and informed by field-based measurements that provide accurate, real-time representations of ecological states and trends [8,16,19,42]. When applied to environmental monitoring and modeling, De Koning et al. [7] see the potential of DTs in their capacity to streamline and structure the development of what-if scenarios based on integrated datasets, as well as to support the forecasting of ecological and evolutionary trends. In parallel, Ewers [19] conceptualizes environmental digital twins as complementary tools that concentrate scientific efforts on "super-sites", pairing these models with automated environmental monitoring technologies, and they enable data-driven simulations with digital twins, further allowing decisions towards locally defined conservation goals, to be continuously revised and adapted in "near-real time". The concept of the ecological digital twin (EcoDT) (Table 1) appeared in 2023 [7] as a dynamic, data–model fusion framework designed to capture ecosystem complexity through the integration of multi-scale ecological observations, mechanistic models, and feedback loops. EcoDTs are considered an analytical and predictive instrument for understanding ecosystem trajectories, assessing resilience, and informing adaptive management strategies [33]. In this framework, De Koning et al. identify EcoDTs as offering five main opportunities for advancing ecological research and management.

1. Dynamic assessment of ecological states: DTs enable the near-real-time or real-time measurement of natural systems, adding a dynamic dimension to otherwise static modeling approaches such as species distribution, vegetation, and habitat suitability maps.
2. Early detection of ecological change: continuous data flows and model updating support the timely identification of trends and intervention needs, which is critical given the rapid pace of environmental change.
3. Integration of drivers and pressures: DTs allow ecosystem trends to be directly linked with environmental conditions and anthropogenic pressures, thereby improving system-level understanding.
4. Evaluation and testing of interventions: DTs can be used reactively, to assess changes before and after interventions, or proactively, by providing a virtual environment for simulating and comparing intervention strategies prior to real-world implementation.
5. Identification of uncertainties and data gaps: DTs help to expose missing knowledge, uncertainties, and gaps in ecosystem data, while providing feedback loops that can improve monitoring practices and maximize the effectiveness of data collection.

Expanding this perspective is the notion of the environmental digital twin (EDT) [8]. Durden defines the EDT as a continuously updated virtual system that assimilates real-time environmental data streams (Table 1), simulation models, and decision support mechanisms to enable sustainable governance at multiple scales.

The two definitions of EcoDTs and EDTs emphasize the coupling of dynamic, high-frequency flows of observational data with modeling frameworks, with the EcoDT prioritizing informed trajectories of biodiversity and conservation outcomes, whereas the EDT is more explicitly oriented towards environmental monitoring and governance objectives. Together, these two definitions signify the conceptual evolution of DTs as tools applied to address the challenges of uncertainty and complexity in ecological systems, situating them as support infrastructures for advancing environmental sustainability and territorial-scale environmental management.

The "territorial digital twin" (TDT) nomenclature, used by Chioni et al. [10], appeared for the first time in 2024, embedding the qualities of "territorial" as a term that could reflect the fragility and variable scales of the landscape—specifically inner mountain territories—with TDTs as tools "supporting and integrating democratic urban design" [10]. This spatial framing draws on the broader planning and governance literature, extending physical landscapes to their intangible and digital dimensions, in which "territory" denotes bounded geographic and administrative spaces subject to collective management and multi-risk vulnerabilities, including coastal, wetland, and marine zones. The term thus captures the scalar, intangible, and jurisdictional complexity characteristic of environmental DT applications, which could empower decentralized communities and establish a resilience network across territorial scales.

Throughout this review, the term "Territorial digital twins" (TDTs) is employed as an umbrella concept encompassing DTs operating across diverse geographic and environmental scales, integrating both physical and intangible dimensions that intersect across landscapes (e.g., citizen-generated data, biodiversity metrics, flora and fauna, and sustainability frameworks). In this broader definition, TDTs are not confined to inner mountain territories, as previously defined by Chioni et al. [10], but are extended to include systems that move beyond discrete assets or closed environments, spanning terrestrial (urban, agricultural, forest, and riverine) as well as marine and oceanic domains. Within this framework, the territorial scale is understood as incorporating the interplay between the material and immaterial components of a physical space.

1.3. European Digital Twin Context: DestinE and EDITO

The Destination Earth (DestinE) program represents the European Union's ambitious effort to develop a high-precision digital twin of the Earth system, launched under the Digital Europe Program, Europe's strategy for data [43], and the EU Green Deal [13,14,24]. DestinE is designed as a layered system of digital twins that integrates high-resolution Earth system simulations, environmental observations, and advanced data analytics to provide actionable insights for science, policy, and society [24,28]. Its objectives extend beyond climate science, encompassing what-if scenarios for climate adaptation, disaster risk reduction, biodiversity management, and resource optimization across critical sectors such as energy, climate, agriculture, water, and public services for supporting the EU's Green Deal [14,28,43]. Central to its design is the principle of interoperability and user co-design, whereby stakeholders can configure workflows, couple simulations with observational data, and visualize outcomes such as what-if scenarios to support informed decision-making [4,24,25,27]. In this respect, DestinE represents an institutional and governance experiment [24], seeking to make advanced Earth system modeling more accessible, participatory, and policy-relevant [13,14,24].

Complementing DestinE, the European Digital Twin of the Ocean [12] initiative constitutes the oceanographic branch of Europe's broader DT strategy, directly linked to the EU mission "Restore our Ocean and Waters by 2030", part of the UN Ocean Decade 2020–2030. EDITO aims to enhance the capacity to integrate marine observations, numerical modeling, AI-based analytics, and decision support tools into a comprehensive digital twin of the ocean [32]. The project's ambition is to provide an operational platform for supporting marine governance, sustainable fisheries, climate resilience, and ocean sustainability in alignment with the European Green Deal and the UN Decade of Ocean Science for Sustainable Development [25]. The program builds on earlier European marine data infrastructures, such as the Copernicus Marine Service, while introducing new layers of interactivity and scenario testing that allow stakeholders to simulate and assess management strategies in virtual environments [29]. In synergy with DestinE, EDITO illustrates the EU's leadership in embedding digital twins at the intersection of Earth system science, marine sustainability, and policy innovation, positioning digital infrastructures as a key tool for tackling global environmental crises [16,32]. The European Digital Twin of the Ocean aims to allow a wide range of users (policymakers, researchers, civic society actors, and private stakeholders) to explore "what-if" scenarios that reflect the dynamic behavior of marine systems and their interactions with human activities. The platform aims to enhance and leverage ocean knowledge, promoting a participatory approach to ocean governance [12,15,25,26,44].

The EDITO project is currently in Phase One of its realization. During this first implementation phase (2022–2025), EDITO focused on laying its core technological and modeling infrastructure. A central achievement of this phase was the development of the EDITO Data Lake, a high-performance, cloud-based environment that brings together datasets from the Copernicus Marine Service and EMODnet. This integration significantly improves data accessibility, interoperability, and reuse across scientific, policy, and governance contexts. Phase One also initiated an open co-construction process, through which services, applications, and digital twin components were developed in collaboration with a broad network of European and international projects. This collaborative model laid the foundations for a shared digital ecosystem and positioned EDITO as a key European contribution to the UN Ocean Decade, creating the conditions for more integrated and sustainable approaches to ocean governance [12]. EDITO is now entering its second, operational phase (2025–2028), which will strengthen the underlying infrastructure and improve accessibility for developers and end users alike. New user-oriented tools, including an integrated smart viewer, are being introduced to facilitate interaction with the platform, while enhanced data onboarding and validation workflows will broaden the scope of the Data Lake. In addition to physical oceanographic data, the platform will increasingly incorporate biogeochemical, socio-economic, and citizen science datasets [26]. Engagement with the scientific community will be further encouraged through open calls supporting the development of new applications, while the co-construction approach initiated in Phase One will be reinforced to ensure continuity and long-term uptake.

Together with DestinE, the EDITO program illustrates the European Union's strategic commitment (data strategy plan) to investing in large-scale DT infrastructures. DestinE is expected to become operational from 2027, while EDITO is projected to reach full operational capacity by 2028, in line with the EU's 2030 policy objectives. These initiatives signal a sustained effort to deploy digital twins as enabling platforms for informed decision-making, supporting the green and blue transitions across territories and large-scale infrastructures.

2. Materials and Methods

The purpose of this review is to examine recent developments in the application of DT technologies at the territorial and environmental scales, with a particular emphasis on their potential to enhance modeling for ecology [7], foster environmental monitoring and modeling [8], and support sustainability frameworks [14], looking at the potential of data science applied to environmental sciences [16,19]. Therefore, the review's focus refers to the umbrella term of territorial digital twins, embedding environmental DTs (EDTs), EcoDTs, and DTs applied to Earth/territory/landscape scales. Given the ongoing and relatively recent nature of these developments, this review seeks to address a gap in the literature by providing a systematic overview of the domains and topics to which digital twins are currently being applied across territorial scales. The review responds to the growing need to understand how DTs, as data-driven and model-based constructs, have been conceptualized, prototyped, and applied to territories, environments, and complex living systems between 2020 and 2025—a period of significant institutional and technological momentum at the core of EU DT programs [12,13,24]. The emergent and interdisciplinary nature of the recently "ubiquitous" DTs poses considerable challenges to terminological clarity and epistemological coherence. Variability in definitions, application domains, and technological maturity levels underscores the necessity of integrative reviews that can synthesize this emergent and fragmented knowledge. Accordingly, this review adopts a systematic approach to map the state of the art, trace conceptual convergences, and identify illustrative real-case applications, prototypes, or concepts relevant to the environmental domain at various territorial scales. This analysis interrogates the broader implications of DT adoption as supporting tools for environmental monitoring, decision support, and governance in the context of global sustainability agendas. To ensure methodological rigor, the review is structured around three explicit criteria: (I) timespan; (II) evaluation parameters and keywords; (III) search engine and data plotting.

2.1. Criterion I—Timespan (2020–2025)

The temporal boundary of the review spans January 2020 to June 2025, thereby capturing the most recent and pertinent contributions to the discourse on environmental digital twins. This timespan was deliberately chosen to coincide with the early years of accelerated investment in DT research and development, while also reflecting the search cut-off point (June 2025), which may yield a partial representation of that year's outputs.

