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Research Article

Mapping The Sustainable Development Goals in Digital Twin Research: Low Code Topic Modeling and LLM-Based Evaluation Framework

Dijital İkiz Araştırmalarında Sürdürülebilir Kalkınma Hedeflerinin Haritalandırılması: Düşük Kodlu Konu Modellemesi ve LLM Tabanlı Bir Değerlendirme Çerçevesi

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Abstract

The adoption of the "2030 Agenda for Sustainable Development" by the United Nations General Assembly in 2015 established a global commitment to achieving the 17 Sustainable Development Goals (SDGs) by 2030. As the deadline approaches, science, technology, and innovation (STI) are considered vital in accelerating progress toward these goals. This study analyzes the relationship between 10,306 digital twin research publications indexed in the Web of Science (WoS) and the SDGs. Using topic modeling with the KNIME platform, hidden themes in the digital twin literature were identified and evaluated for their alignment with specific SDGs. Sub-goal relationships for each topic were established using new and the most popular models, locally via Ollama and remotely via OpenRouter. In addition, meso and micro-level analyses highlight the temporal evolution, thematic density, and research focus within digital twin technologies. The findings offer a detailed understanding of the intersection between digital twin technologies and sustainable development, providing strategic insights for developing future STI policies. The study also outlines key sustainability areas to focus on in digital twin research and provides researchers with an SDG-focused roadmap, creating a comprehensive framework for analyzing the impacts of technological innovations on sustainability.

Keywords: *digital twin, sustainable development goals, innovation, science and technology policy, artificial intelligence*

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Öz

Birleşmiş Milletler Genel Kurulu'nun 2015 yılında "Sürdürülebilir Kalkınma için 2030 Gündemi"ni kabul etmesi, 2030 yılına kadar 17 Sürdürülebilir Kalkınma Hedefine (SKH) ulaşma konusunda küresel bir taahhüt oluşturmuştur. Son tarih yaklaşırken, bilim, teknoloji ve inovasyon (BTİ), bu hedeflere doğru ilerlemeyi hızlandırmada hayati öneme sahip olarak kabul edilmektedir. Bu çalışmada; Web of Science'da (WoS) indekslenen 10.306 dijital ikiz araştırma yayının SKH'lerle olan ilişkisi analiz edilmiştir. KNIME platformu ile konu modellemesi kullanılarak, dijital ikiz literatüründeki gizli temalar belirlenmiş ve belirli SKH'lerle uyumluluk açısından değerlendirilmiştir. Her konu için alt hedef ilişkileri, yerelde Ollama uzakta ise OpenRouter aracılığıyla yeni, popüler modeller aracılığıyla yapılmıştır. Ek olarak, mezo ve mikro düzey analizler, dijital ikiz teknolojileri içindeki zamansal evrimi, tematik yoğunluğu ve araştırma odağını vurgulamaktadır. Bulgular, dijital ikiz teknolojileri ile sürdürülebilir kalkınma arasındaki kesişim noktasına dair ayrıntılı bir anlayış sunarak, gelecekteki BTİ politikalarının geliştirilmesi için stratejik bilgiler sağlamaktadır. Çalışma ayrıca, dijital ikiz araştırmalarında odaklanılması gereken temel sürdürülebilirlik alanlarını özetlemekte ve araştırmacılar için SKH odaklı bir yol haritası sunarak, teknolojik yeniliklerin sürdürülebilirlik üzerindeki etkilerini analiz etmek için kapsamlı bir çerçeve oluşturmaktadır.

Anahtar Kelimeler: *dijital ikiz, sürdürülebilir kalkınma hedefleri, inovasyon, bilim ve teknoloji politikası, yapay zeka*

1. INTRODUCTION

Sustainability has emerged as a pressing ethical imperative in recent years. It is commonly conceptualized as the balanced integration of three foundational pillars: social, economic, and environmental dimensions, underpinned by principles of good governance (Griggs et al., 2013; Sachs, 2015). The United Nations (UN) General Assembly's adoption of the SDGs in 2015 marked a pivotal moment, establishing an ambitious agenda to foster a sustainable, equitable, and inclusive future for humanity by 2030 (United Nations, 2015). Building upon decades of global collaboration and institutional efforts (Nakicenovic et al., 2019), the SDGs constitute a transformative framework aimed at bridging critical gaps in sustainability by addressing the most pressing ecological, social, and economic challenges confronting humanity. The 17 SDGs and their 169 associated targets, as outlined in the "2030 Agenda for Sustainable Development," serve as a universal blueprint for advancing peace, prosperity, and planetary well-being. With less than a decade remaining to achieve these goals, the urgency of coordinated global action across both developed and developing countries has intensified, prompting the implementation of an expanding set of policy measures to accelerate progress (Sachs et al., 2019; Nakicenovic et al., 2019). Within this context, STI are widely recognized as critical enablers of the SDG agenda.

Among these enablers, digitalization has increasingly been positioned as a key catalyst for translating sustainability ambitions (Martínez-Peláez et. al, 2023) into actionable and scalable solutions (Seele & Lock, 2017). In recent years, the growing adoption of digital technologies such as artificial intelligence, machine learning, cloud computing, blockchain, fintech, and the Internet of Things has reconfigured industrial dynamics (Akarsu, Bağış, & Kurutkan, 2025). Collectively, these technologies provide the technological foundations for digital twin applications, which enable the real-time integration of physical and digital systems and increasingly contribute to sustainability-oriented innovation (Fuller, Fan, Day, & Barlow, 2020). By enhancing system-level monitoring, optimization, and decision-making capabilities, digital twins have emerged as a promising mechanism (Xu et. al, 2024) through which digitalization can support the advancement of the SDGs (Sajadieh & Noh, 2025, p. 6).

Despite the growing recognition of digital twins as a key mechanism through which digitalization can support the advancement of the SDGs (Allam & Jones, 2021; Galkin, Samchuk, Kopytkov, and Thompson, 2025), existing research remains fragmented in terms of both scope and analytical depth. In particular, there is limited systematic evidence on which SDGs are most directly advanced by digital twin research (Patel, Ghaffarianhoseini, Ghaffarianhoseini, & Burgess, 2024) and which technological subdomains underpin these contributions. Addressing this gap, the present study systematically maps the sustainability impact of the digital twin literature using an LLM-assisted bibliometric framework. In doing so, it offers the first integrated and scalable assessment of how digital twin research aligns with and contributes to the SDG agenda.

In the broader methodological landscape of large-scale text analytics, recent studies increasingly emphasize the role of LLM-enhanced pipelines for improving both scalability and interpretability. Invernici et al. (2025), for instance, propose an automated pipeline that retrieves content from the Scopus database and categorizes it into five SDG groups. This framework integrates topic modeling based on BERTopic to identify latent themes in large textual corpora, while also enabling keyword-based search and temporal topic frequency analysis. The approach is further strengthened through LLM-based embedding representations of scientific abstracts and a hyperparameter optimization mechanism designed to improve computational efficiency. The resulting outputs are visualized through interactive dashboards, facilitating the examination of SDG-related trends in scientific literature between 2006 and 2023 and providing a reproducible and generalizable workflow for large-scale text analysis.

Complementing these advances, Gunes, Florczak, and Yildirim (2026) highlight the importance of methodological sensitivity in LLM-based text classification tasks, particularly with respect to prompt engineering. Their study systematically manipulates prompt components such as label definitions, instructional cues, and few-shot examples to evaluate their impact on classification performance in social science contexts. The findings demonstrate that limited additions to prompt context can significantly improve accuracy, whereas overly complex prompts tend to yield diminishing or even negative returns. This variability across model settings and task configurations underscores the necessity of task-specific validation, rather than relying on standardized or universal prompt design strategies. Collectively, these studies reinforce the importance of carefully designed and empirically validated LLM-based workflows in large-scale textual analysis.

Building upon these methodological foundations, this study is further grounded in mission-oriented innovation theory to interpret the systemic implications of the identified SDG linkages. In mission-oriented innovation theory, Hekkert, Janssen, Wesseling, & Negro (2020, p. 77) defines a mission based on societal challenges as an urgent and strategic goal requiring transformative systemic change (Brown, 2021, p. 740) to address complex and difficult-to-solve societal problems. This perspective has guided the European Commission's recent trend toward formulating missions with more clearly defined and measurable goals, particularly in areas such as climate change adaptation and healthy oceans. The mission-oriented innovation approach treats the resolution of societal challenges as multi-stakeholder, guided innovation processes structured around specific objectives (such as the SDGs) (Meuleman, 2021). In this context, digital twin technologies are not merely tools for enhancing operational efficiency, but also provide a strategic coordination and simulation infrastructure for the realization of missions aligned with the SDGs (Al-Jayyousi, Amin, Al-Saudi, Aljassas, & Tok, 2023, p. 16). Thanks to their capacity for real-time data integration and scenario analysis, digital twins enable policymakers and organizations to guide their decisions (Akarsu, 2025, p. 109) regarding sustainability goals in a predictive and evidence-based manner. For example, in their study, Casanas and Kovacic (2025) conclude that in the context of Spain, the pursuit of a mission-oriented innovation policy for energy twin transitions can be explained by innovation imagery that addresses the problem of policy-making to cope with major challenges, regardless of the extent to which specific technologies solve these complex problems. Thus, digital twins are positioned as a critical tool in the practical implementation of the directed, measurable and impact-focused innovation processes required by the mission-oriented innovation approach (Karagiannis, 2024).

Similarly, in socio-technical systems theory, Geels (2004); Sony & Naik (2020) argue that digital systems are not merely a technical tool but also a product of the interaction between technology, people, institutions, policy, and the environment. The socio-technical systems approach emphasizes that technological transformations are shaped not only by technical infrastructure, but also by organizational structures, networks of actors and social norms. Within this framework, digital twins create a multi-layered interaction space by bridging the gap between physical systems and their digital representations, thereby accelerating transformation processes towards the SDGs (Ghosh, Hughes, Hughes, and Hodgkinson, 2025). However, this transformation is not limited to technological integration alone but requires the concurrent consideration of socio-technical elements such as data governance, stakeholder coordination and organizational alignment (Papadonikolaki, 2025). Consequently, the contribution of digital twins to the SDGs is directly linked not so much to their technical capacity, but to the adaptability and transformative capacity of the socio-technical system in which they operate. Building on these theoretical perspectives, the next step of the study empirically maps how digital twin research aligns with mission-relevant SDGs across different analytical levels.

After identifying the top four SDGs most frequently addressed in digital twin research (SDG-9, n=3,703; SDG-12, n=3,321; SDG-11, n=1,739; SDG-3, n=1,081), Table 1 presents the distribution of associated meso-level and micro-level WoS codes. For SDG-9, the dominant meso-level category is “Design and Manufacturing” (3,362 publications), while “Industry 4.0” (2,951) leads at the micro-level by a wide margin. A similar pattern appears for SDG-12, where “Design and Manufacturing” and “Industry 4.0” again rank first, although micro-level areas such as “Supply Chain and Logistics” (125) and “Advanced Processing” (98) also stand out. In SDG-11, “Telecommunications” (503) is the main meso-category, with “IoT and Edge Computing” (401) leading at the micro-level. For SDG-3, “Telecommunications” (401) again tops the meso-level, while health-focused micro-themes such as “Protein Purification” (64) and “Surgical Robotics” (37) emerge as distinctive. Full code lists for all SDGs are provided in the supplementary materials.

The detailed classification based on meso and micro-level thematic codes presented in Table 1 reveals the contextual depth of digital twin research with sustainability goals.