The analytical timespan of this review, 2020–2025, is aligned with the institutional trajectory of digital twin (DT) programs initiated within the European Union. The year 2020 marked the formal launch of major EU research and innovation agendas, such as Destination Earth (DestinE) and the associated Horizon Europe frameworks, which explicitly positioned DTs as key infrastructures for Earth system simulation, territorial-scale environmental monitoring, and climate services [24]. These initiatives catalyzed significant acceleration in scholarly and applied outputs, stimulating interdisciplinary collaborations and fostering prototype developments across marine, climate, urban, and ecological domains. At the same time, this period captures the early phase of implementation, as many of the flagship projects remain in progress and their full operationalization is anticipated only beyond 2025 [12,13]. This review unfolds within this temporal frame: it analyzes how DT research has unfolded in response to EU strategic priorities, highlights the emergence of thematic clusters, and critically reflects on the rapidly evolving nature of the application themes. By framing 2020–2025 as a period of conceptual consolidation and prototype experimentation, the review underscores both the momentum generated by European DTs and policy drivers and the ongoing need for integrative approaches to realize the promise of DTs for sustainability and territorial governance.

2.2. Criterion II—Evaluation Parameters

The review prioritizes case studies and documented prototypes that exemplify DT deployment at the territory scale, with a specific focus on environmental monitoring and applications. Selection was informed by relevance to the scholarly and technical literature, particularly those studies that explicitly situate DTs within the domains of ecosystems (marine, forestry, water bodies, glaciers, etc.) and environmental governance (urban and smart city domains, agriculture, environmental monitoring). In doing so, this review addresses both conceptual explorations, early demonstrators, and proofs of concept, thus providing a representative overview of the current experimental and applied landscape.

The review adopts a classification framework comprising sixteen criteria, which are outlined as follows: DOI/ID (I); authors (II); year (III); title (IV); application segment (V); application theme (VI); objective (VII); output type (VIII); validation method (IX); governance objective (X); DT sustainability (XI); technology readiness level (XII); use of remote sensing data (XIII); data-related challenges (XIV); sensor types (XV); challenges/future developments (XVI). Moreover, the objective of each study was recorded (monitoring, optimization, simulation, management, assessment, scenarios), together with its output type (conceptual framework, prototype system, pilot demonstrator, or full-scale implementation). This approach further allows an examination of where DT technologies are employed, for what purposes, and the extent to which certain sectors demonstrate recurring or expanding application trends. To assess the methodological robustness of the selected cases, the validation method employed was analyzed (simulation-based, empirical field validation, or benchmarking). The review examined each paper's governance objectives, with a particular emphasis on whether the DT was mobilized for risk reduction, efficiency, assessment, sustainability, inclusivity, or planning objectives. A specific parameter was DT sustainability, assessing impacts on social/economic/environmental scales. It should be noted that this sustainability classification is based on the aims, intentions, and proposed opportunities articulated in each paper, rather than on measured sustainability outcomes; this distinction is further discussed in the Section 3. Given the significance of geospatial and sensor data in environmental contexts, the classification further recorded the use of remote sensing data, specifying the platform type (satellite, airborne, UAV, or in situ autonomous sensors) and associated sensor technologies (optical, radar, acoustic, multi-parameter oceanographic instruments). Finally, attention was given to the data-related challenges identified in the studies, such as interoperability, uncertainty, or computational limitations, and the articulation of future directions, including the call for standardization, enhanced governance frameworks, and cross-sectoral integration. For the sake of conciseness, this review focuses on application themes, application segments, and the annual distribution of publications (Sections 3.1.1–3.1.3), alongside the sustainability-related themes, challenges, and objectives addressed therein (Sections 3.1.4 and 3.1.5). The parameters analyzed served to catalog and assess whether the papers were effectively aligned with the research objectives. These parameters are available in the dataset provided as an annex to this review, in accordance with the principles of open science.

Classification and Categorization

In order to operationalize the second criterion, which emphasized the identification of real-case applications, prototypes, and early-stage concepts in real-world applications and environmental monitoring at the territorial scale, the review included the systematic classification of the 117 papers retrieved within the designated timespan (2020–2025). The categorization followed a structured analytical framework, enabling the mapping of contributions across multiple parameters. Specifically, each study was indexed by DOI (I), author (II), year (III), and title (IV), thereby establishing a bibliographic foundation for further analysis. The orientation of each paper was then divided along two main axes: the application segment (industrial or institutional) and the application theme (Table 2). The application segment delineates the distinction between contributions emerging from the industrial sector, primarily associated with private enterprises and industry-led initiatives, and those situated within the institutional domain, encompassing academia, European Union programs, research laboratories, and civic or community-based stakeholders. This differentiation allows for the identification of contrasting orientations in digital twin development, with the former often driven by market applicability and technological innovation and the latter more closely aligned with scientific inquiry, policy frameworks, and public-interest objectives.

Table 2. Application theme classification and categorization of the review corpus.

Application Theme	NO. of Papers	% of Total	References
Urban	23	21.1%	[23,36,37,40,45–62]
Environmental	10	9.2%	[6,8,10,11,16,19,27,42,63,64]
Coastal	9	8.3%	[65–73]
Ecology	7	6.4%	[7,9,33,74–77]
Agriculture	8	7.3%	[30,31,78–83]
Rivers/Lakes	7	6.4%	[84–90]
Forestry	7	6.4%	[83,91–96]
Marine Ecosystems	6	5.5%	[29,97–101]
Earth System	6	5.5%	[5,102–106]
Building Sustainability	5	4.6%	[107–111]
Energy	4	3.7%	[112–115]
Climate	4	3.7%	[28,116–118]
Smart Cities	4	3.7%	[40,119–121]
Biodiversity	2	1.7%	[75,122]
Mobility	1	0.9%	[123]

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Table 2. *Cont.*

Application Theme	NO. of Papers	% of Total	References
Glaciers	1	0.9%	[124]
Policy/Research Infrastructures	1	0.9%	[125]
Wildland Fires	1	0.9%	[126]
Circular Economy	1	0.9%	[35]
Cultural Heritage	1	0.9%	[127]
Sustainability	1	0.9%	[128]
TOTAL	109	100.0%	

The application theme specifies the different domains and subjects through which environmental and territorial digital twin developments are articulated. The twenty-one application themes (Table 2) were derived from the keywords associated with each paper and subsequently reorganized. Given that the review focuses on DTs' practical applications, domains such as "urban" and "smart cities", "coastal" and "marine ecosystems", and "environmental" and "ecology" were treated as distinct categories. This separation reflects the substantial differences in methodological approaches, disciplinary framing, and application objectives. For instance, "urban" encompasses broad urban planning and infrastructure modeling, whereas "smart cities" specifically addresses sensor-driven, IoT-enabled urban management; similarly, "coastal" focuses on shoreline dynamics and erosion processes, while "marine ecosystems" addresses open-ocean and marine-ecological systems. Theme assignment was performed by a single coder based on each paper's primary keywords and stated objectives; while no formal inter-coder reliability test was conducted, consistency was checked through the iterative review of borderline cases.

Table 2 presents the classification of the application themes and the number of papers identified within each application theme across the total corpus of 109 publications.

By delineating the application themes throughout the review corpus, this classification provides a systematic means of tracing how DT applications are distributed across environmental and territorial domains, while also highlighting the areas in which cross-sectoral integration and interdisciplinary collaboration are most evident. It should be noted that the theme "risks/disasters" appears in the temporal and alluvial figures but is subsumed under related thematic categories (coastal, climate, environmental) in Table 2, as the corresponding publications address risk and disaster contexts within these broader domains. These categories capture the variety of contexts in which TDTs are currently being deployed at the territorial scale, spanning ecological and environmental monitoring to modeling urban systems, as they reflect the complexity of the interplay between material and immaterial assets layered in territories. As data-centric structures, TDTs embed and reflect the complexity of heterogeneous sources and elements characteristic of living systems.

2.3. Criterion III—Keywords, Search Engine Strategy, Data Plotting, and PRISMA-ScR

The literature retrieval strategy was implemented using Scopus and Google Scholar. Keyword queries were designed to balance breadth and specificity, commencing with general terms such as *"digital twin + environment"*, *"digital twin + earth"*, and *"digital twin + ecology"* and subsequently narrowing to context-specific combinations including *"digital twin + marine monitoring"*, *"digital twin + urban applications"*, *"eco-digital twin"*, *"environmental digital twins"*, *"earth digital twins"*, *"territory + digital twin"*, *"territorial digital twins"*, and *"digital twin + ocean"* [6,9,29–31,37,129,130]. This corpus enables the present review both to capture the diversity of applications at the environmental and territorial scales and to situate them within the wider conceptual and technological discourse on DTs. This iterative approach ensured the inclusion of interdisciplinary sources spanning topics such as urban planning, Earth observation, environmental science, ecology, Earth systems, and applied technological domains.

The corpus of selected papers was systematically classified using a structured Excel-based data extraction framework aligned with the predefined analytical categories outlined (Section 2.2). Each publication was coded according to these criteria to ensure consistency and traceability across the review process. The resulting dataset was subsequently exported in comma-separated value (CSV) format to facilitate downstream analysis and visualization.

Quantitative and categorical patterns emerging from the review were visualized using Excel and RAWGraphs 2.0, an open-source data visualization platform, by directly plotting the CSV datasets. This approach enabled the transparent and reproducible generation of comparative and distributional graphs across the classification dimensions.