Table 1. Most Frequent Meso and Micro-Level Citation Topics in Digital Twin Research for the Four Primary SDGs (Top 5 per Category)

SDG (n articles)	Top Meso-level Categories (n)	Top Micro-level Categories (n)
SDG-9 (3,703)	Design & Manufacturing (3,362) Nanofibers, Scaffolds & Fabrication (120) Distributed & Real-Time Computing (87) Sustainability Science (60) Telecommunications (21) Other 14 categories (53)	Industry 4.0 (2,951) Digital Construction (411) Additive Manufacturing (120) Software Defined Networking (65) Circular Economy (25) Other 19 categories (131)
SDG-12 (3,321)	Design & Manufacturing (2,951) Supply Chain & Logistics (125) Manufacturing (98) Sustainability Science (61) Polymer Science (18) Other 12 categories (68)	Industry 4.0 (2,951) Advanced Machining (98) Manufacturing Scheduling (81) Supply Chain Optimization (44) Circular Economy (25) Other 22 categories (122)
SDG-11 (1,739)	Telecommunications (503) Sustainability Science (230) Testing & Maintenance (210) Transportation (130) Electrochemistry (105) Other 32 categories (561)	IoT & Edge Computing (401) Damage Detection (175) Building Energy Efficiency (165) Lithium-ion Battery (105) Traffic Flow (73) Other 65 categories (820)
SDG-3 (1,081)	Telecommunications (401) Chromatography & Electrophoresis (68) Computer Vision & Graphics (49) Cardiac Arrhythmia (40) Robotics (37) Other 64 categories (486)	IoT & Edge Computing (401) Protein Purification (64) Surgical Robotics (37) Deep Visual Recognition (34) Cardiac Electrophysiology (22) Other 137 categories (523)

Following this thematic mapping, Table 2 presents the distribution of SDGs across WoS indices for digital twin publications. WoS indexes are divided into four main groups: (i) Core Citation Indexes (SCI-EXPANDED, SSCI, A&HCI), (ii) Emerging Sources Citation Index (ESCI), (iii) Conference Proceedings (CPCI-S, CPCI-SSH), and (iv) Book Indexes (BKCI-S, BKCI-SSH). The groups are highlighted in different shades in the table. While the majority of the 8,647 studies indexed in SCI-Expanded are related to SDG-9 (n=2,993) and SDG-12 (n=2,698), these two goals together account for

65% of SCI-Expanded publications. The same trend is observed in ESCI and SSCI; however, it is noteworthy that themes related to global cooperation and climate action, such as SDG-13 (n=53) and SDG-17 (n=39), have a proportionally higher representation in SSCI. In contrast, socially oriented SDGs (SDG-1, SDG-5, SDG-10) are very underrepresented across all indices, reaching their highest values with only 9 publications (SDG-5 in SCI-Expanded). When all indices are combined, the highest association is observed for SDG-9 (3,949 publications in total), followed by SDG-12 (3,532) and SDG-11 (1,825). This distribution reveals that digital twin research is primarily concentrated in technology-infrastructure-focused areas such as industrial transformation, resource efficiency, and sustainable urbanization, while dimensions such as social equity and inclusivity are largely neglected. Yang et al. (2025), in their study examining the use of digital twins in urban life, emphasize that existing research has largely focused on technical aspects, whilst studies addressing social dynamics remain limited. This finding is consistent with the results presented in Figure 1, which show that SDG-based digital twin studies are predominantly concentrated in technological fields.

Table 2. Distribution of Digital Twin Studies across SDGs by Web of Science Index (Top 4 SDGs highlighted)

WoS Index		n	SDG-9	SDG-12	SDG-11	SDG-3	Other SDGs (total)
Core Citation Indexes	**SCI-EXPANDED**	8,647	2,993	2,698	1,512	947	497
	SSCI	539	306	275	114	34	110
	A&HCI	34	6	3	6	1	18
Emerging Sources Citation Index	**ESCI**	1,441	602	516	182	119	22
Book Indexes	**BKCI-S**	41	20	19	2	11	9
	BKCI-SSH	7	4	4	1	-	2
Conference Proceedings	**CPCI-S**	45	18	17	8	2	-
	CPCI-SSH	1	-	-	-	-	1 (SDG-4)

This study aims to systematically map the relationship between the digital twin literature and the SDGs through topic modeling and an LLM-supported evaluation framework, and to reveal which goals and sub-goals these contributions focus on. Guided by this objective and to operationalize the proposed analytical framework, the study is structured around the following research questions.

RQ1: Which SDGs and associated targets are most prominently addressed by digital twin research, and how are these contributions distributed across different technological subdomains of the digital twin literature?

RQ2: How has the alignment between digital twin research and the SDGs evolved in terms of thematic focus, intensity, and research maturity, as revealed through LLM-assisted bibliometric and topic modeling analyses?

The dataset of this study was constructed through a systematic search of the WoS database, focusing on studies addressing digital twins in relation to the SDGs. To ensure analytical relevance, the review was confined to the four SDGs with the highest volume of related publications. Accordingly, the synthesis centers on SDG-3 (Good Health and Well-being), SDG-9 (Industry, Innovation and Infrastructure), SDG-11 (Sustainable Cities and Communities), and SDG-12 (Responsible Consumption and

Production). The findings show that the vast majority of digital twin research is strongly and directly related to SDG-9 and SDG-12. A more limited but significant research concentration was identified in SDG-11 and SDG-3. Within these four goals, digital twins make tangible sustainability contributions, such as industrial transformation, circular economy, smart city infrastructures, and personalized health applications, respectively. Furthermore, sub-goal mappings obtained through topic modeling and multi-LLM analyses in these areas reveal a systematic alignment of the technical literature with sustainable development priorities.

The remainder of this article is structured as follows. In the second section, the previous literature on the intersection of sustainability and digital twins is discussed controversially and grouped according to micro and meso codes. In the third section, explanations are provided regarding the study method, methodological explanations are given regarding topic modeling and LLM-based mapping, and details on micro and meso-level coding are provided. The findings of the research are presented in the fourth section, and the discussion and conclusion sections are presented to the reader in the final section.

2. LITERATURE REVIEW

Sustainable development focuses on the necessary efforts to ensure the sustainability of nature while also aiming to improve people's living conditions (United Nations, 1982). As a result of the significant increase in income inequality since the 1980s due to globalization and the digital age, many negative consequences have arisen, such as malnutrition, health problems, and problems accessing education (Sachs, 2012). To address these problems and contribute to sustainable development, the United Nations announced the Millennium Development Goals (MDGs), consisting of eight development goals to be achieved between 2000 and 2015 (United Nations, 2000). Although significant progress has been made toward each of the MDGs, which are of considerable importance in terms of establishing clear and measurable targets for global development, some targets have not reached the intended level of success (United Nations, 2015; Ghosh, 2015; Hák, Janoušková, & Moldan, 2016). In 2015, the United Nations announced the SDGs with the aim of addressing the shortcomings of the MDGs and reshaping them to cover current issues.

The SDGs, consisting of 17 goals and 169 targets to be achieved by 2030, aim for balanced and sustainable growth across economic, social, and environmental areas (United Nations, 2015). There is a strong connection between each of these goals, and each goal concerns the entire world (Nilsson, Griggs, & Visbeck, 2016). Given that it is quite difficult to physically monitor the current status of sustainable development goals, which cover a very wide geography, digital twins are attracting attention as an important tool that can be used to track the process (Tzachor, Sabri, Richards, Rajabifard, & Acuto, 2022).

Digital twins, which were first used in the manufacturing and production industries, are defined as real-time representations of living or non-living entities created in a virtual environment (Boschert & Rosen 2016; Tzachor et al., 2022). The entity for which a digital twin is created can be a physical object, a business process, or any system (Bolton et al., 2018). For these structures, which work with near-real-time data belonging to entities, to be successful, the security of the data used and the reliability of the algorithms used to develop/update the models are crucial (Wright & Davidson, 2020).

With the development of new generation information technologies, Semeraro, Lezoche, Panetto, & Dassisti (2021) emphasize the importance of integration between virtual and real environments and state that the use of digital twins will contribute to transparency, accuracy, and efficiency. Digital twin technologies are being used to monitor SDGs, which Sachs et al. (2019) consider a concept requiring the efforts of many countries across a wide area. Particularly after 2015, the widespread access to electricity and a 70% increase in internet connectivity have reduced the impact of a significant problem hindering the use of digital twins (United Nations, 2025). However, Tao & Qi (2019) emphasize that there are still many obstacles to designing sensor data from thousands of sources to make the most accurate predictions. Niederer, Sacks, Girolami, & Willcox (2021) share the concerns of Tao & Qi (2019), stating that they have doubts about whether these solutions are scalable for data from a wide geographical area, as current digital twins are based on technical solutions designed for specific, limited situations. A review of the literature on the concept of digital twins reveals that research has focused on three main areas: the examination of sector-specific applications; technical infrastructure and modelling;

and the analysis of policies proposed in line with sustainable development goals. This situation makes it difficult to assess digital twins holistically within the context of the SDGs.

Tzachor et al. (2022), on the other hand, focus on the benefits of creating a digital twin capable of making accurate predictions regarding the implementation of SDGs, rather than the obstacles to its creation. The first of the four key benefits listed by Tzachor et al. (2022) is more efficient resource allocation. Real-time data allows the current situation to be monitored, and alternative conditions can be tested on digital copies. The second benefit is that digital twins provide a virtual environment where green technologies can be tested, allowing potential risks in innovation efforts to be kept under control. Thirdly, digital twins enable scientific and political partnerships by ensuring that data related to relevant systems is accessible independently of physical location with the help of cloud-based technologies. Tzachor et al. (2022) explain the fourth important benefit of using digital twins as a means of monitoring progress in SDGs.

Although there are certain challenges to creating digital twins in line with sustainable development goals, the potential benefits are driving researchers to focus on this topic. Figure 1 provides a summary of the literature on the contributions of digital twin usage towards each sustainable development goal.

As noted by Sachs et al. (2019), there is a natural interconnection between the SDGs. Consequently, each of the studies presented in Figure 1 and discussed in the following paragraphs has a direct or indirect link to one or more SDGs. As the focus of this study is to examine the relationship between research on digital twins and the SDGs, there is a relatively higher number of studies linked specifically to SDG-9 (Industry, Innovation and Infrastructure).

Cordes, Sefah, & Marinova (2024) examine the role of digital twins in eliminating poverty in Sub-Saharan Africa through a case study that addresses both technical and socio-economic aspects. This study, which contributes to sustainable development in terms of participation in the digital economy and income-generating activities in poor countries, is particularly relevant to SDG-1 and SDG-10 and SDG-11 as well as an indirect link to SDG-9. Guidani, Ronzoni, & Accorsi (2024) create a digital twin model representing the stages in food supply chains for access to safe, high-quality, and affordable food. This study, which also aims to increase efficiency in decision-making processes with decision support systems, has a direct link to SDG2 (Zero Hunger) and SDG-12, as well as an indirect link to SDG-8, SDG-9, and SDG-9, and SDG-13.

Sarp, Kuzlu, Zhao, & Gueler (2023) aim to enable early diagnosis and timely treatment through their model for using digital twins to monitor chronic wounds. This study is directly linked to SDG-3 and indirectly linked to SDG-9. Zhang et al. (2024) describe the implementation of a digital twin-based learning system in the education of engineering students. This study, which aims to improve the quality of education, is directly linked to SDG-4 (Quality Education) and indirectly linked to SDG-9 due to its innovative infrastructure. Cáceres García de Marina et al. (2025) propose a digital twin design specifically for women to ensure their physical safety and emergency management. This study is directly linked to SDG-5 (Gender Equality) and SDG-11. It also has an indirect link to SDG-3 due to its contribution to physical security and psychological well-being.

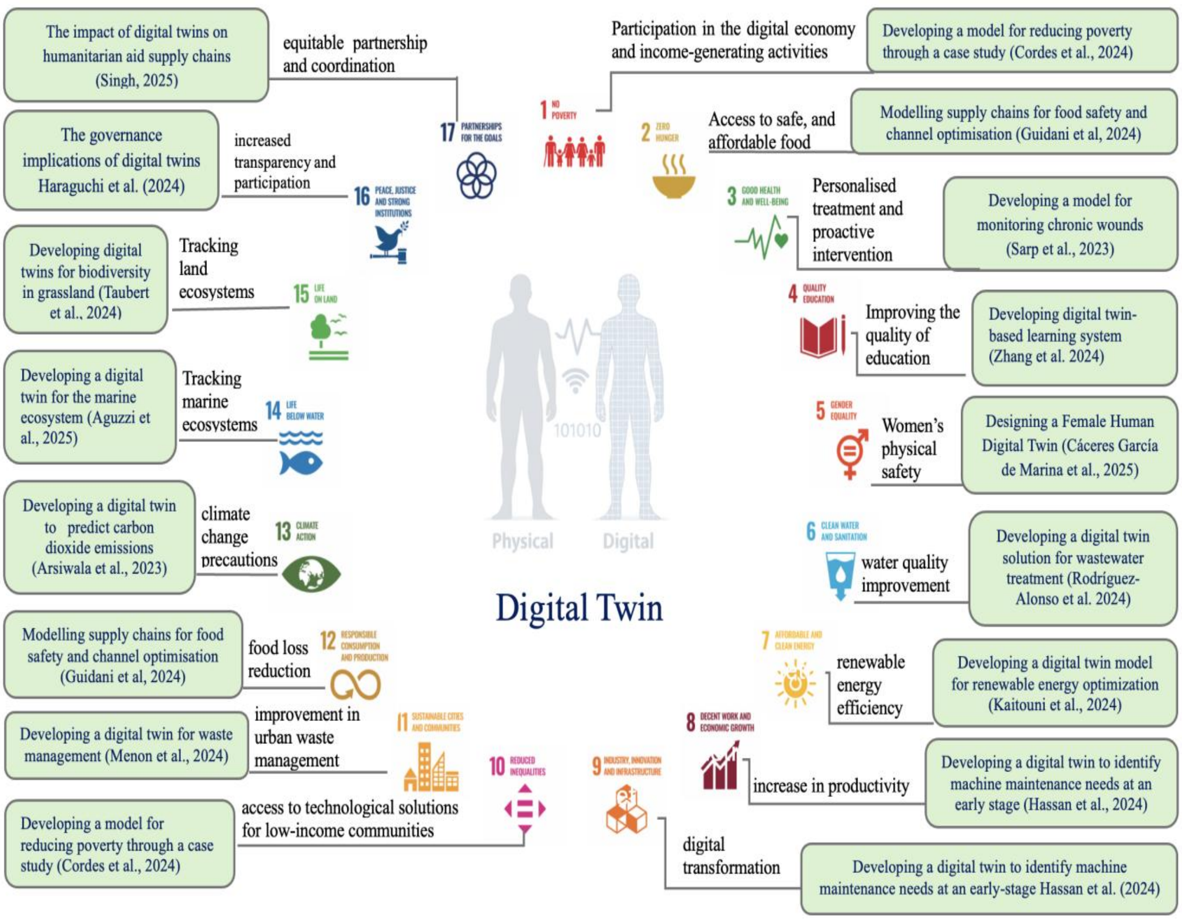
Rodríguez-Alonso, Pena-Regueiro, & García (2024) focus on enabling process optimization through a digital twin they developed for wastewater treatment plants. This study, which is related to improving water quality, is directly linked to SDG-6 (Clean Water and Sanitation) and is also indirectly linked to SDG-3, as it will contribute to protecting public health as a result of access to clean water. In their work, Kaitouni et al. (2024) present a model that enables the detection and diagnosis of faults using a digital twin they developed for the optimization of solar energy systems, which is linked to SDG-7 (Affordable and Clean Energy), SDG-9, and SDG-11. Additionally, this study has an indirect link to SDG-12 due to the impact of effective fault detection and maintenance on responsible production processes.

Hassan, Svadling, & Björsell (2024) address the use of digital twins for the early detection of machine maintenance needs. This study directly aligns with SDG-8 (Decent Work and Economic Growth) in terms of increased productivity and reduced economic losses, while also directly aligning with SDG-9 (Industry, Innovation and Infrastructure) in terms of digital transformation and innovation. Menon, Sai Ganesh, & Saikrishna (2024) state in their study that certain harmful gases are emitted from waste separation and disposal centers and propose a digital twin model for monitoring and predicting this harmful gas emission. This study, which is directly linked to SDG-11 and SDG-12, also has an indirect link to SDG-9 and SDG-13.

Arsiwala, Elghaish, & Zoher (2023), in their work directly linked to SDG-13 (Climate Action), focus on predicting carbon dioxide emissions through digital twins and providing decision support for strategy development. Aguzzi et al. (2025) directly link their work to SDG-14 (Life Below Water), tracking existing biodiversity for the sustainability of the oceans, while Taubert et al. (2024) directly link their work to SDG-15 (Life on Land), designing a digital twin model to track biodiversity in grasslands. Haraguchi, Funahashi, & Biljecki (2024) examine the governance impacts of digital twins through their maturity model presented in their work aligned with SDG-16 (Peace, Justice and Strong Institutions) via public participation accountability. Singh (2025) examines the impact of digital twins on supply chain processes related to humanitarian aid that encourage multi-stakeholder collaboration in their work directly linked to SDG-17 (Partnerships for the Goals). In summary, an overview of the academic studies presented in Figure 1 reveals that a significant proportion of the research aligns directly or indirectly with SDG-9, SDG-11 and SDG-12. This observation is parallel to the conclusions presented by Galkin et al. (2025). Whilst this study emphasizes the strong alignment between digital twin applications and SDG-9, SDG-11 and SDG-12, it also notes that empirical evidence measuring the impact of digital twins on sustainability is not yet sufficient.

Furthermore, many studies also contribute indirectly to SDG-3. Moreover, when these studies are assessed as a whole, it is notable that digital twin initiatives are more prevalent in certain sectors than in others. Whilst these initiatives are concentrated in the energy, healthcare and manufacturing sectors, it is evident that digital twin initiatives remain relatively limited within the scope of SDGs with strong social dimensions, such as poverty and inequality. Similarly, research conducted by Yang et al. (2025) on the use of digital twins in cities highlights that, whilst existing studies focus on technical details, they remain limited in their ability to support social dynamics. Figure 1 presents a selection of SDG-based digital twin studies.

Figure 1. Digital Twin Studies in the Literature



A cross-cutting reading of the empirical studies summarised above reveals three analytical tensions that remain underexplored in the literature. First, there is a divergence in the expected scalability of digital twins for SDG monitoring: while Tzachor et al. (2022) emphasise their transformative potential for resource allocation and multi-stakeholder partnerships, Niederer et al. (2021) and Tao & Qi (2019) caution that existing solutions are designed for specific, small-scale systems and may not be generalisable to large-geography SDG indicators. Second, a methodological divide exists between technically oriented optimisation studies (e.g., Warke et al., 2021; Kaitouni et al., 2024; Hassan et al., 2024) that focus on operational efficiency, and socio-economically focused investigations (e.g., Cordes et al., 2024; Cáceres García de Marina et al., 2025) that address inclusion, poverty, or gender. The former dominate the publication landscape, whereas the latter remain episodic. Third, despite the frequent claim that digital twins generate co-benefits across multiple SDGs (Nilsson et al., 2016), very few studies provide quantitative or systematic evidence of such cross-goal spill-overs. Most contributions rely on single-case or sector-specific designs, making it difficult to compare findings across domains. Consequently, the literature offers rich but fragmented insights: it identifies promising applications yet lacks a comprehensive, data-driven mapping of which SDG sub-targets are actually addressed by digital twin research – a gap that the present study systematically fills.

Looking at bibliometric studies on the SDGs, Geng, Li, Farsangi, Xu, and Tam (2025) present a bibliometric analysis of studies on reducing carbon emissions through the use of digital technologies in construction technologies. Warke, Kumar, Bongale, and Kotecha (2021) conducted a bibliometric analysis to examine the literature on the use of digital twins in smart manufacturing. Galkin et al. (2025) present a general framework of studies focusing on the use of digital twins in logistics through their bibliometric analysis. Bhati, Goerlandt and Pelot (2025) examined the use of digital twins in the blue economy, which refers to the transformation of ocean and marine resources into economic value in line with the SDGs. In a study by Bhati et al. (2025), a bibliometric analysis of studies on the use of digital twins in the blue economy, again framed as the transformation of ocean and marine resources into economic value aligned with the SDGs, is presented.

Complementing these perspectives, Terrill and Cotos (2025) investigate GenAI's potential in literature searches through a "human-in-the-loop" approach, where machines assist in information extraction and content classification under human oversight. In their study, research synthesis guidelines were applied for article classification, and outputs from GenAI models such as GPT-3.5 and GPT-4 were evaluated against human judgments; the findings raise concerns about model effectiveness and recommend caution when relying on GenAI outputs, particularly in teaching literature search skills. In our literature review conducted within the framework of these analyses, we did not encounter any LLM-based topic modeling study focusing on the use of digital twins in alignment with the SDGs, which strongly highlights the originality of our study.

To address this gap, the present study adopts a hybrid bibliometric and semantic analytical framework, combining topic modeling, multi-LLM sub-goal mapping, and expert validation. The full methodological pipeline is detailed in Section 3.

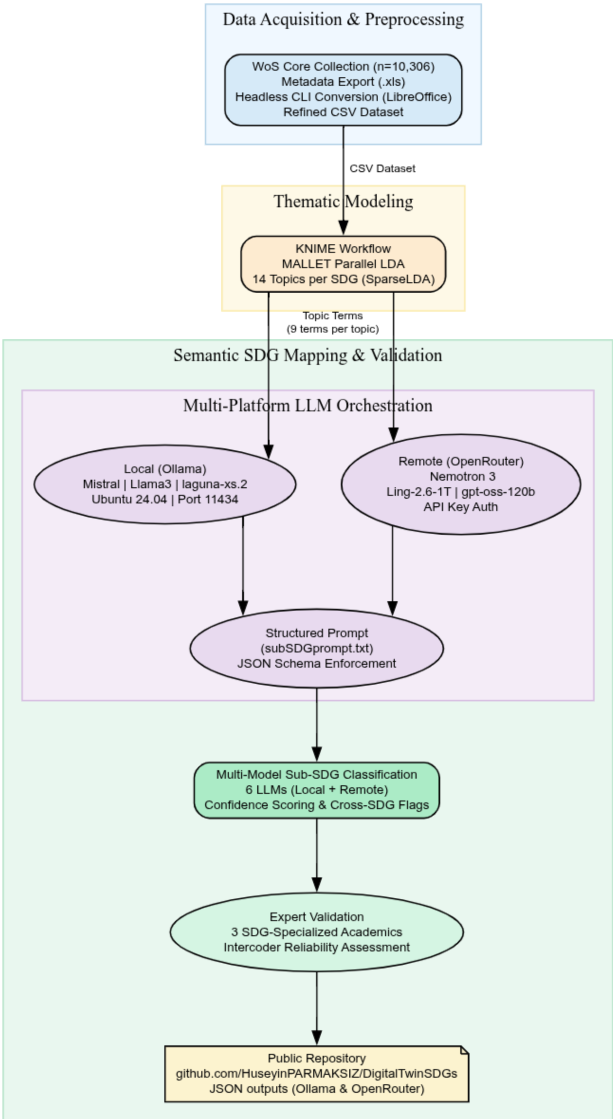
3. METHODOLOGY

This study adopts a hybrid bibliometric and semantic analytical framework to systematically investigate the intersection between Digital Twin (DT) research and the SDGs. The methodological pipeline integrates large-scale bibliographic data extraction, topic modeling, and LLM-based sub-goal mapping, supported by both meso and micro-level thematic categorization. Figure 2 presents the overall workflow of the study, from bibliographic data retrieval and preprocessing to topic modeling, multi-LLM sub-goal mapping, and final visualization. The subsequent subsections detail each step.

Bibliographic records were sourced from the WoS Core Collection using the following search query executed on August 4, 2025:

Query: TS="digital twin" and Article (Document Types) and English (Languages) and Article (Document Types) , yielding 10,306 publications.

Figure 2. The big picture, which is the summary of the study.



Bibliographic metadata (including titles, abstracts, keywords, and citation information) were exported in .xls format and converted to .csv using the headless *"libreoffice --headless --convert-to csv DT-SDG11.xls"* command. This ensured automated, scalable preprocessing compatible with downstream computational workflows. The computational setup and the matching procedure between topic clusters and SDG sub-goals are detailed in Sections 3.1 and 3.2, respectively.

3.1. Topic Modeling

Topic modeling was performed using the KNIME (Konstanz Information Miner) Analytics Platform with the structure shown in Figure 3. The text set tracked in Parmaksız (2025) (preprocessing steps in Figure 4) underwent standard natural language preprocessing. To determine the optimal number of hidden topics for each SDG set, consistency scores and complexity metrics were empirically evaluated at various topic numbers (ranging from 5 to 20). As a result of the experimental methods, each SDG-specific sub-text set was independently modeled to preserve contextual nuances, and 14 different topics and 9 terms for each topic were determined for each SDG.

Topic extraction was performed using a Parallel LDA node within KNIME, leveraging the MALLET (Machine Learning for Language Toolkit) library's SparseLDA implementation. This approach not only achieved up to twice the computational speed of conventional fast sampling methods (Yao, Mimno & McCallum, 2009) but also required substantially less memory.