The study selection process was documented following the PRISMA extension for Scoping Reviews (PRISMA-ScR; [131]). The present review adopts a scoping review format, consistent with its aim of mapping the breadth and nature of an emerging body of literature, rather than appraising the quality of individual studies. Scoping reviews are designed to synthesize evidence and delineate the extent of available research on a given topic [131] and are particularly suited to identifying knowledge gaps, surveying heterogeneous bodies of literature, clarifying key concepts, and examining patterns in research conduct [132]. As this review relied on two databases (Scopus and Google Scholar), without a pre-registered protocol, the work is framed as a structured scoping review rather than a compliant PRISMA systematic review. A total of 438 records were initially identified through database searching (Scopus, n = 312; Google Scholar, n = 126) and other sources, including EU program reports, white papers, and citation searching (n = 18). After removing 83 duplicates, 373 unique records were screened by title and abstract, of which 196 were excluded due to a lack of relevance to environmental or territorial digital twin applications. The remaining 177 full-text sources were assessed for eligibility against the inclusion criteria: English language, publication date between January 2020 and June 2025, and explicit focus on environmental or territorial DT applications. Of these, 60 were excluded for the following reasons: not in English (n = 9), outside the 2020–2025 timeframe (n = 14), no environmental or territorial DT focus (n = 27), and insufficient methodological detail or grey literature not meeting quality thresholds (n = 10). A small number of programmatic and institutional documents (e.g., EU project reports and white papers) were retained where they provided essential context for understanding flagship DT initiatives such as DestinE and EDITO; these exceptions are noted in the reference list. The final corpus comprised 117 sources of evidence: 109 applied studies documenting case-specific DT deployments or prototypes and 8 review articles providing broader syntheses of DT developments across various domains. The complete selection process is illustrated in the PRISMA-ScR flow diagram (Figure 1).

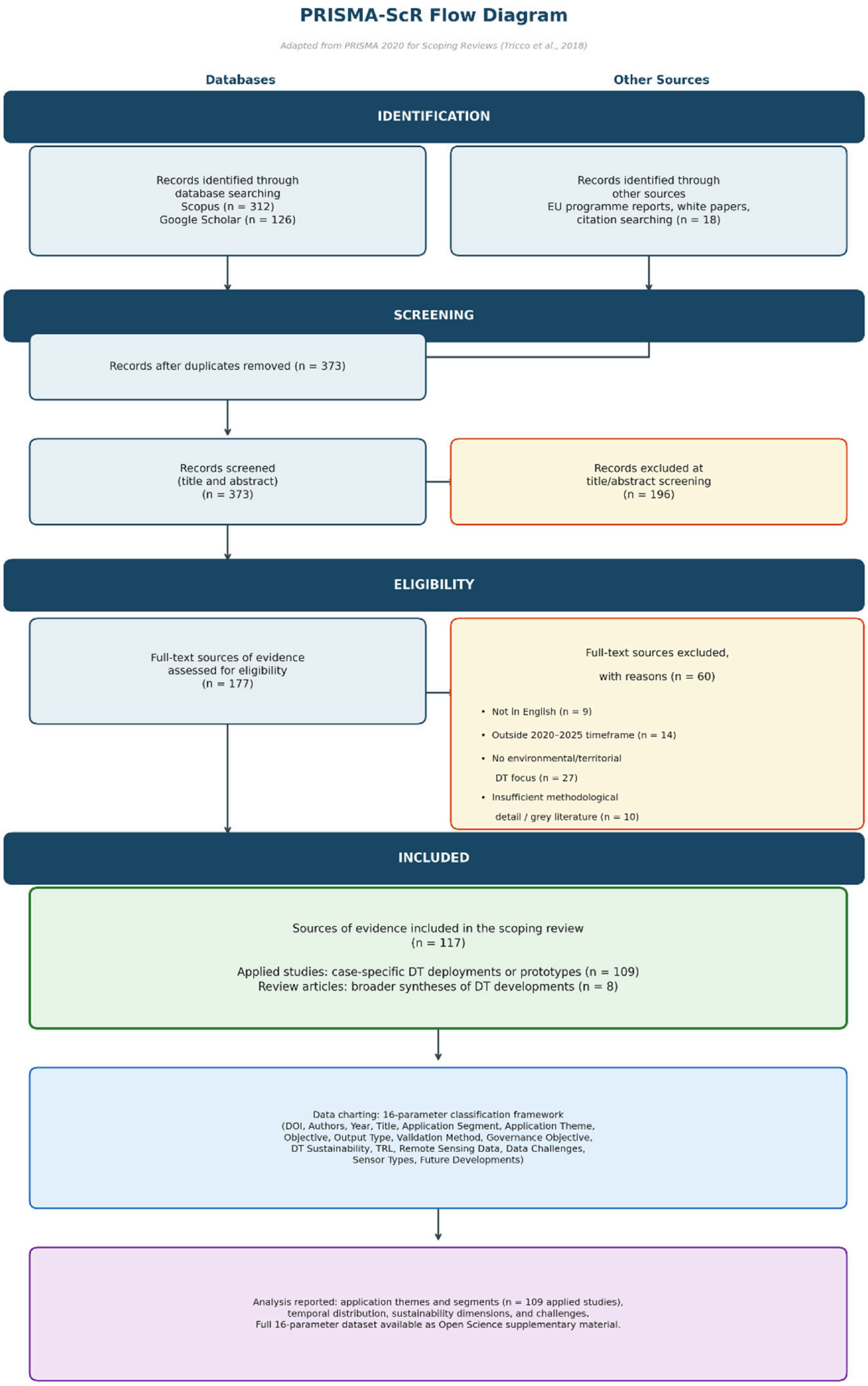

Figure 1. PRISMA-ScR flow diagram illustrating the identification, screening, eligibility assessment, and inclusion of sources of evidence in the present scoping review. Adapted from PRISMA 2020 for Scoping Reviews (Tricco et al., 2018 [131]).

3. Results

3.1. Temporal Distribution and Thematic Correlation of Application Domains

3.1.1. Temporal Distribution of Application Themes

Figure 2 shows the temporal distribution of digital twin application themes within the corpus in the years 2020–2025.

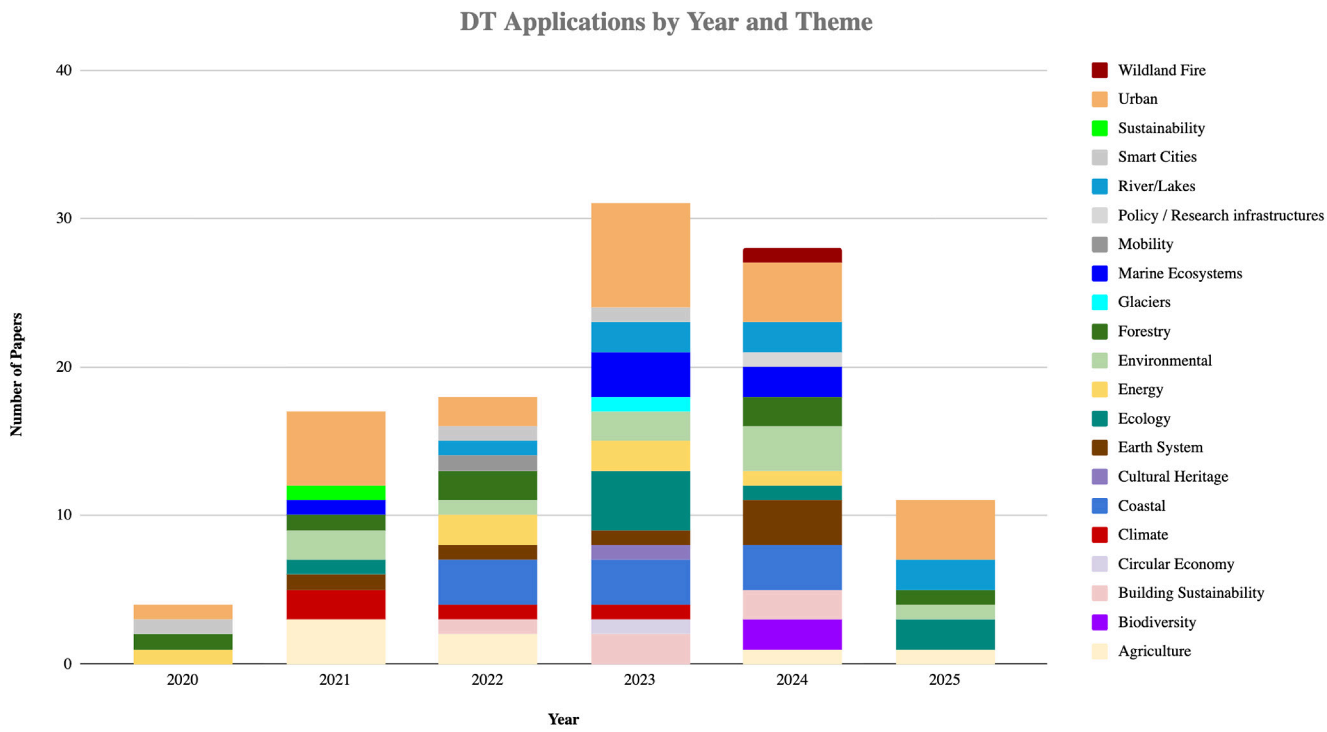

Figure 2. Bar chart of DT application theme proportions by year.

The temporal distribution of themes within the corpus reveals both the emergence of new research directions and the consolidation of established domains. Certain topics, such as glaciers [124], forestry [91], biodiversity [122], wildfires [126], cultural heritage [63], and rivers, lakes, and fjords [84,86,89,90] only begin to appear in the literature after 2022, indicating their status as emergent areas of application. Urban emerges as one of the most consistent and dominant themes, represented across nearly all years and accounting for a substantial proportion of the overall publications [78]. Similarly, energy, environment, and agriculture maintain steady contributions throughout the review period, aligning with the existing literature that shows these domains as more established in the application of digital twin technologies [6,9,29–31,37,129].

Marine ecosystems [29,97–101], rivers/lakes [84,86,118], and coastal [42,101], together with ecology [7,9,33,74–77] themes, recorded a marked rise in output during 2023–2024, reflecting the growing recognition of DTs in addressing marine-related and ecological challenges during the ongoing UN Ocean Decade (2020–2030). In parallel, applications within institutional segments intensified after 2022, signaling a shift in emphasis from predominantly technical and industrial implementations towards broader societal and governance-oriented uses.