Figure 3. Digital Twin Research by SDGs and Topic Modeling with KNIME

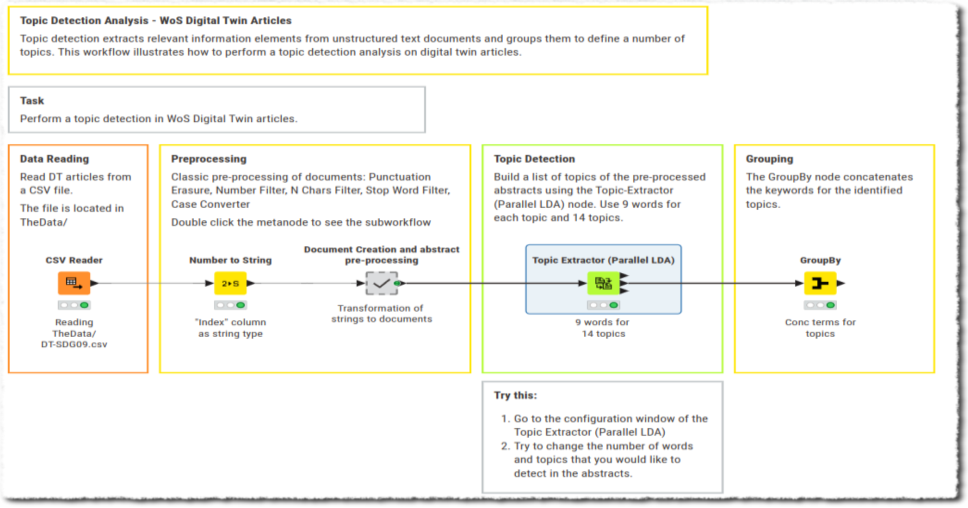
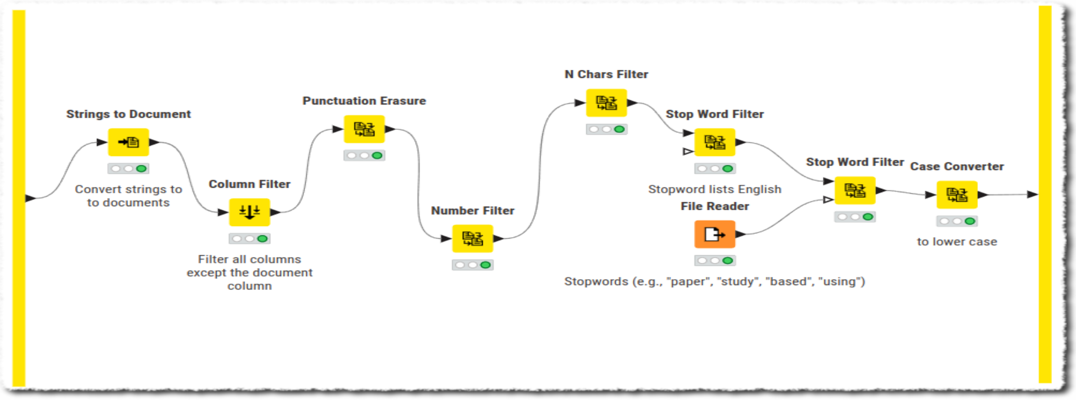


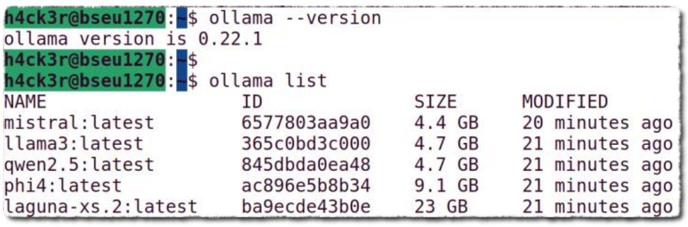
Figure 4. Document creation and abstract preprocessing steps using KNIME.



3.2. SDG Sub-Goal Mapping via Large Language Models

The local computational environment was established on an Ubuntu 24.04.3 LTS operating system by executing the command "curl -fsSL https://ollama.com/install.sh | sh", which deployed the Ollama framework. The Mistral model was launched locally via ollama run mistral, making it accessible through "http://localhost:11434/". All local models listed in Figure 5 (Mistral, llama3, laguna-xs.2) were installed using Ollama.

Figure 5. List of models used on the local.



```
h4ck3r@bseu1270:~$ ollama --version
ollama version is 0.22.1
h4ck3r@bseu1270:~$
h4ck3r@bseu1270:~$ ollama list
NAME                  ID              SIZE      MODIFIED
mistral:latest        6577803aa9a0    4.4 GB    20 minutes ago
llama3:latest         365c0bd3c000    4.7 GB    21 minutes ago
qwen2.5:latest        845dbda0ea48    4.7 GB    21 minutes ago
phi4:latest           ac896e5b8b34    9.1 GB    21 minutes ago
laguna-xs.2:latest    ba9ecde43b0e    23 GB     21 minutes ago
```

On this basis, we designed a structured command-line framework to determine the alignment of the 14 topics derived for each SDG with specific sub-SDGs using the LDA implementation in KNIME. This framework was executed locally using the aforementioned Ollama-based models (Mistral, llama3, laguna-xs.2) as well as remotely via OpenRouter using three free models: NVIDIA's Nemotron 3 Nano Omni, inclusionAI's Ling-2.6-1T, and OpenAI's gpt-oss-120b. The primary objective of this matching procedure was to uncover cross-cutting relationships between the term clusters derived from SDG-specific topics and other SDG groups beyond their original assignment.

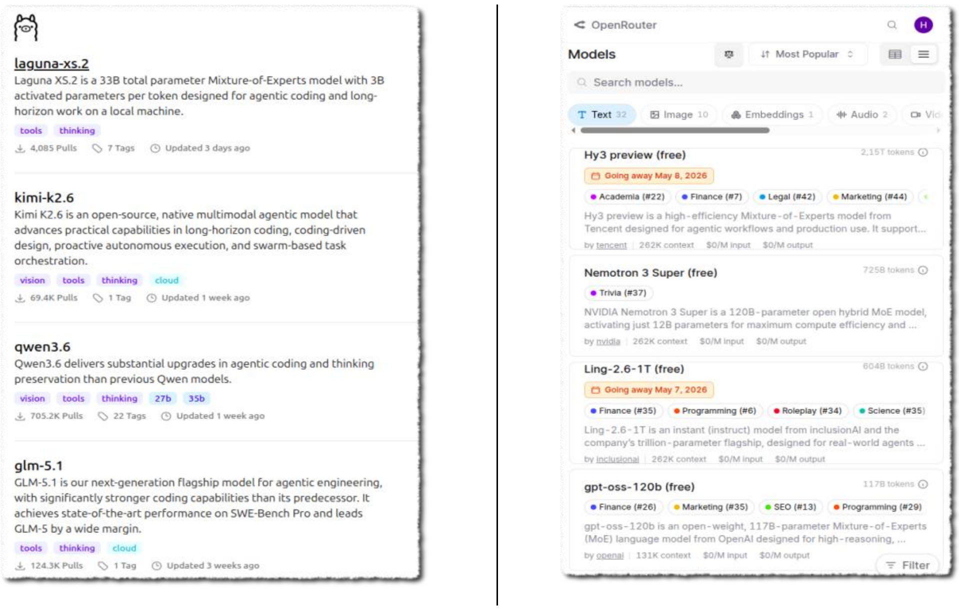
Among the local models, Mistral (7B) was selected for its low latency and compatibility with limited hardware resources, while Llama3 (8B) can process queries in various languages, including Turkish, thanks to its multilingual capabilities. Laguna-xs.2 (23B) was chosen for its higher semantic capacity and ability to process complex contexts. Among the remotely accessible models, gpt-oss-120b (120B) has the largest knowledge base, Nemotron 3 Nano Omni (8B) stands out for its success with technical texts, and Ling-2.6-1T has an advantage in broad-scope SDG alignments thanks to its MoE (Mixture of Experts) architecture trained on 1 trillion tokens. The models' performances were evaluated comparatively, similar to the LLM-based topic modeling approach proposed by Invernici et al. (2025).

To apply the sub-SDG command line to the Llama3 model and obtain output locally using Ollama, simply run the command `ollama run llama3 "$(cat subSDGprompt.txt)" in the terminal of an open-source Linux operating system. This model is also available locally via the API at "http://localhost:11434/". As shown in Figure 5, the laguna-xs.2 model is 23 GB in size, and unlike the Ollama version (0.11.10) used with other models, the Ollama version 0.22.1 must be specifically updated to run this model locally. Additionally, an example of the model to be used locally is shown on the left side of Figure 6 at "https://ollama.com/".

After the API key obtained from OpenRouter is saved to the api-key.txt file, output can be generated using the curl tool in the local operating system terminal with the help of the script provided below. Support for Python and TypeScript is also available. The models used in this study were selected because they are available for free on OpenRouter and are listed in the "most popular" category (right side of Figure 6).

```
h4ck3r@bseu1270:~$ curl -s https://openrouter.ai/api/v1/chat/completions \
  -H "Content-Type: application/json" \
  -H "Authorization: Bearer $(cat api-key.txt)" \
  -d "$(jq -n \
    --arg model "nvidia/nemotron-3-nano-30b-a3b:free" \
    --arg prompt "$(cat subSDGprompt.txt)" \
    '{model: $model, messages: [{role: "user", content: $prompt}]}')"
```

Figure 6. Overview of model availability (left side: recently released models accessed via Ollama; right side: widely used free models provided through OpenRouter).



All files related to the process have been publicly shared at "https://github.com/HuseyinPARMAKSIZ/DigitalTwinSDGs" to ensure reproducibility and transparency. The prompt template prepared for this process is the "subSDGprompt.txt" file. The classifications obtained, including sub-SDG mappings and associated confidence scores, have been systematically stored and provided in JSON format at the relevant address.

To quantify the consistency of SDG sub-target assignments across different LLMs, we conducted an inter-model reliability assessment. All six models (three local: laguna-xs.2, llama3, mistral; three remote: NVIDIA Nemotron 3 Nano Omni, inclusionAI Ling-2.6-1T, OpenAI gpt-oss-120b) were treated as independent coders. For each of the four focal SDGs (SDG-9, SDG-11, SDG-3, SDG-12), we constructed a 14 (topics) × 6 (models) coding matrix containing the assigned sub-target codes (e.g., “9.5”, “11.2”, “cross”, “not_related”). Cohen’s Kappa is suitable only for two raters; therefore, for six LLMs we employed two chance-corrected agreement statistics:

- Fleiss’ κ (Fleiss, 1971), suitable for multiple raters with nominal categories, interpreted according to Landis & Koch (1977): κ < 0.00 poor, 0.00–0.20 slight, 0.21–0.40 fair, 0.41–0.60 moderate, 0.61–0.80 substantial, 0.81–1.00 almost perfect.

- Krippendorff’s α (Krippendorff, 2018), which handles missing data and arbitrary metric levels; values below 0.667 are considered unreliable, between 0.667 and 0.800 tentative, and above 0.800 acceptable.

Also, we calculated the majority agreement rate – the proportion of topics where at least four out of six models assigned the same sub-target. This served as a conservative threshold for reporting consensus mappings in the main tables (Tables 3-6). All calculations were performed using the `irr` and `DescTools` packages in R with Positron.

3.3. Meso and Micro-Level Thematic Coding

To situate the findings within the broader landscape of established scientific domains, each publication was systematically annotated using Clarivate’s Citation Subjects taxonomy. This hierarchical classification scheme organizes knowledge into two principal levels:

Meso-level categories (e.g., Design and Manufacturing, Telecommunications, Sustainability Science), which capture broad disciplinary fields;

Micro-level areas of expertise (e.g., Industry 4.0, Internet of Things and Edge Computing, Circular Economy), which denote specialized research fronts.

The frequency distributions of these codes across the four focal SDGs (presented in Table 1) reveal distinct disciplinary concentrations and technological emphases within the digital twin literature. To further elucidate the conceptual architecture of the field, co-occurrence networks and thematic landscapes were constructed using VOSviewer. Network generation employed the relationship strength normalization method for link calculation and the fractional counting approach for node weighting, ensuring that the resulting visualizations accurately reflect the relative importance of each term while mitigating biases introduced by multi-authored or multi-keyword publications. The resultant VOSviewer outputs are presented and discussed in Figures 7 through 10 within the Findings section.

4. FINDINGS

In this section, Tables 3-6 present a systematic mapping of DT research to specific SDG sub-goals through an integrative methodology that combines unsupervised topic modeling with multiple LLM semantic evaluations. This approach enhances the interpretability of DT applications, often expressed in highly technical dictionaries, and illuminates their tangible contributions to global sustainability agendas. The analysis focuses on four core SDGs: SDG-9, SDG-12, SDG-11, and SDG-3. First, 14 different thematic topics were extracted from SDG-specific subtexts using parallel LDA on the KNIME analytics platform. Model selection prioritized both statistical robustness and human interpretability, while preprocessing steps such as tokenization, stem word finding, and rigorous stop word extraction were applied to ensure semantic consistency. Each identified topic was represented by the nine most prominent terms and then tagged with the relevant SDG sub-goals using models that we could run on our local computer thanks to the advanced Ollama. Alternative SDG sub-goal mappings were also performed remotely via OpenRouter with the most popular models. All outputs are presented in full compliance with the official UN Sustainable Development Goals classification. Tables (3-6) present the sub-SDG outputs along with the coherence values given by the models as a result of the prompt applied to the models.

The comparative evaluation of LLMs for SDGs sub-target classification highlights significant performance differentials that extend beyond basic accuracy, emphasizing challenges related to instruction adherence, semantic reasoning, and the normative complexities of sustainability science. In this context, models exhibiting stronger semantic consistency and contextual interpretability demonstrated a clear advantage under the established evaluation framework. Under these validated parameters, remotely accessed models such as NVIDIA's Nemotron 3 Nano Omni and OpenAI's gpt-oss-120b demonstrated superior structural and semantic alignment, consistently yielding confidence scores above 0.80. This performance advantage stems from extensive instruction-tuning and exposure to heterogeneous technical corpora, enabling robust disambiguation of polysemous sustainability terminology across diverse policy contexts.

Among locally deployed models, laguna-xs.2 emerged as the most consistent performer across SDG-9, SDG-11, SDG-12, and SDG-3, primarily due to its systematic deployment of cross-SDG flags. This capacity to acknowledge conceptual overlap mitigates analytical over-reductionism and preserves the multidimensional nature of digital twin research, whereas llama3 proved contextually valuable but exhibited domain-specific strengths, showing optimal alignment exclusively within health-related classifications. Conversely, mistral's pronounced conservatism, frequently defaulting to "not_related" despite semantically plausible mappings, renders it insufficient for rigorous sub-SDG taxonomy assignment.

These classification divergences should not be interpreted merely as technical inconsistencies but as epistemological reflections of the conceptual fluidity inherent in sustainability science; for instance, laguna-xs.2's tendency to link healthcare digitalization to innovation targets (SDG-9.5) versus llama3's preference for service delivery frameworks (SDG-3.8) reveals the structural tension between technological enablers and developmental outcomes. Such patterns resonate with mission-oriented innovation theory, which emphasizes the deliberate channeling of technological capabilities toward societally defined challenges rather than siloed technical optimization.

Nevertheless, the integrative breadth of larger remote models carries normative risks: overconfident target assignment without explicit consideration of distributional impacts, participatory governance, or institutional readiness may obscure critical socio-technical questions regarding equity, accessibility, and the systemic conditions required for transformative SDG implementation.

Table 3. Mapping of Digital Twin Research Topics to SDG-9 Sub-Targets (Consensus Across Six LLMs)

	Topic ID	**Consensus SDG-9 Sub-Targets**	**Confidence Range (Min–Max)**	**Cross-SDG Relation**
SDG-9 - Industry Innovation And Infrastructure	topic_0	9.5	0.80-1.00	-
	topic_1	9.b	0.75-0.85	SDG-3 (health)
	topic_2	9.4	0.70-0.80	-
	topic_3	9.5	0.70-0.90	-
	topic_4	9.1/9.4*	0.60-0.82	Model-dependent
	topic_5	9.c	0.60-0.90	-
	topic_6	9.1	0.70-0.80	SDG-11 (cities)
	topic_7	9.4	0.80-0.90	-
	topic_8	9.5	0.60-0.80	-
	topic_9	9.4	0.60-0.85	SDG-7, SDG-12
	topic_10	9.5	0.60-0.80	-
	topic_11	9.4	0.75-0.85	-
	topic_12	9.b	0.74-0.80	SDG-2 (agriculture)
	topic_13	9.1	0.60-0.80	SDG-11 (construction)

For SDG-9, sub-goal 9.5 (improving scientific research and enhancing technological capabilities) is the most frequently assigned target across all models, highlighting digital twins as a driving force for R&D and innovation. This target is particularly represented by terms such as prediction, accuracy, detection (topic_0) and research, analysis, technology (topic_3), which reflect the role of digital twins in accelerating prediction and R&D processes through machine learning. Indeed, Berwanger, Silva, Soares & Coutinho (2023) have demonstrated that digital twin platforms support knowledge-based approaches in engineering design. Local models show varying consistency: while laguna-xs.2 effectively links terms to other SDGs (e.g., healthcare with SDG-3), remote models (Nemotron, gpt-oss-120b) demonstrate higher confidence and stronger alignment with the formal SDG-9 sub-goals. Cross-SDG assignments reveal diverse interpretations of urban digital twins, whereas issues related to digital connectivity and resilient infrastructure (e.g., topic_4: framework, integration, monitoring) are consistently linked to 9.1 and 9.4 – a finding consistent with Masi, Sellitto, Aranha & Pavleska (2023), who emphasized the use of digital twins for cyber-physical security of critical infrastructure. Overall, Table 3 shows a strong consensus on sub-goals 9.5 and 9.4, alongside noteworthy but often overlooked co-benefits for other sustainability areas, which aligns with mission-driven innovation theory.

Table 4. Mapping Topics in Digital Twin Topics to SDG-12 Sub-Targets (Consensus Across Six LLMs)

	Topic ID	Consensus SDG-12 Sub-Targets	Confidence Range (Min–Max)	Cross-SDG Relation
SDG-12 - Responsible Consumption And Production	topic_0	12.2	0.60-0.85	-
	topic_1	12.2	0.75-0.90	-
	topic_2	12.2	0.65-0.80	-
	topic_3	12.2	0.50-0.90	SDG-9 (energy)
	topic_4	12.2	0.66-0.80	SDG-9 (robotics)
	topic_5	12.2	0.70-0.85	-
	topic_6	12.2/12.5*	0.70-0.90	Model-dependent
	topic_7	-	-	SDG-3 (health)
	topic_8	12.2	0.60-0.85	SDG-9 (industry)
	topic_9	12.2	0.70-0.80	-
	topic_10	12.2	0.40-0.85	SDG-6 (water/agriculture)
	topic_11	12.2	0.70-0.85	SDG-11 (cities)
	topic_12	12.2	0.60-0.80	-
	topic_13	12.2	0.70-0.85	SDG-9

For SDG-12 (Responsible Consumption and Production), sub-goal 12.2 (sustainable management and efficient use of natural resources) is the most consistently referenced goal among the models, demonstrating a focus on resource efficiency in production. Differences emerge in the assignment of topics such as Topic_1 (supply chain, logistics, waste); this topic is linked to both 12.3 (food loss) and 12.2 or 12.5 (waste prevention), highlighting the ambiguity between the role of digital twins in waste reduction and their role in resource efficiency. Predictive maintenance topics show varying mappings between 12.4 and 12.5 depending on model interpretation. Links between SDGs are significant; some topics are consistently linked to other SDGs such as SDG-3 (health services) and SDG-6 (water security). Variability in assignments illustrates the methodological complexities involved in classifying sustainability practices. While the models generally consider 12.2 as the primary target, some models, such as llama3, demonstrate domain sensitivity, linking energy-related issues to SDG-9.4. Specifically, different assignments were made to urban infrastructure issues; this reflects the potential of digital twins to enhance both resource efficiency and sustainable urban development. Table 4 shows that the models converge on 12.2 and 12.5, while 12.3 and 12.4 receive moderate attention. Consistent cross-assignments to additional SDGs suggest that digital twin applications can have unexpected positive impacts on health, water, and urban sustainability.

Table 5. Mapping Topics in Digital Twin Research Topics to SDG-11 Sub-Targets (Consensus Across Six LLMs)

	Topic ID	Consensus SDG-11 Sub-Targets	Confidence Range (Min–Max)	Cross-SDG Relation
SDG-11 - Sustainable Cities And Communities	topic_0	11.6	0.80-0.90	SDG-9 (energy in buildings)
	topic_1	-	-	Weak consensus, focus on SDG-9
	topic_2	-	-	Weak consensus, SDG-9 / SDG-3
	topic_3	11.2	0.65-0.80	-
	topic_4	11.5	0.80-0.90	-
	topic_5	-	-	Weak consensus, SDG-9 / SDG-11.b
	topic_6	11.b/11.6*	0.60-0.75	Model-dependent
	topic_7	11.1/11.2	0.60-0.84	SDG-9 (structural health)
	topic_8	11.2	0.80-0.95	-
	topic_9	11.3/11.6	0.60-0.80	SDG-9 / SDG-12
	topic_10	-	-	Very low trust, the majority are indifferent
	topic_11	11.6	0.75-0.85	SDG-12 (circular economy)
	topic_12	-	-	Weak consensus, focus on SDG-9
	topic_13	11.2	0.75-0.90	SDG-7 / SDG-9 (batteries)

For SDG-11 (Sustainable Cities and Communities), various sub-targets reflect urban sustainability's complexity, with 11.2 (sustainable transport) and 11.6 (environmental impact reduction) being most prominent. High confidence scores indicate consensus that digital twins enhance urban mobility. Divergence is noted in the assignment of building energy efficiency to either 11.6 or SDG-9, pointing to differing interpretations. Cross-SDG relationships are common, highlighting connections between urban infrastructure and industrial innovation. Models like laguna-xs.2 demonstrate strong cross-SDG flagging, while others exhibit varied interpretations. Notably, the application of metaverse technologies for transport planning is debated, further emphasizing the intricate nature of urban sustainability. Table 5 shows that the consensus generally ranges between 11.2 and 11.6; these figures have significant links to SDG-9 and reflect the interplay between urban sustainability and industrial progress.

Table 6. Mapping Topics in Digital Twin Research Topics to SDG-3 Sub-Targets (Consensus Across Six LLMs)

	Topic ID	Consensus SDG-3 Sub-Targets	Confidence Range (Min–Max)	Cross-SDG Relation
SDG-3 Good Health And Well-Being	topic_0	-	0.20-0.80	Almost all models are uninterested
	topic_1	3.4	0.70-0.90	-
	topic_2	-	0.28-0.80	Weak consensus, SDG-9/SDG-3.d
	topic_3	3.8/3.b*	0.80-0.90	SDG-9 (biomechanical)
	topic_4	3.8	0.50-0.80	SDG-9 (robotics)
	topic_5	3.8/3.b	0.70-0.80	-
	topic_6	3.3/3.d	0.40-0.80	SDG-6 (water)
	topic_7	3.3	0.80-0.95	-
	topic_8	3.4	0.60-0.90	-

	topic_9	3.4	0.70-0.80	-
	topic_10	-	0.20-0.70	Almost all models are uninterested
	topic_11	-	0.20-0.90	Weak consensus, focus on SDG-9
	topic_12	3.4	0.60-0.84	-
	topic_13	3.4/3.d	0.20-0.80	SDG-11 (urban health)

For SDG-3 (Good Health and Well-being), the most frequently assigned sub-targets are 3.4 (reduce mortality from non-communicable diseases) and 3.8 (universal health coverage). Topics related to cardiac care (topic_1), cancer (topic_8), respiratory support (topic_9), and metabolic conditions (topic_12) are consistently mapped to these targets, with high confidence scores across most models. Remote models and laguna-xs.2 show strong agreement, while mistral again frequently defaults to not_related. Cross-SDG flags are notable: topic_3 (biomechanical, implants) and topic_2 (network, computing) are linked to SDG-9, and topic_6 and topic_13 show cross-relations to SDG-6 (water) and SDG-11 (cities), respectively. Pandemic-related topics (topic_7) are almost unanimously assigned to 3.3 (communicable diseases). Table 6 shows that the consensus centers on 3.4 and 3.8, with cross-connections to SDG-9, SDG-6, and SDG-11, illustrating the interconnected nature of digital health innovations with industrial, environmental, and urban systems.