Figure 2 presents an analysis of the relative proportions of the DT application themes over the period 2020–2025. In absolute counts, the chart reveals a clear temporal trajectory characterized by a gradual increase from 2020 to 2022, followed by a pronounced peak in 2023. This peak reflects the highest volume of publications across nearly all application themes, indicating a period of intensified scholarly engagement with DT technologies in environmental contexts. After 2023, a reduction in counts is observed in 2024, which is more marked in 2025; however, the 2025 figure reflects only partial-year coverage (January–June 2025) and should not be interpreted as a real decline in research activity (see Section Limitations).

Agriculture, climate, urban environments, and smart cities emerge as early and persistent themes, contributing consistently to the overall counts throughout the observed period.

In contrast, domains such as Earth system science, rivers and lakes, risks and disasters, and policy and research infrastructures show a notable increase, particularly between 2022 and 2024. This suggests a shift from sector-specific and operational applications towards more integrated, location-based, varied applications of DTs.

Depicting the proportional distributions, Figure 2 provides further insight into changes in thematic emphasis over time. While early years are dominated by a limited number of application areas (agriculture, urban systems, and climate), the proportional composition becomes progressively more balanced after 2021. By 2022 and 2023, besides the constant presence of urban themes, no single domain overwhelmingly dominates the distribution, indicating increasing diversification and interdisciplinarity in territorial DTs. Moreover, 2023 marks the year of the largest number of contributions and, together with 2024, marks the period with major theme occurrence (14 themes). The proportional contributions of the policy and research infrastructure, Earth system application, wildfire, and river/lake themes increase in the later years. This trend reflects the growing recognition of digital twins as strategic instruments for decision support, policy development, and risk management [85,88,100,118,126]. Similarly, the increasing presence of marine ecosystem applications highlights expanding engagement with water systems, often characterized by high uncertainty and strong climate linkages. These trends show DT applications across environmental and territorial domains evolving from initial concentration in a small number of sectors to a diversified and increasingly broad range of themes (Figures 2 and 3).

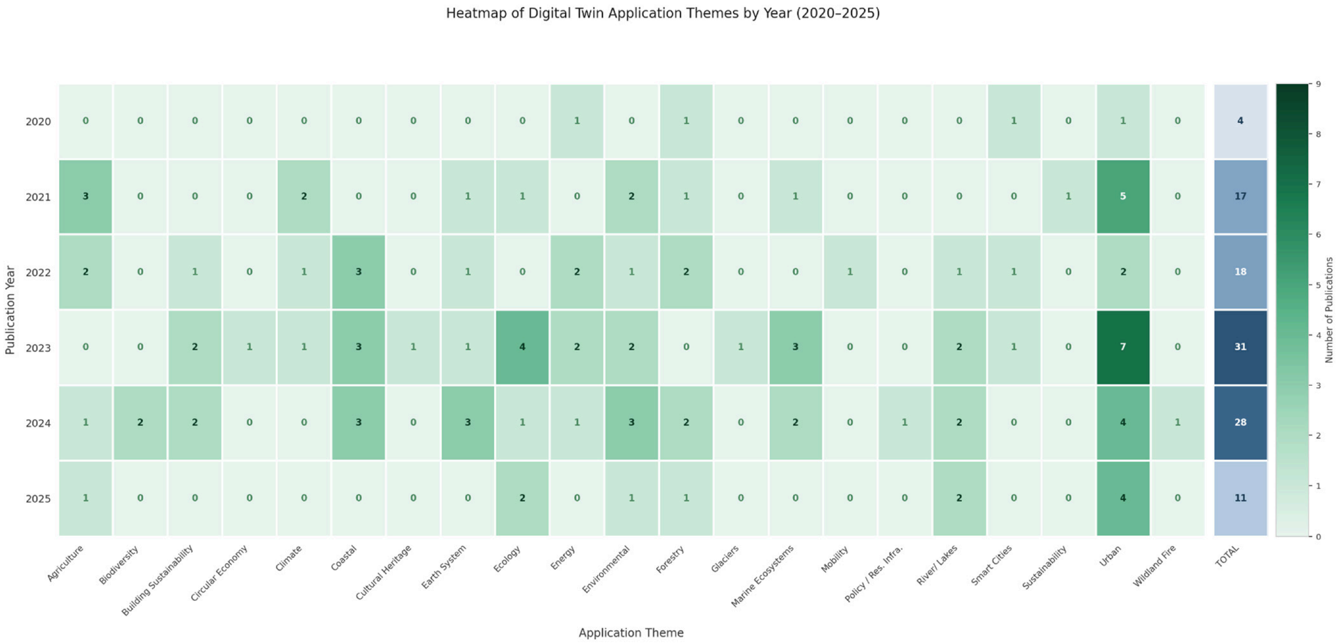

Figure 3. Heatmap diagram of application themes per year.

The heatmap chart provides a temporal perspective on the recurrence and growth of DT application themes between 2020 and 2025. Marine and coastal applications display a steady increase, reflecting the institutional and policy-driven momentum associated with ocean management and the UN Decade of Ocean Science. Urban systems emerge as the most consolidated research domain (n = 23), peaking in 2023 (n = 7) yet maintaining sustained output through 2024–2025, indicative of a maturing field with distributed scholarly engagement. Coastal and environmental themes jointly constitute the second tier (n = 9 each), reflecting institutional momentum tied to climate adaptation frameworks and ecological monitoring agendas. Ecology (n = 7), forestry, agriculture, and rivers/lakes (n = 7 each) occupy an intermediate tier, with ecology exhibiting notable concentration in 2023, suggestive of accelerated uptake linked to biodiversity policy cycles, while the remaining three display more temporally dispersed patterns consistent with gradually consolidating application areas. Biodiversity, cultural heritage, glaciers, wildland fires, and policy/research infrastructures each record a single publication across the full observation window, exposing structural gaps in these emerging application themes at the intersection of digital twin methodologies and domains under acute environmental and governance pressure. The year 2023 constitutes a clear inflection point in the corpus (n = 31), marking a transition from early-adopter concentration towards broader disciplinary diffusion—a trajectory whose consolidation into sustained research programs across underrepresented themes remains, as yet, uncertain.

3.1.2. Recurrency of Application Themes

The bubble chart (Figure 4) illustrates the relative weights of the application themes, with the bubble size corresponding to the cumulative number of publications across the review period. The distribution shows the marked dominance of the urban theme, which constitutes the largest bubble, and underscores its status as the most extensively researched area within the dataset. A cluster of medium-to-large themes, including environmental monitoring, forestry, coastal and marine ecosystems, ecology, and agriculture, attracts substantial attention, reflecting their alignment with EU and global priorities such as sustainable green transitions, ecosystem resilience, and food security [2,14].

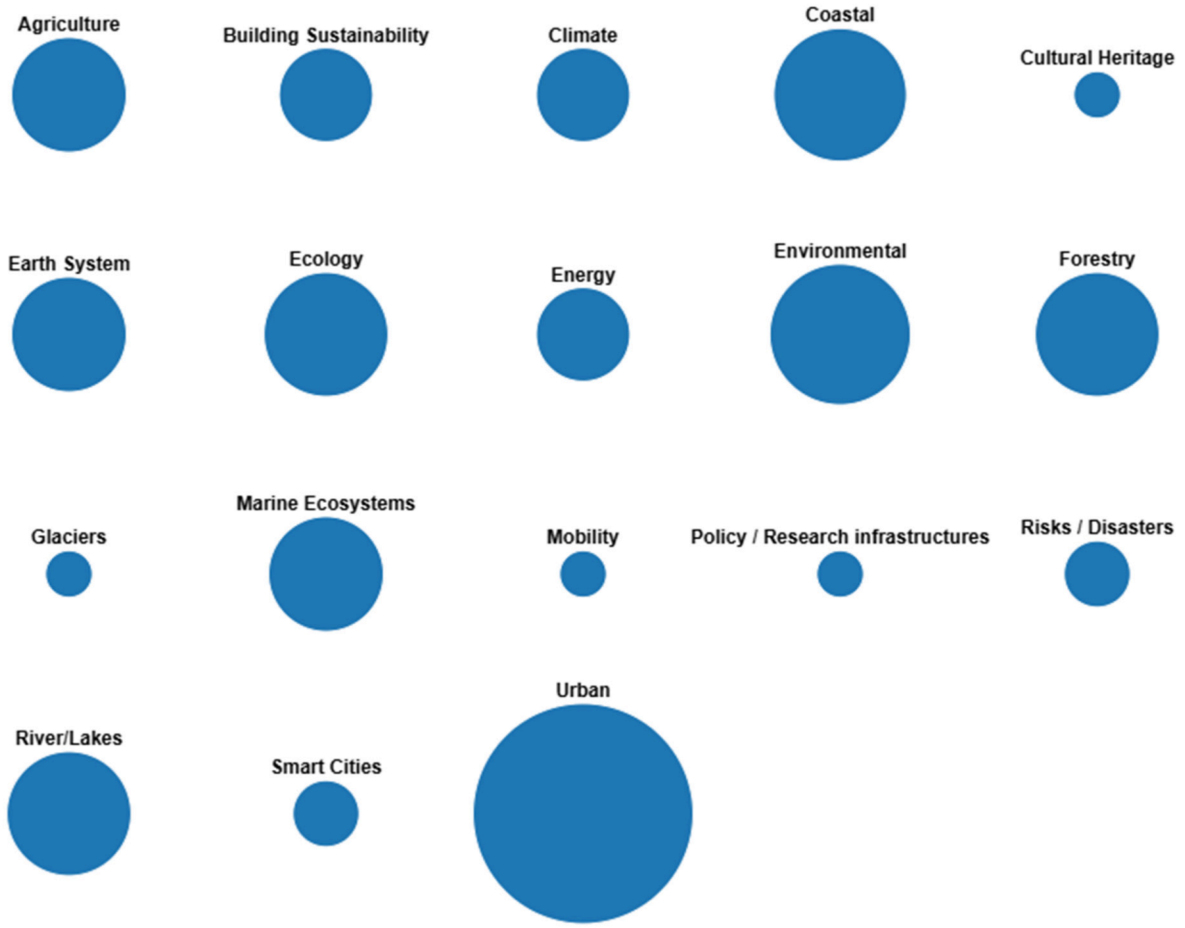

Figure 4. Bubble chart showing proportions of application themes across the total span (2020–2025).