Among the locally deployed models, laguna-xs.2 stands out for its systematic use of cross-SDG flags, revealing how digital twin research often contributes simultaneously to multiple sustainability goals. For instance, topic_1 (healthcare, health, patient, personalized) is primarily assigned to SDG-9.5 (innovation capacity) but flagged as cross-related to SDG-3.8 (universal health coverage). This dual alignment reflects the observation by Björnsson et al. (2019) that medical digital twins not only improve personalized health outcomes but also strengthen innovation infrastructure. Similarly, topic_6 (urban, cities, planning, water) is mapped to SDG-9.a (technology support for sustainable development) with a cross-flag to SDG-11.2 (sustainable transport systems), consistent with Deren, Wenbo & Zhenfeng (2021), who emphasized that digital twins in smart city planning simultaneously enhance technological infrastructure and urban mobility. Another illustrative case is topic_10 (water, agriculture, sensor, farming), which laguna-xs.2 assigns to SDG-12.2 (resource efficiency) while flagging SDG-6 (clean water). This aligns with Petri et al. (2025), who demonstrated that dynamic life cycle assessment via digital twins contributes to both resource efficiency and water access. These cross-linkages, which other local models (llama3, mistral) capture only sporadically or not at all, underscore the added value of cross-flag-aware models for revealing the multi-dimensional sustainability impacts of digital twins – a finding that directly supports mission-oriented innovation theory, where technological solutions are expected to generate co-benefits across policy domains.

Table 7 summarizes the agreement among the six LLMs for each SDG. Overall, agreement levels ranged from poor to fair. SDG-9 achieved the highest consensus (Fleiss' $\kappa = 0.234$, Krippendorff's $\alpha = 0.236$), while SDG-12 showed negative agreement ($\kappa = -0.040$, $\alpha = -0.038$), indicating performance worse than chance. Majority agreement (≥4 models) was also modest, ranging from 21.4% (SDG-11) to 42.9% (SDG-9). These results suggest that mapping digital twin topics to SDG sub-targets remains inherently ambiguous, particularly for SDG-3, SDG-11, and SDG-12. Consequently, we adopted a conservative reporting strategy: only topics with majority agreement (≥4 models) are presented in the main tables; all individual model outputs are available in the supplementary files.

Table 7. Inter-Model Agreement Statistics Across Six LLMs

SDG	Fleiss' κ	Krippendorff's α	Majority agreement (≥4/6 models)
SDG-9	0.234 (Fair)	0.236	42.9% (6/14 topics)
SDG-11	0.077 (Slight)	0.079	21.4% (3/14)
SDG-3	0.102 (Slight)	0.104	28.6% (4/14)
SDG-12	-0.040 (Poor)	-0.038	35.7% (5/14)
Note: Fleiss' κ interpreted following Landis & Koch (1977); Krippendorff's α thresholds from Krippendorff (2018).			

From a socio-technical perspective, classification trends indicate a persistent gap between technology and societal transformation. Models often associated infrastructure-related terms with SDG targets but neglected the associated institutional, participatory, or equity aspects. This reflects a methodological challenge in sustainability informatics: LLMs trained predominantly on technical literature may overlook crucial normative and procedural dimensions, thus reproducing a bias favoring efficiency over justice. The underutilization of prompt fields designed to capture ambiguity or cross-cutting implications indicates that current prompt engineering might inadequately support reflexive reasoning needed for navigating the norms of SDG implementation.

Future classification frameworks should incorporate explicit criteria for evaluating distributive impacts, participatory design elements, and institutional readiness to better align analytical efforts with the goals of mission-oriented innovation policy. Researchers utilizing LLMs for sustainability classification should consider several strategic approaches: employing ensemble methods to combine predictions and reduce individual biases, developing dynamic confidence thresholds tailored to specific SDG domains, and implementing human-in-the-loop validation processes. Recognizing model divergences as opportunities for scholarly dialogue and policy refinement could transform classification uncertainties into constructive resources. While LLM-based frameworks aim to provide accurate classifications, their true value lies in developing systematic, transparent, and repeatable interactions with the complex task of aligning technological innovation with societal and planetary well-being. This requires both algorithmic sophistication and critical thinking on the foundations of sustainable development.

Alongside the detailed insights obtained from topic modeling and LLM-based sub-goal mapping, co-occurrence network visualizations produced by VOSviewer (Figures 7-10) provide a comprehensive, topology-oriented view of the conceptual framework of DT research in relation to each SDG. The maps, derived from bibliometric keyword co-occurrence data obtained from WoS-indexed publications, illustrate thematic density, semantic proximity, hierarchical clustering, and cross-domain interconnections that contextualize and enhance the micro-level topic assignments shown in Table 1.

Figure 7 (SDG-9) displays a theme network visualization obtained from Web of Science-indexed digital twin research, created using VOSviewer. The core element, "digital twin," is intricately linked with essential facilitators of sustainable industrial transformation, such as smart manufacturing, Industrial IoT (IIoT), and cyber-physical systems (CPS). These clusters have a high co-occurrence with essential operational topics, including predictive maintenance, digital simulation, and AI-driven process management, highlighting the significance of digital twins in improving industrial efficiency, resilience, and sustainability. The significance of concepts like "innovation ecosystems" and "technology transfer" indicates a systemic emphasis on information dissemination and collaborative research and development, directly corresponding with SDG-9.5 ("Enhance scientific research, upgrade technological capabilities… in all countries"). This congruence has been regularly corroborated by iterative LLM-based adjudication, enhancing the methodological rigor of the thematic mapping. The visualization elucidates contextual connections to Industry 4.0/5.0, machine learning, big data, and BIM, demonstrating how digital twin technologies function as integrative platforms for interdisciplinary innovation, thus promoting industrial modernization and broader sustainable development goals under SDG-9.

Hwang, Puntha, and Jitanugoon (2025) demonstrate that, from a socio-technical systems perspective, AI-enabled transformation enhances circular economy capacity through collaboration-based cognition and knowledge integration, and that these mechanisms produce sustainable innovation outcomes that directly contribute to SDG-9 (Industry, Innovation and Infrastructure), SDG-12 (Responsible Consumption and Production) and SDG-13 (Climate Action).

Figure 7. VOSviewer visualization of key sustainability themes underpinning SDG-9 in Web of Science-indexed digital twin research

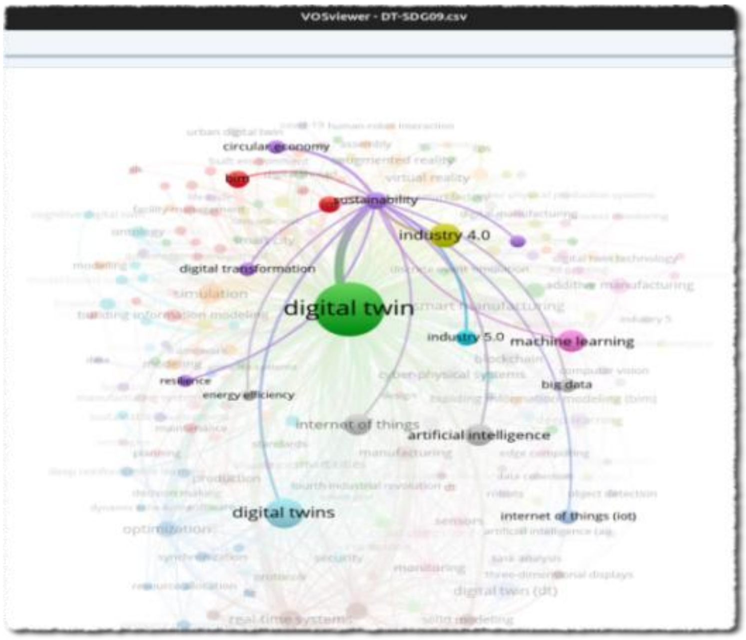
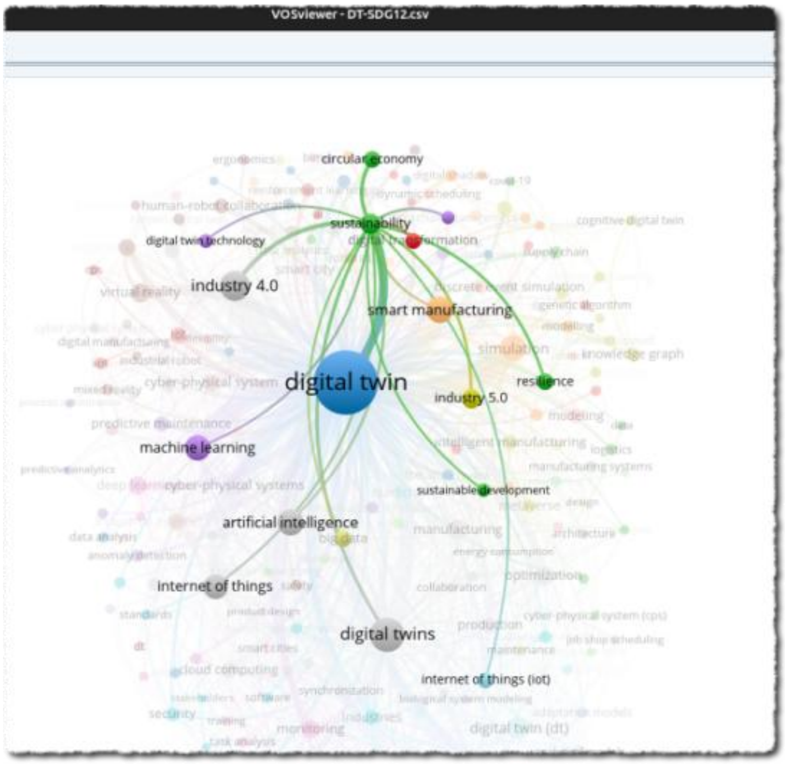


Figure 8 illustrates research on digital transformation in relation to SDG-12 (Responsible Consumption and Production), revealing a highly interconnected, polycentric network structured around three principal thematic clusters. The first cluster, Circular Economy and Resource Efficiency, encompasses concepts such as circular economy, resource efficiency, lifecycle assessment, and waste reduction. The second, Smart Manufacturing and Industrial Sustainability, includes smart manufacturing, intelligent manufacturing, production optimization, and sustainable development. The third cluster, Digital Enablers and System Integration, comprises digital twin, cyber-physical systems (CPS), artificial intelligence, machine learning, and Industry 5.0. The "digital twin" node occupies a position of high centrality, connected by strong, weighted edges to all three clusters, underscoring its dual role not merely as a discrete technological artifact but as an integrative platform that mediates operational efficiency, environmental stewardship, and systemic innovation. Peripheral yet semantically salient nodes, such as predictive maintenance, sustainability information, and knowledge graphs, demonstrate how digital twins augment data-driven decision-making across product lifecycles, thereby directly supporting SDG-12's Target 12.5, which calls for minimizing waste through prevention, reduction, recycling, and reuse.

This topological configuration corroborates key findings from the topic modeling phase: for instance, topic_1 ("supply chain, sustainable, logistics, waste") and topic_11 ("circular, construction, economy, waste") are visually embedded within the "circular economy" cluster, while topic_0 ("digital, model, system, process, intelligent") aligns with the "smart manufacturing" core. Moreover, the emergence of Industry 5.0 and human–robot collaboration signals a paradigmatic shift toward human-centered, adaptive, and ethically attuned industrial systems, an evolution not explicitly codified in the official SDG-12 targets but increasingly vital to their effective implementation. Thus, Figure 7 transcends mere thematic representation; it elucidates the structural interdependencies and conceptual synergies that position DT technologies as pivotal enablers of systemic sustainability transformation, bridging technical innovation with planetary boundaries and socio-economic equity.

Figure 8. VOSviewer visualization of key sustainability themes underpinning SDG-12 in Web of Science-indexed digital twin research



When examining initiatives aligned with SDG-11 (Sustainable Cities and Communities), one observes a strong interconnection with key domains such as sustainability science, smart city development, artificial intelligence applications, the circular economy framework, and the integration of digital twin technologies. Figure 9 (SDG-11) illustrates a polycentric framework in which smart city infrastructure serves as a connective nexus among urban resilience, sustainable mobility, energy-efficient buildings, and disaster risk mitigation. The conjunction of digital twin technology with urban metabolism and participatory planning indicates a transition towards comprehensive, data-driven urban governance, aligning topic_4 (urban planning and disaster resilience) with SDG-11.5 and topic_8 (autonomous traffic systems) with SDG-11.2.