By contrast, several niche or emerging themes are represented by small bubbles, notably glaciers, policy infrastructures, and cultural heritage sites. These areas can be interpreted as either emerging research directions or peripheral applications, suggesting that, while they have yet to consolidate a substantial evidence base, they may hold potential for future expansion as the digital twin paradigm diversifies.

The scatterplot chart (Figure 5) provides a timeline perspective on the distribution of application themes, with each dot representing an individual paper positioned by theme (vertical axis) and year (horizontal axis) and color-coded by application segment (grey for industrial, turquoise for institutional).

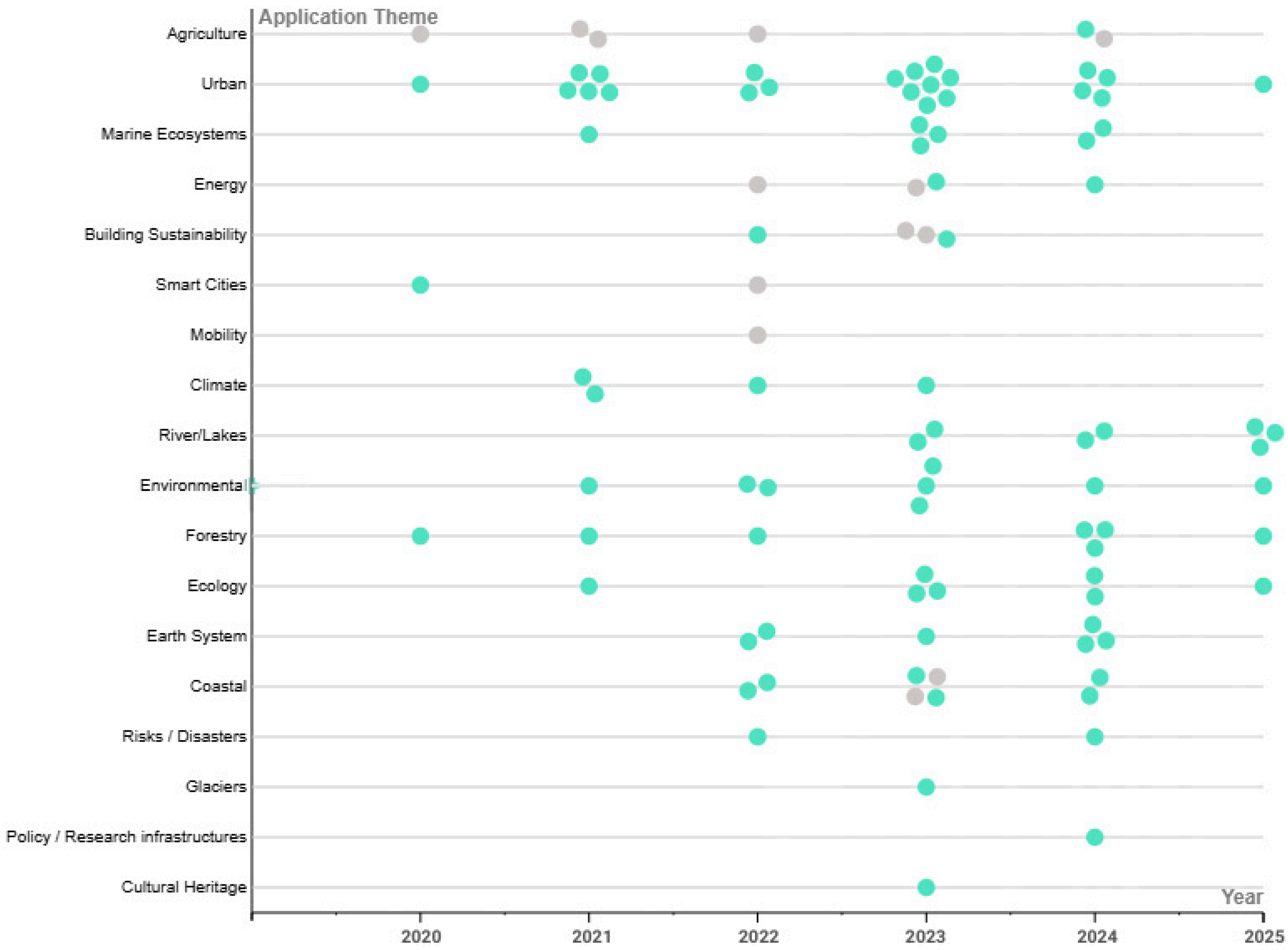

Figure 5. Scatterplot of application themes per year and application segment (grey/turquoise) (2020–2025).

The overall split is approximately 82% turquoise dots to 18% grey dots. Since the colors represent the institutional-vs-industrial segment, the institutional segment dominates strongly, with an exclusively institutional presence for climate, rivers/lakes, glaciers, policy/research infrastructures, and cultural heritage, while energy and mobility show the most balanced distribution (50/50).

The visualization highlights several dynamics. Emerging topics include glaciers, which first appeared around 2023 and signal a recent research interest; policy and research infrastructures, visible only from 2024 onwards; and cultural heritage, which remains sporadic and niche. In contrast, a set of stable themes—notably agriculture and urban—maintains a continuous presence across the entire period, while environmental, forestry, ecology, and energy also recur consistently, underscoring their centrality in the development of DT applications. The chart also reveals growth moments, with urban topics showing marked expansion after 2022 and becoming one of the dominant themes, while marine ecosystems, rivers/lakes, and Earth system applications increase visibly from 2023 onwards. Collectively, these patterns illustrate both the consolidation of core domains and the gradual diversification of DT applications into new and emerging areas, with the prevalence of the institutional segment (turquoise dots, Figure 5) as the major cluster of investigation and production regarding territorial DTs.

3.1.3. Diversification of Application Themes

The alluvial diagram (Figure 6) illustrates the temporal distribution and evolution of digital twin (DT) applications across environmental and territorial domains over the period 2020–2025. The cumulative height of the streams reflects the overall volume of scholarly activity, while the relative thickness of individual flows indicates the prominence of specific application domains over time. Overall, the diagram reveals a clear growth trajectory in DT-related research across environmental sectors, with pronounced expansion between 2020 and 2022, followed by a phase of diversification and partial consolidation after 2023. This pattern suggests an initial exploratory phase, during which DT concepts were rapidly adopted across multiple domains, followed by a maturation stage characterized by more targeted and increasingly specialized applications.

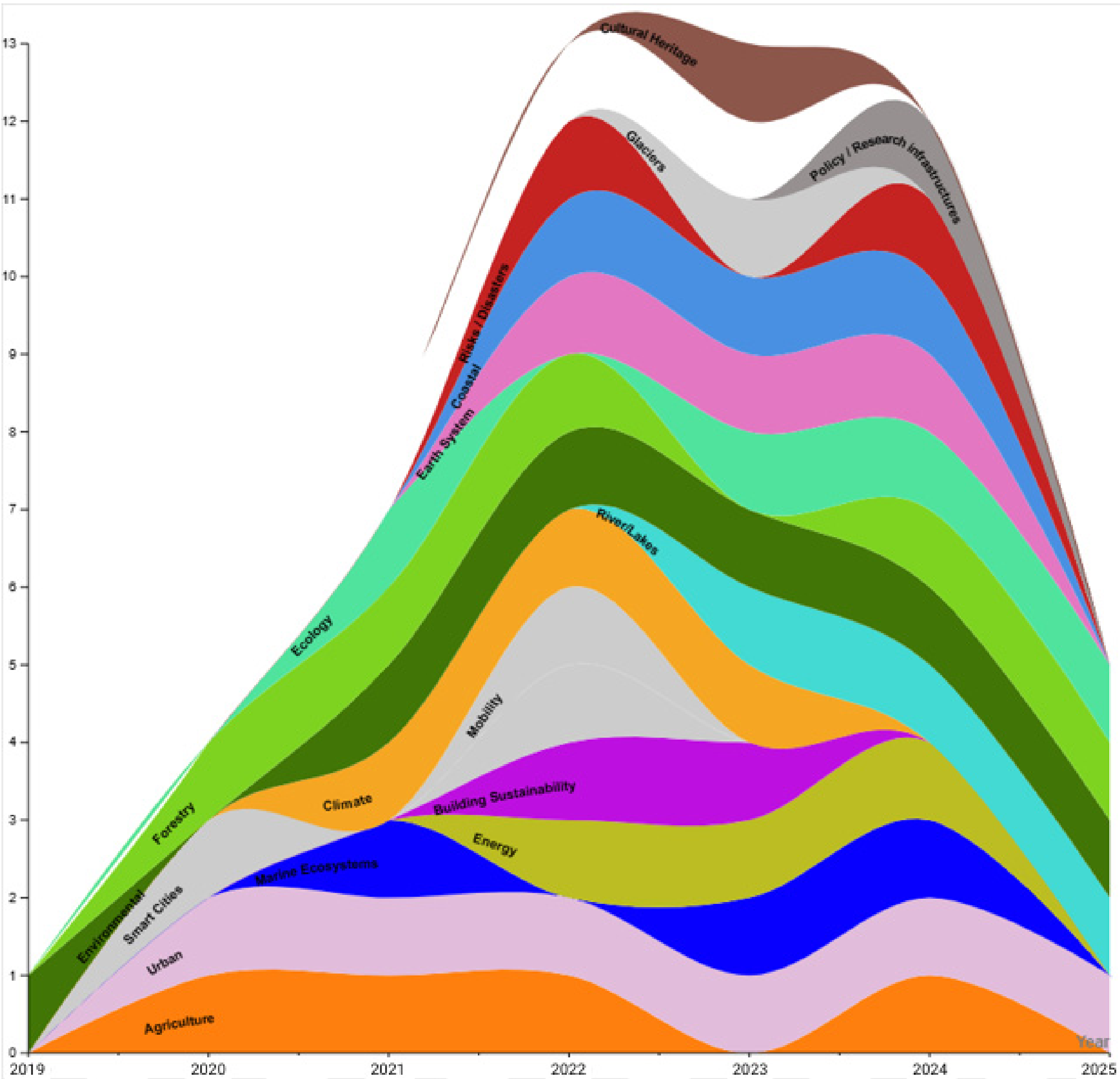

Figure 6. Alluvial diagram of DT application themes between 2020 and 2025.

In the early years (2020–2021), DT applications were primarily concentrated in agriculture, urban environments, smart cities, and forestry. These domains exhibit steadily increasing representation, reflecting early adoption driven by data availability, established modeling practices, and policy relevance. Concurrently, marine ecosystems and climate-related applications emerge as growing areas, indicating the early recognition of the potential of DTs for large-scale environmental monitoring and climate-related challenges. The period between 2021 and 2022 marks the significant intensification and diversification of DT applications. During this phase, strong growth is observed in climate, ecology, river and lake systems, and energy-related domains, alongside the emergence of building sustainability and mobility as distinct application areas. The expansion of Earth system science, coastal risks and disasters, and glacier-related DTs during this interval highlights a shift towards more complex, integrated, and large-scale water-based environments and systems, often associated with high-resolution modeling and risk assessment. This peak period corresponds to the highest cumulative volume of applications, suggesting heightened research interest and increased investment in DT-enabled environmental modeling.

From 2023 onwards, the diagram indicates partial redistribution rather than a uniform decline. While some early domains, such as agriculture and urban applications, fluctuate, others, like river and lake systems, energy, and Earth system applications, maintain a relatively stable presence. At the same time, policy and research infrastructures, cultural heritage, and sustainability-oriented domains become more visible, pointing to a growing emphasis on governance, decision support, and socio-environmental integration. The later years (2024–2025) show the convergence of multiple streams rather than dominance by a single sector. This convergence reflects increasing miscellaneous and varied topics, contributing to the emergence of territorial digital twins that integrate more site-specific dimensions (cultural heritage, rivers/lakes, glaciers). The appearance and persistence of policy and research infrastructures during this phase further underscore the institutionalization of DTs within broader sustainability, planning, and decision-making support frameworks.

The alluvial diagram highlights three key trends:

1. An initial phase of experimentation concentrated in data-rich and operationally mature domains (agriculture, urban, smart cities);
2. Rapid expansion to diverse environmental topics during the mid-years 2023–2024 (rivers/lakes, forestry, marine, coastal, risks, cultural heritage);
3. A recent shift towards more varied territorial applications. These results support the interpretation of digital twins as an evolving methodological and infrastructural paradigm, increasingly positioned as an enabling technology for environmental sustainability, governance, and long-term territorial planning.

3.1.4. Challenges and Sustainability Recurrences

Figure 7 presents the frequency distribution of recurrent nouns extracted from the sections explicitly addressing challenges and future developments within the reviewed corpus. This analysis is based on the systematic identification and counting of recurring nouns across the selected papers. The preprocessing involved the tokenization of relevant textual passages, lemmatization to group inflected forms (e.g., "scaling" and "scalability" were merged), and the removal of generic stopwords (including "DTs", "DT", and "challenges") that did not convey substantive thematic information, under the assumption that noun recurrence reflects the dominant conceptual and practical concerns shaping the current and prospective development of digital twins in environmental and territorial domains.

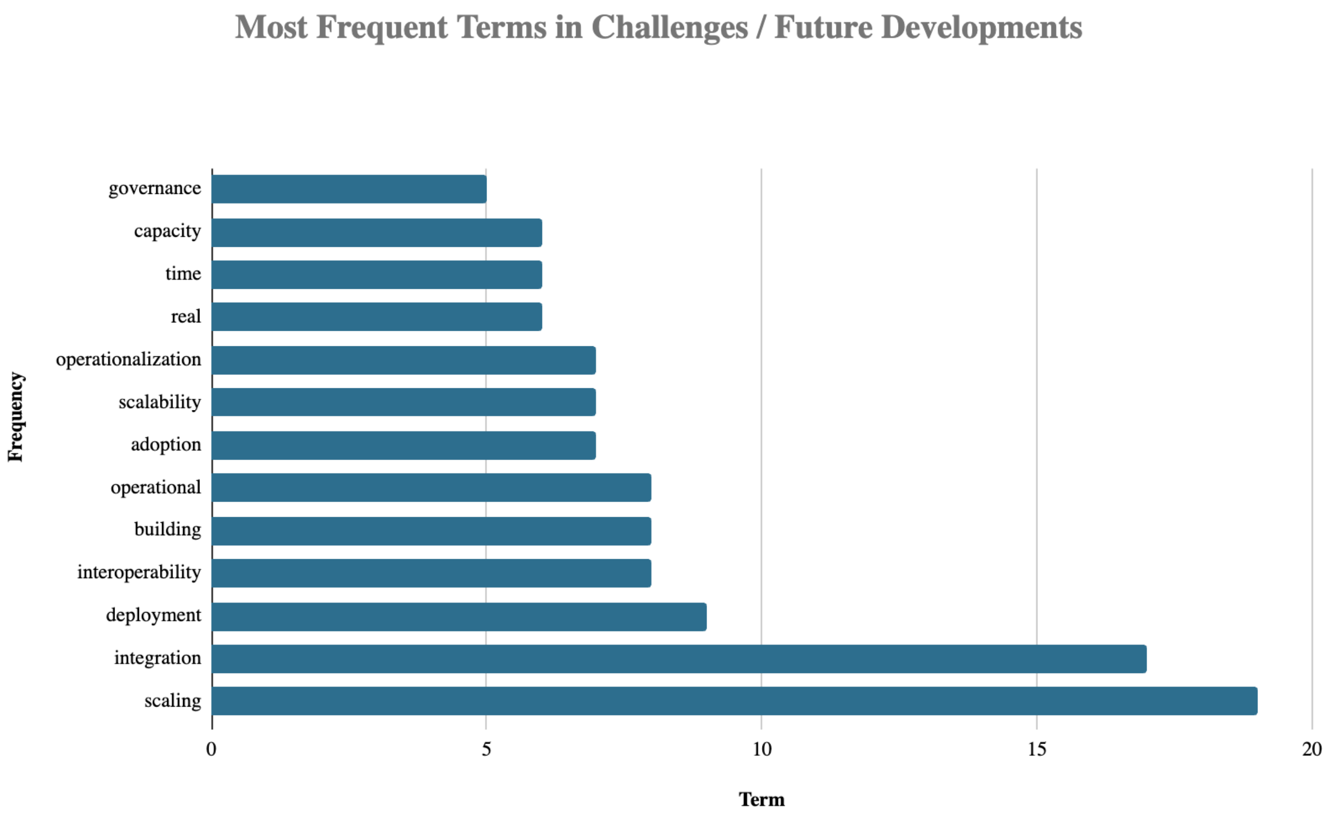

Figure 7. Bar chart of word recurrences regarding challenges and future developments.

The results reveal the strong concentration of recurring terms related to scale, integration, and implementation, indicating that the primary challenges identified in the literature are not conceptual in nature but rather concern the translation of digital twin frameworks into operational, scalable, and interoperable systems. Generic foundational terms such as "DTs", "DT", and "challenges" were treated as stopwords and removed from the frequency analysis, as they do not provide meaningful insight into substantive challenges. The most frequently occurring term, "scaling", clearly dominates the distribution, underscoring the widespread recognition that extending digital twin applications from pilots or local case studies to territorial DTs and system-level contexts remains a critical unresolved challenge.

The analysis highlights several recurrent concerns in the review's selected papers. Foremost among these are scaling (20 mentions) and integration (17 mentions), which dominate the discussion of challenges. This emphasis suggests that researchers regard the expansion of DT systems to larger, more complex environments, and their effective integration with existing infrastructures, as the most pressing hurdles. A second cluster of issues relates to deployment and interoperability. The frequent references to these terms reflect the persistent difficulty of moving from experimental prototypes and pilot projects towards fully operational, real-world systems. This underscores the challenge of bridging the gap between conceptual or technical development and practical implementation. The dual concerns of scalability and adoption further illustrate the multidimensional nature of these barriers, while technical limitations, context-based governance systems, and funding constrain the scaling of DT architectures. In addition, governance emerges as a recurring theme, pointing to the need for coherent policy frameworks, standards, and regulatory structures to guide DT development. Closely linked concerns are real-time challenges, where the demand for low-latency synchronization (and near-real-time performance) remains critical, particularly in application domains such as smart cities, risks, and environmental areas.

Figure 8 illustrates the distribution of sustainability dimensions [133] addressed by digital twin (DT) applications within the reviewed corpus, classified according to environmental, social, and economic pillars, as well as their various combinations. The frequency distribution is based on recurrent nouns extracted from the sections explicitly addressing sustainability aspects (aim, goals, challenges) within the reviewed corpus. The results show the dominance of the environmental dimension, which emerges as the most frequently addressed sustainability pillar. This finding reflects the strong alignment between digital twins applied to environmental monitoring and modeling and the environmental sustainability objectives, particularly in relation to climate change, ecosystem dynamics, biodiversity modeling and monitoring, and resource management. The prevalence of environmentally focused studies reflects the focus of this review, i.e., territorial DTs.