Figure 9. VOSviewer visualization of key sustainability themes underpinning SDG-11 in Web of Science-indexed digital twin research

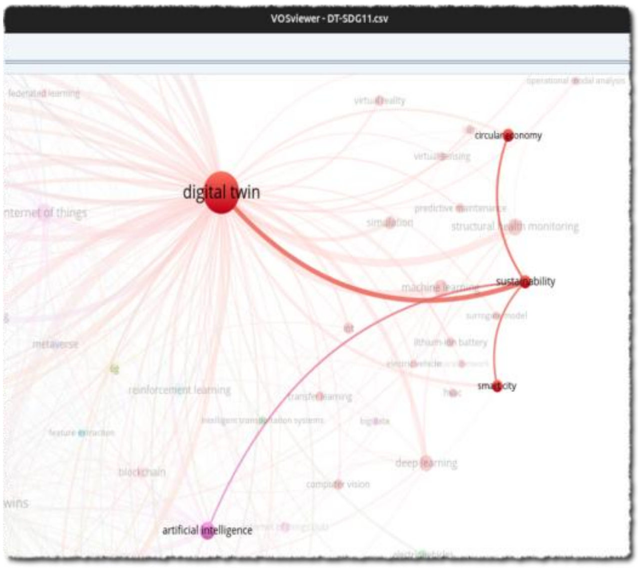
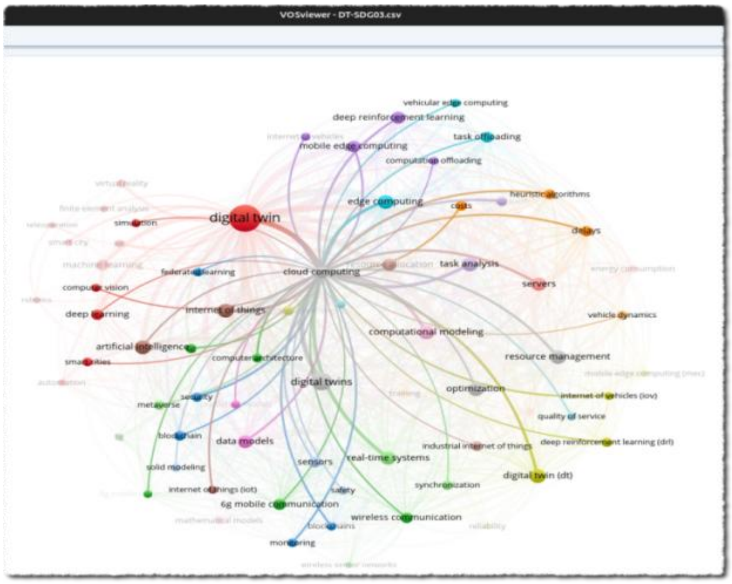


Figure 10 depicts the theme landscape of digital twin research in relation to SDG-3, as represented by VOSviewer based on publications indexed in WoS. The semantic network is clinically centered on fundamental topics, including personalized care, patient-specific modeling, telehealth, and medical simulation. These are bolstered by additional clusters focusing on pandemic response systems, healthcare resource optimization, and clinical decision support, illustrating the increasing incorporation of digital twins into actual healthcare delivery.

The significant co-occurrence of "digital twin" with phrases such as "AI," "deep learning," "computational modeling," and "real-time systems" validates the technology's function in facilitating data-driven, predictive, and adaptive healthcare interventions. This thematic coherence bolsters high-confidence LLM-based allocations to SDG-3.4 (“Reduce premature mortality from non-communicable diseases”) and SDG-3.8 (“Achieve universal health coverage”), especially via the improvement of diagnostic accuracy, treatment customization, and systemic resilience. Collectively, these visual thematic maps not only corroborate the results from our computational linguistics pipeline but also reveal inter-SDG synergies, such as the intersection between SDG-11 and SDG-12 regarding circular urban infrastructure, or between SDG-9 and SDG-3 concerning AI-enabled medical devices, thereby underscoring the cross-cutting potential of Digital Twin technologies in furthering the 2030 Agenda.

From a Mission-Oriented Innovation (MOI) perspective, digital twin systems can be understood as enabling infrastructures that operationalize SDG localization, particularly in relation to SDG-17 (Partnerships for the Goals), SDG-9 (Industry, Innovation and Infrastructure), and SDG-11 (Sustainable Cities and Communities) by supporting data-driven coordination, multi-stakeholder alignment, and system-level experimentation within place-based transformation processes (Boorman, Jackson, & Burkett, 2023).

Figure 10. VOSviewer visualization of key sustainability themes underpinning SDG-3 in Web of Science-indexed digital twin research



This network topology demonstrates the high interconnectivity between the circular economy (CE), smart manufacturing, and digital enablers, showing that digital twins are not merely technical optimizers but also system integrators that support closed-loop control and resource optimization, as proposed by Sajadieh & Noh (2025) within the framework of the “Digital Twin Nexus”. This aligns with the theory of socio-technical systems formulated by Geels (2004): the transformative impact of digital twins arises from the interaction between technological components and organizational and environmental factors.

5. CONCLUSION, DISCUSSIONS AND POLICY RECOMMENDATIONS

Emerging as one of the advanced instruments of the digital transformation era, Digital Twin technologies are increasingly playing a pivotal role in the planning and implementation of the SDGs by enabling real-time monitoring, simulation, and predictive analytics of complex socio-technical systems.

A growing body of literature substantiates this assertion, highlighting not only the technological dimension's decisive influence in dynamically managing industrialization processes but also emphasizing strategic alignment, change management, skill development, job security, and environmental compatibility as critical variables for sustainability and inclusivity (Sharma & Gupta, 2024). By establishing a dynamic linkage between physical systems and their digital representations, Digital Twins facilitate more integrated and data-driven decision-making, particularly in domains such as industry, urban development, healthcare, and resource management, thereby enhancing the overall efficacy of SDG-oriented initiatives. Within this broader context, systematically elucidating the relationship between the Digital Twin literature and the SDGs has become a matter of significant scholarly and practical importance.

This study explores the relationship between Digital Twin research and the SDGs using an analytical framework that combines topic modeling and multi-LLM evaluation. The research identifies a strong focus in the Digital Twin literature on four specific SDGs: Industry, Innovation, and Infrastructure (SDG-9), Sustainable Cities and Communities (SDG-11), Responsible Consumption and Production (SDG-12), and Good Health and Well-being (SDG-3). These domains demonstrate how Digital Twins contribute to sustainability initiatives ranging from industrial transformation and smart governance to circular economy practices and personalized healthcare. There is a strong link between SDGs, and efforts made for one can serve multiple SDGs (Nilsson et al, 2016). The fact that Digital Twins require technological infrastructure to be created indirectly contributes to efforts for other SDGs (including SDG-9). This explains why the strongest focus in the literature is on Industry, Innovation and Infrastructure (SDG-9). The study conducted by Menon et al. (2024) has a direct link to SDG-11 and SDG-12, as well as an indirect link to SDG-9, and the study conducted by Guidani et al. (2024) focuses on SDG-2 and SDG-12 while also having an indirect link to SDG-8, exemplifying this situation. Furthermore, as a result of digital twins first emerging in the manufacturing industry (Boschert & Rosen 2016), Responsible Consumption and Production (SDG-12) has been one of the most studied topics. However, a key limitation is that Digital Twin research is not evenly distributed across all 17 SDGs, highlighting a selective engagement where many goals are underrepresented. In line with Yang et al. (2025), this study reveals that, despite the increasing focus on technology-driven research within the framework of SDG-11, social dynamics have been relatively neglected. Consequently, the findings emphasize that Digital Twins should be regarded not merely as a tool for operational efficiency, but also as key drivers of sustainability-focused socio-technical transformations. This perspective positions Digital Twins as integrative instruments that bridge physical systems, data infrastructures, organizational routines, and policy aims, suggesting a need for broader engagement with the SDGs in future research.

Current findings indicate that research on digital twins is concentrated around SDG-9 (Industry, Innovation and Infrastructure; n = 3,703) and SDG-12 (Responsible Consumption and Production; n = 3,321), whilst social objectives such as SDG-1 (No Poverty), SDG-5 (Gender Equality) and SDG-10 (Reduced Inequalities) occupy an extremely limited space in the literature (Gao, Zhuang & Geng, 2026). This asymmetry observed across the goals reflects not merely a bibliometric distribution pattern but also a multi-layered epistemological situation pointing to the historical roots of digital twin technology, the institutional political economy of knowledge production, and the structural tendencies of digital capitalism. The dominance of SDG-9 in the findings stems largely from the foundational link between digital twins and the manufacturing industry. Indeed, Boschert and Rosen (2016) demonstrate that this technology was conceptualized within mechatronic simulation processes, whilst subsequent bibliometric studies (Fuller et al., 2020; Tao, Zhang, Liu, & Nee, 2019) document that the volume of publications has multiplied rapidly since 2016. Consequently, the fact that SDG-9 dominates the literature to such an extent in its intersection with digital twin research reflects the direct impact of the technology's sectoral emergence on scientific knowledge; interpreting this situation merely as a prioritization of academic interest could lead to an analytical fallacy.

To interpret this pattern at a deeper critical level, it is necessary to draw upon both the mission-oriented innovation theory (Mazzucato, 2018) and the socio-technical systems perspective (Geels, 2004). Mazzucato (2018) emphasizes that the SDGs should be conceived not merely as targets for technical efficiency, but as multi-stakeholder and transformative missions. However, the vast majority of the digital twin literature remains centered on technical optimization and industrial simulation, thereby limiting this transformative potential. Geels (2004), on the other hand, argues that technological change can only lead to a lasting socio-technical transformation when it evolves in tandem with the institutional environment, normative structures and actor practices. Viewed from this perspective, the fact that digital twins remain confined to the axes of productive efficiency and resource management within the framework of SDG-9 and SDG-12 is indicative of the manner in which technology is integrated into the existing capitalist mode of production. In other words, digital twins are deployed in a manner that reinforces the current logic of rent accumulation within 'digital capitalism'. Indeed, the dominance of micro-categories such as smart manufacturing, supply chain optimization and Industry 4.0 both reflects and legitimizes the integration of technology into value-creation processes within capital-intensive sectors. In this context, the lack of visibility of SDG-1, SDG-5 and SDG-10 in the literature raises a political question regarding whose needs are prioritized in research funding and technology development practices, and demonstrates that issues such as poverty, gender inequality and income inequality are rendered virtually invisible by the digital twin research agenda.

The contribution of this situation to the social sciences is evident on at least two levels. Firstly, there is the issue of the digital divide: Tzachor et al. (2022, p. 824) emphasise that access to digital twin technology remains structurally limited in low-income countries where digital infrastructure is inadequate, and that this condition directly contradicts the SDGs' 'leave no one behind' principle. This finding aligns with studies showing that digital inequalities are further exacerbated by gender. Globally, men's internet access rates lag behind women's by approximately five percentage points, and this inequality is far more pronounced in low-income countries (UN Women, 2024). Research indicates that factors such as limited access to technology, gender stereotypes and economic barriers deepen the digital gender divide, and that current digital inclusion strategies are insufficient to reduce this inequality. Consequently, the fact that digital twin research overlooks SDG-5 and SDG-10 suggests that these technologies are not neutral in terms of equality; rather, they carry the risk of reproducing historical disadvantages.

Secondly, there is the issue of policy-research alignment: inconsistencies in digital twin policies at the national level and gaps in the supply environment constitute a significant barrier to SDG success, and there is a serious gap in research into the links between national policy, digital twins, and SDG success. As the scope of digital twin applications expands from a manufacturing-centric origin towards the socio-technical domain, a distinct gap is emerging between social requirements and the technical infrastructure of these technologies. This gap gives rise to significant research challenges regarding the adoption of socio-technical design methods and the addressing of various epistemological concerns. The unique contribution of the social sciences to this debate becomes particularly evident at this juncture. As in this research, questioning not merely the technological capacity but for whom, under what institutional conditions, and within what power relations that capacity is designed represents an epistemic shift that moves digital twin research from an engineering paradigm to a social science paradigm.

Digital Twin research primarily focuses on technology, revealing limited intersections with social dimensions of the SDGs, such as No Poverty (SDG-1), Gender Equality (SDG-5), and Reduced Inequalities (SDG-10). This predominance of technical themes underlines a gap in addressing vital issues like social inequality and poverty alleviation, as supported by existing literature (Tzachor et al., 2022, p. 824). Consequently, it is proposed that Digital Twins be reconceptualized as socio-technical systems that must integrate social, ethical, and institutional contexts (Sony & Naik, 2020; Yu, Xu, & Ashton, 2023). The study highlights that while SDGs centered on technology are represented, goals related to social and institutional dimensions are marginalized. The findings indicate that infrastructure-driven SDGs cannot achieve meaningful impact without inclusive governance (SDG-16) and equity-focused policies (SDG-10). For instance, smart city applications may exacerbate spatial inequalities unless inclusivity is prioritized. This risk is particularly acute in the transport sector, where unplanned technological integration can favor motorized vehicle owners over public transit users. As Joshi, Vaidya & Deshmukh (2017) observe in the Indian context, land is a precious resource, and simply building more roads to meet the doubling rate of personal motor-vehicle ownership is not a sustainable solution; rather, a well-designed, technology-enabled transport system must be coupled with governance frameworks that ensure equitable access. Therefore, digital twin deployments for SDG-11.2 must go beyond traffic optimization to include participatory design elements (aligned with SDG-16) to prevent deepening existing socio-economic divides. Similarly, climate-focused Digital Twins must rely on robust institutional frameworks to be effective. As such, a critical future research agenda is proposed to connect technological advancements with comprehensive governance and human well-being considerations essential for the achievement of the SDGs.