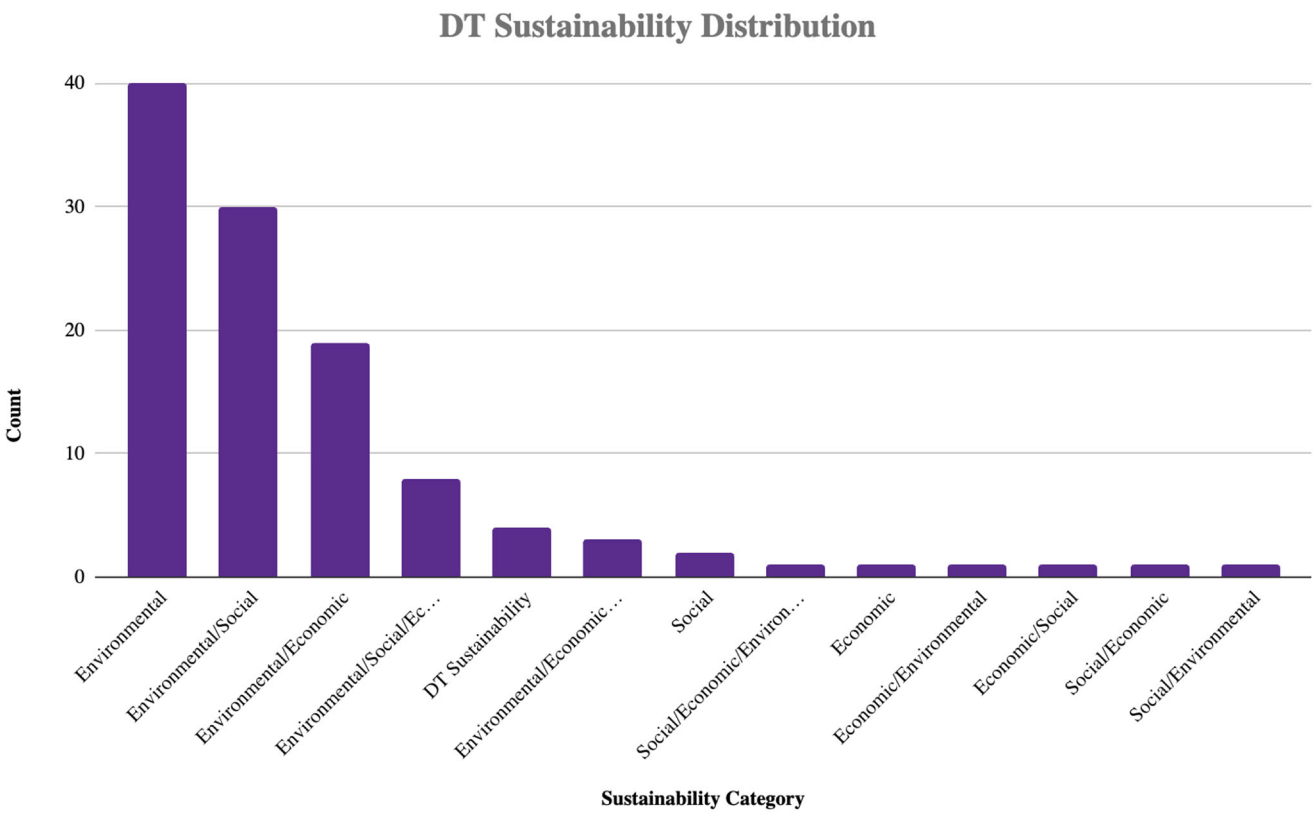

Figure 8. Bar chart of sustainability objectives' distribution across the review.

Combinations involving the environmental dimension, namely environmental–social and environmental–economic pairings, also feature prominently. This pattern indicates the growing recognition of the interdependencies between environmental processes and social or economic systems, especially in contexts such as urban planning, land-use management, and climate adaptation.

The presence of studies addressing all three sustainability pillars [133,134] simultaneously, while less frequent, signals emerging but still limited engagement with fully integrated sustainability frameworks. This aligns with the aim and application of DTs as tools that can manage complexity and multi-layered datasets, addressing multiple layers of data as well as complexity, embedding multi-source data and overlapping social and environmental cartographies. This aligns with the goals of the EU's DTs, DestinE and EDITO, aiming to provide comprehensive analyses and overviews of environments and territories and address multi-crisis contexts. By contrast, applications focusing exclusively on social or economic dimensions are comparatively rare. This imbalance suggests that, while digital twins are increasingly acknowledged as tools with broader societal and economic implications, these aspects are often treated as secondary or implicit outcomes rather than as primary analytical objectives. The relatively low representation of social-only and economic-only categories points to the underdevelopment of explicitly human-centered and socio-economic digital twin applications within the environmental literature.

The ambiguous category "DT sustainability" occupies an intermediate position in the distribution. This suggests that a subset of studies might address sustainability in a more abstract or overarching manner, without clearly disaggregating impacts across the three classical pillars. Overall, the distribution reveals a clear environmental predominance in territorial DTs. Taken together, the temporal, thematic, and sustainability analyses presented in Sections 3.1.1–3.1.4 provide the empirical basis for answering the three research questions, which are synthesized in the Discussion (Section 4). Digital twins are increasingly framed as instruments for supporting sustainable development, but their application remains predominantly environmentally driven, with social and economic considerations often incorporated only in combination with environmental objectives. This highlights an important opportunity for future research to develop more balanced, explicitly socio-environmental and socio-economic digital twin frameworks, particularly at the territorial and governance scales. It should be noted that this classification is based on the aims, intentions, and proposed opportunities or future developments articulated in each paper (this triple classification has been provided in this review). However, the sustainability assessment itself requires further deepening, particularly through the development of a broader and more precise definition of what sustainability entails in relation to the sustainable development goals (SDGs) and concrete measures of improvement.

3.1.5. Additional Classification Dimensions

Beyond the thematic, temporal, and sustainability dimensions reported in Sections 3.1.1–3.1.4, the 16-parameter classification framework also captured technology readiness levels (TRLs), validation methods, governance objectives, the use of remote sensing data, and sensor types. While an in-depth analysis of these dimensions falls outside the primary scope of this review, a summary overview is provided here (Figure 9) to offer preliminary quantitative evidence across the 109 applied studies. Regarding technological maturity, the majority of DT initiatives remain at the prototype stage (TRL 3–4, 43%), followed by conceptual or early-stage contributions (TRL 1–2, 34%), while only 23% of studies report validated demonstrations or operational pilots (TRL 5–6). This confirms that environmental and territorial DTs are still predominantly in the developmental phases, with limited deployment in real-world operational contexts. The validation approaches are diverse: case studies and pilot implementations account for the largest share (25%), closely followed by expert and literature syntheses (25%), conceptual or reference-based approaches (14%), and model-based validation (11%); only 8% of studies employ sensor-based or field validation, indicating that empirical verification remains an underexplored area. The governance objectives pursued by the reviewed DTs are led by sustainability and efficiency goals (25%), followed by risk reduction (18%) and conservation or environmental monitoring (18%), with governance and planning applications (9%) and pollution or air quality management (6%) representing smaller shares. Remote sensing data play a central role in environmental DTs: 63% of studies use remote sensing as a primary data source, with an additional 17% using it in a secondary or ancillary capacity; only 12% of studies do not employ remote sensing data at all. The sensor landscape is highly heterogeneous, with IoT and in situ environmental sensors (21%) being the most frequently reported category, followed by hydrological and oceanographic instruments (12%), optical and LiDAR systems (11%), atmospheric and meteorological sensors (9%), and satellite-based Earth observation platforms (9%). Notably, 19% of studies did not explicitly report the sensor types used, pointing to a reporting gap in the current literature. A systematic, cross-tabulated analysis of these dimensions—examining, for instance, how the TRL varies across application themes, or how validation methods relate to sensor configurations—constitutes a dedicated future research track that will build upon the dataset assembled in this review. The full 16-parameter dataset is available as Supplementary Material in accordance with open science principles, enabling such further investigation by the wider research community.

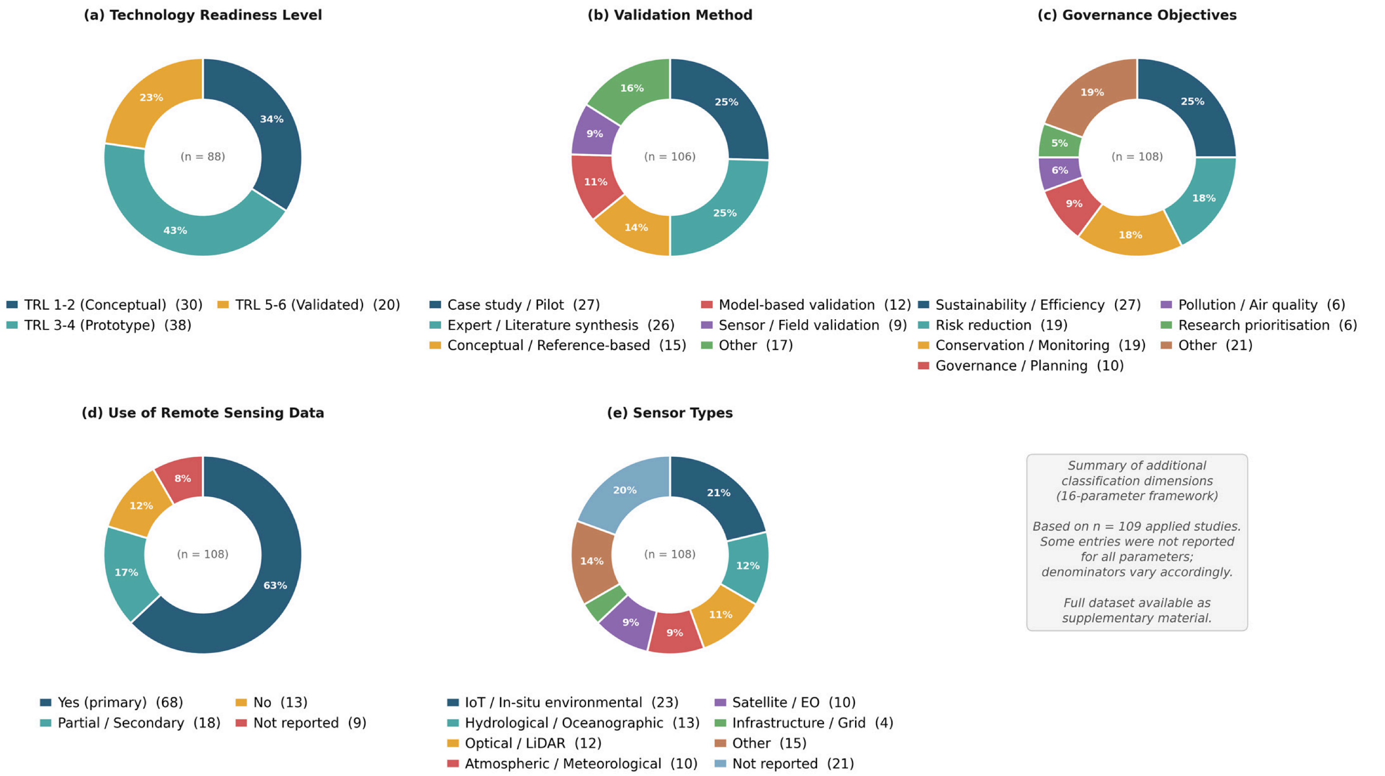

Figure 9. Distribution of additional classification dimensions across the corpus of 109 applied studies: (**a**) technology readiness level; (**b**) validation method; (**c**) governance objectives; (**d**) use of remote sensing data; (**e**) sensor types. Some entries were not reported for all parameters; denominators vary accordingly.

4. Discussion

Returning to the three research questions that guided this review (Table 3), concerning RQ1, the findings confirm that DT technology is in an active state of methodological diversification in environmental contexts, moving from a proof of concept towards institutional deployment, although full operationalization at the territorial scale remains nascent, aligning with the EU's DT programs' timelines. With respect to RQ2, the literature has not yet converged on a single definition for environmental or ecological digital twins; EcoDTs [7], EDTs [8], and TDTs [10] represent partially overlapping but distinct framings, with EcoDTs emphasizing biodiversity and ecological trajectories, EDTs foregrounding governance and monitoring objectives, and TDTs fostering community and inner area resilience. With respect to RQ3, the period 2020–2025 has seen both consolidation in established domains (urban, agriculture, energy) and diversification and the emergence of new themes, marking the exploration of new territories (marine ecosystems, coastal, rivers/lakes, glaciers, cultural heritage, forestry, biodiversity), with institutional actors driving the most outputs.

Table 3. Synthesis of research questions RQ1–3, key findings, supporting evidence, and corresponding figures.

RQ1: What is the current state of the art in digital twin (DT) technology as applied to environmental contexts?	DT technology is experiencing active methodological diversification in environmental contexts, moving from proof of concept towards institutional deployment. Most DTs remain at prototype stage (TRL 3–4, 43%); only 23% reach validated/operational levels (TRL 5–6). Institutional actors drive the majority of outputs. Validation relies predominantly on case studies (25%) and literature syntheses (25%), with limited empirical field validation (8%).	Sections 1.1, 3.1.1, 3.1.2, 3.1.5 and 4	Table 1 (definitions); Figure 2 (temporal trends); Figure 5 (segments); Figure 9a (TRLs); Figure 9b (validation)
RQ2: How are the notions of territorial digital twins (TDTs), environmental digital twins (EDTs), and ecological digital twins (EcoDTs) defined and conceptualized within the literature?	No single definition has emerged. EcoDTs emphasize biodiversity and ecological trajectories; EDTs foreground governance and monitoring objectives; TDTs foster community resilience and territorial integration. These are partially overlapping but distinct framings, reflecting three conceptual shifts: (I) from industrial to living/non-living entities; (II) from discrete objects to Earth system scale; (III) from deterministic models to ecological, multi-scale approaches.	Sections 1.1, 1.2 and 4	Table 1 (definition evolution 2002–2025)
RQ3: In which sectors have DTs been applied at the environmental and territorial scales, and how have these applications evolved and diversified during the period 2020–2025?	The period 2020–2025 shows consolidation in established domains (urban, agriculture, energy) and diversification into new territories (marine ecosystems, coastal, rivers/lakes, glaciers, cultural heritage, forestry, biodiversity). Urban applications dominate (21%); 21 thematic domains identified across 109 applied studies. Sustainability objectives are predominantly environmental (63% primary remote sensing use); scaling, integration, and interoperability are the most recurrent challenges.	Sections 3.1.1–3.1.4 and 4	Table 2 (themes); Figures 2 and 3 (temporal); Figure 4 (bubble); Figure 6 (alluvial); Figure 7 (challenges); Figure 8 (sustainability); Figure 9c–e (governance, RS, sensors)

The results of this review demonstrate that DTs within environmental and territorial domains have undergone a process of expansion, diversification, and partial consolidation over the period 2020–2025. The temporal and thematic analyses collectively indicate that DTs have evolved from early, sector-specific applications, firstly concentrated in data-rich and operationally mature domains such as urban systems, agriculture, climate, and energy, towards a broader and more heterogeneous set of environmental, ecological, and territorial-oriented uses.

The constant dominance of urban applications reflects established structural advantages in this domain: widespread sensor networks, established BIM and GIS infrastructures, a strong institutional demand from city planners, and smart city programs. These conditions lower the threshold for DT implementation compared to less "connected" environments such as forests, glaciers, or ocean systems. The emergence of marine and ecological applications from 2022 onward can be partially attributed to the EU's institutional investment through EDITO and DestinE, which may have provided both funding and interoperability frameworks that partly compensated for the sparser data environments. This suggests that, in order for DTs to expand into underserved environmental domains, a necessary precondition is a policy framework alongside technological readiness. The growing prevalence of the institutional segment signals a conceptual transition: DTs are increasingly framed as governance support tools embedded within sustainability strategies, planning frameworks, and research infrastructures. The analysis of challenge recurrence shows the dominance of terms such as scaling, integration, deployment, and interoperability, indicating that the principal barriers to DT adoption are related to and grounded in infrastructural aspects. While proof-of-concept implementations are abundant, extending DTs to larger territorial scales and embedding them within existing institutional, governance, and technical ecosystems remains a major unresolved challenge. The recurrent emphasis on governance and real-time capabilities further underscores the need for policy frameworks and long-term funding models capable of sustaining DT infrastructures beyond pilot phases, which aligns with the ongoing EU DT programs. From a sustainability perspective, environmental objectives overwhelmingly dominate the corpus, in line with the territorial focus of the review. Although environmental–social and environmental–economic combinations are increasingly present, fully integrated approaches addressing all three sustainability pillars [133,134] (environmental, social, economic) remain comparatively limited. The DT paradigm appears as an evolving methodological and infrastructural framework within environmental and territorial applications, having moved beyond an initial exploratory phase to one characterized by diversification, institutionalization, and growing relevance. The future challenges and directions characterizing DT deployment depend on addressing persistent challenges related to interoperability, scalability, and integration, as well as on developing sustainability frameworks that integrate tools for long-term territorial planning and sustainability. This will require not only technical innovation but also stronger engagement with social, economic, and institutional dimensions.

Limitations

This review has several methodological limitations that should be acknowledged. First, the literature search was limited to two databases (Scopus and Google Scholar); the exclusion of Web of Science, IEEE Xplore, and other discipline-specific databases may have introduced retrieval bias, particularly regarding engineering and computing studies. Google Scholar, while offering broad coverage, produces non-reproducible result sets, which limits the replicability of the search. Second, the corpus is restricted to English-language publications, excluding potentially relevant contributions in other languages. Third, the 2025 coverage is partial (January–June), and the observed reduction in publication counts for this year should not be interpreted as a decline in research activity. Fourth, the 16-parameter classification was conducted by a single coder without formal inter-rater reliability testing; this represents a methodological limitation that may affect the consistency of thematic assignments. Fifth, while 16 parameters were collected (including the TRL, validation method, sensor types, and governance objectives), the present analysis focuses on a subset of these dimensions; the full dataset is available as Supplementary Material for further analysis. Sixth, the sustainability classification is based on stated aims and intentions rather than empirically measured outcomes. Finally, no formal review protocol was registered (e.g., PROSPERO or OSF) prior to conducting this review. Given these constraints, this work is best characterized as a structured scoping review rather than a fully compliant PRISMA systematic review.

5. Future Research Directions

Two further critical dimensions have not yet been explored in this review. The first concerns the quality of the data serving DT infrastructures, and, upon examining the practical interaction between human actors and digital twins, a series of critical considerations emerges, encompassing access and control, trustworthiness, user acceptance, accountability, and the equitable utilization of both the data inputs to and outputs generated by such systems [34]. A particularly recent paradigm in this regard is the F.A.I.R., C.A.R.E., and T.R.U.S.T. framework [135–137], which addresses data reliability, data ethics considerations, and civic dimensions—these underpin the foundational principles of digital twins as data-centric structures. These principles raise critical questions regarding who has access to DT-generated knowledge, how trustworthiness is established and verified, which accountability mechanisms govern DT outputs, and how equitable participation in DT design and use can be ensured. Future research should systematically investigate these dimensions, developing governance frameworks that integrate F.A.I.R., C.A.R.E., and T.R.U.S.T. principles into DT architectures from the design stage, rather than as post hoc additions. The second concerns the effective sustainability of digital twin infrastructures themselves, particularly with regard to their energy consumption and resource intensity [138–140]. If DTs are positioned as enablers of environmental sustainability, their deployment and operation rely on data-intensive processes, continuous sensing, real-time computation, cloud-based storage, and high-performance modeling—all of which carry non-negligible environmental and energy costs [138–140] over territories. As DT applications scale from local pilots to extended territorial, national, or Earth system levels, these resource demands are likely to increase substantially. Consequently, sustainability must be assessed not only in terms of the outcomes that DTs can support (like assisting informed decision-making, improved environmental management, or what-if scenarios for climate adaptation), but also in relation to the life cycle impacts of the DT infrastructures themselves. Integrating such considerations at the ethical level is essential to avoid paradoxical outcomes (whereby tools designed to support sustainability might contribute to increased environmental burdens and social inequalities), making territorial digital twins effective sustainable components for uncertain futures and challenging present(s).

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Abbreviations

The following abbreviations are used in this manuscript:

DT	Digital Twin
DTs	Digital Twins
EDT	Environmental Digital Twin
EcoDT	Ecological Digital Twin
TDT	Territorial Digital Twin
DTO	Digital Twin of the Ocean
EDITO	European Digital Twin of The Ocean (EU DT)
DESTINE	Destination Earth (EU DT)

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