Building on empirical insights, this study proposes integrated policy recommendations to improve the sustainability impact of digital twin initiatives. Policymakers should adopt an integrative SDG governance approach that connects technology-oriented goals (SDG-9 and SDG-11) with social and institutional SDGs (SDG-10 and SDG-16) to prevent technological advancement from outpacing governance and worsening socio-economic disparities. Digital twin deployments in the public sector should follow human-centered and participatory design principles to ensure inclusivity and representation (SDG-5 and SDG-10) from the outset. Authorities are encouraged to establish cross-SDG impact assessment frameworks to evaluate the systemic effects of digital twins on multiple sustainability objectives.

Our model results indicate that digital twin research is primarily focused on technological targets such as SDG-9.5 (R&D capacity) and SDG-12.2 (resource efficiency). Therefore, policymakers are encouraged to establish tax incentives or grant programs to promote digital twin-based R&D projects (SDG-9.5), mandate the use of digital twins in industrial symbiosis and waste reduction projects (SDG-12.5), and develop privacy-protected data governance frameworks that support the integration of federated learning in smart city applications (SDG-11.b) (Ramu et al., 2022). These measures are also consistent with the digital twin maturity path for circular manufacturing proposed by Sajadieh & Noh (2025).

Without sustained investment in capacity building, regulatory readiness, and organizational learning, the transformative potential of digital twins may remain underutilized, limiting their role in achieving inclusive and resilient development pathways. The LLM-based evaluation framework utilized in this study offers a scalable method for analyzing emerging technological trends in the sustainability context. By processing a vast corpus of scholarly publications, this research provides a timely, data-driven perspective on the thematic orientation of the field, making it a valuable resource for future research and evidence-informed policy design leading up to 2030.

Like any scholarly inquiry, this study is subject to several limitations. First, the reliance exclusively on the WoS database constrains the scope of the literature surveyed, potentially omitting relevant research indexed in other academic repositories. Second, the selection of LLMs was constrained by the computational resources available for local deployment; consequently, only models compatible with our hardware specifications were utilized. Due to limited access to high-memory RAM and GPU infrastructure, we were unable to train or fine-tune domain-specific LLMs tailored to sustainability or Digital Twin contexts. Additionally, international dissertation databases such as ProQuest were not incorporated into the corpus, which may have excluded valuable doctoral-level insights and emerging perspectives from graduate research. While these constraints reflect practical realities of resource availability, they also delineate avenues for methodological refinement in future studies.

A further methodological limitation concerns the low inter-model agreement in the SDG sub-target mapping process. As detailed in Section 3.2, we assessed consistency among the six LLMs using Fleiss' κ and Krippendorff's α. The results (reported in Table 7) showed only fair to slight agreement for most SDGs: SDG-9 ($\kappa = 0.234$, $\alpha = 0.236$), SDG-11 ($\kappa = 0.077$, $\alpha = 0.079$), SDG-3 ($\kappa = 0.102$, $\alpha = 0.104$), and SDG-12 ($\kappa = -0.040$, $\alpha = -0.038$). According to Krippendorff's threshold ($\alpha \geq 0.667$ for acceptable reliability), these values are substantially below the acceptable range. Several factors explain this low agreement. First, the architectural diversity of the six models (ranging from 7B to 120B parameters, with different training corpora and fine-tuning objectives) leads to divergent interpretations, especially for topics involving cross-cutting SDG relationships (e.g., "cross" codes). Second, the inherent subjectivity of SDG classification means that even human experts often disagree on whether a digital twin application primarily serves SDG-9 (innovation) or another SDG (e.g., SDG-3 for healthcare, SDG-11 for cities). Third, the sparse category space – with more than ten possible sub-targets per SDG but only 14 topics per SDG – makes chance-corrected statistics highly sensitive to random disagreement.

Consequently, the consensus-based mappings presented in Tables 3–6 should be interpreted as exploratory hypotheses rather than definitive classifications. To mitigate this limitation, we adopted a conservative reporting threshold (majority vote ≥4 out of 6 models) and have made all raw model outputs publicly available at "https://github.com/HuseyinPARMAKSIZ/DigitalTwinSDGs".

Looking forward, two complementary directions for future research emerge. First, to improve mapping reliability, subsequent studies should incorporate human expert validation, ensemble methods, or fine-tuned domain-specific LLMs. Second, to address the substantive gaps beyond methodological concerns, future research should establish interdisciplinary teams to investigate the social dimensions of Digital Twins more rigorously. Moreover, adapting the LLM-based evaluation framework developed in this study to other emerging technology domains, such as artificial intelligence, blockchain, and green hydrogen, could significantly contribute to the targeted and effective shaping of science, technology, and innovation (STI) policies during the remaining period of the 2030 Agenda. In this context, Fankhauser & Clematide (2024) demonstrate that parameter-efficient fine-tuned, double-quantized LLMs are highly effective in classifying scientific abstracts according to SDGs, improving computational efficiency while reducing processing time. They further show that the Decompose-Synthesize-Refine-Extract (DSRE) framework enhances interpretability for longer documents through intermediate reasoning steps and supports ongoing efforts in multi-label classification via DSRE-based pre-annotation to assist human coding processes.

Finally, the methodology presented herein serves not only as a tool for assessing Digital Twin research but also as a transferable reference model for evaluating the sustainability impacts of any technological innovation, thereby offering a scalable and systematic approach to aligning technological advancement with global sustainability imperatives.

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Supplementary Information for extended Table 1

SDG Number	Citation Topics Meso (Number of Research Articles)	Citation Topics Micro (Number of Research Articles)
SDG-9 - Industry Innovation And Infrastructure (3703)	Design & Manufacturing (3362), Nanofibers, Scaffolds & Fabrication (120), Distributed & Real-Time Computing (87), Sustainability Science (60), Telecommunications (21), Climate Change (20), Management (19), Geometrical Optics (4), Social Reform (3), Economics (2), Operations Research & Management Science (2), Economic Theory (1), Political Science (1), Risk Assessment (1)	Industry 4.0 (2951), Digital Construction (411), Additive Manufacturing (120), Software Defined Networking (65), Circular Economy (25), Life Cycle Assessment (24), Cloud Resource Scheduling (22), Satellite-terrestrial Integration (21), Stormwater Management (20), Sharing Economy (9), Renewable Energy Transition (6), Carbon Mitigation (5), Wireless and Free-space Optics (4), Innovation Strategies (4), Corporate Social Responsibility (4), Urban Underground Space (3), Foresight (2), Data Envelopment Analysis (1), Finance-growth Nexus (1), Antitrust (1), Defense Economics (1), University-industry Collaboration (1), Performance Management (1), Strategic Adaptation (1)
SDG-12 Responsible Consumption And Production (3321)	Design & Manufacturing (2951), Supply Chain & Logistics (125), Manufacturing (98), Sustainability Science (61), Polymer Science (18), Metallurgical Engineering (16), Mineral & Metal Processing (15), Management (14), Ionic, Molecular & Complex Liquids (7), Concrete Science (4), Bioengineering (3), Agricultural Policy (3), Ceramics (2), Spectrometry & Separation (1), Herbicides, Pesticides & Ground Poisoning (1), Paper & Wood Materials Science (1), Social Psychology (1)	Industry 4.0 (2951), Advanced Machining (98), Manufacturing Scheduling (81), Supply Chain Optimization (44), Circular Economy (25), Life Cycle Assessment (24), Alloy Solidification (14), Sustainable Ironmaking (13), Injection Molding (12), Sharing Economy (9), Reactive Distillation (7), Municipal Solid Waste (7), Carbon Mitigation (5), Lean Manufacturing (5), Advanced Concrete (4), Chemical Recycling (3), Polymer Crystallization (3), Anaerobic Digestion (3), Dietary Sustainability (2), Ceramic Waste Utilization (2), Metal Matrix Composites (2), Steelmaking Slag Dynamics (2), Solvent Extraction (1), Microplastics (1), Paper Properties (1), Food Sovereignty (1), Pro-environmental Behavior (1)
SDG-11 Sustainable Cities And Communities (1739)	Telecommunications (503), Sustainability Science (230), Testing & Maintenance (210), Transportation (130), Electrochemistry (105), Automation & Control Systems (73), Supply Chain & Logistics (54), Robotics (51), Climate Change (41), Concrete Science (36), Power Systems & Electric Vehicles (35), Knowledge Engineering & Representation (35), Geotechnical Engineering (35), Mechanics (35), Metallurgical Engineering (30), Oceanography, Meteorology & Atmospheric Sciences (16), Hospitality, Leisure, Sport & Tourism (14), Distributed & Real Time Computing (13), Nuclear Fusion (11), Environmental Sciences (11), Combustion (10), Nuclear Engineering (10), Management (9), Energy & Fuels (7), Forestry (5), Remote Sensing (5), Explosives (4), Art (3), Social Reform (3), Geochemistry, Geophysics & Geology (3), Computer Vision & Graphics (2), Electrical - Harvesting & Discharging (2), Modelling & Simulation (2), Sensors & Tomography (2), Herbicides, Pesticides & Ground Poisoning (1), Agricultural Policy (1), Human Geography (1), Thermodynamics (1)	IoT And Edge Computing (401), Damage Detection (175), Building Energy Efficiency (165), Lithium-ion Battery (105), Traffic Flow (73), UAV Communications (69), Vehicle Routing Problem (42), Simultaneous Localization And Mapping (37), Electric Vehicles (35), Composite Damage Mechanics (35), Wheel-rail Contact (34), Fatigue Crack Growth (30), Multi Agent Systems (28), Vehicular Ad Hoc Networks (25), Circular Economy (25), Volunteered Geographic Information (24), Life Cycle Assessment (24), Evacuation Modeling (20), Stormwater Management (20), Rock Mechanics (20), Adaptive Control (18), Seismic Masonry (18), Urban Heat Island (16), Urban Mobility (15), Multibody Systems (14), Vehicle Dynamics Control (13), Warehouse Optimization (12), Climate Change Adaptation (12), Traffic Safety (11), Real-time Systems (11), Crowdsourcing And Crowdsensing (11), Tokamak Dynamics (11), Soil-structure Interaction (11), Ultimate Strength (10), Fire Dynamics (10), Nuclear Reactor Neutronics (10), Urban Green Spaces (9), Sharing Economy (9), Gesture Recognition (8), Wireless Localization (8), Seismic Concrete Structures (8), Air Transport Systems (7), Municipal Solid Waste (7), Spontaneous Combustion (7), Air Pollution (7), Visual Servoing (6), Renewable Energy Transition (6), Ecosystem Services (5), Light Pollution (5), Tourism Impacts (5), Train Scheduling (4), Environmental Justice (4), Pipeline Integrity (4), Impact Dynamics (4), Atmospheric Aerosols (4), Architectural Identity (3), Energy Security (3), Urban Underground Space (3), Earthquake Dynamics (3), Video Object Tracking (2), Distributed Storage Systems (2), Water Resource Optimization (2), Water Governance (2), Composite Insulators (2), Musical Acoustics (2), Seismic Inversion (2), Microplastics (1), Climate Security (1), Food Sovereignty (1), Urban Politics (1), Cable Stayed Bridges (1), Solar Desalination (1)
SDG-3 Good Health And Well-Being (1081)	Telecommunications (401), Chromatography & Electrophoresis (68), Computer Vision & Graphics (49), Cardiac Arrhythmia (40), Robotics (37), Climate Change (25), Cardiology - General (19), Safety & Maintenance (18), Nursing (15), Assisted Ventilation (15), Knowledge Engineering & Representation (14), Numerical Methods (14), Drug Delivery Chemistry (13), Environmental Sciences (13), Diabetes (11), Molecular & Cell Biology - Genetics (11), Sensors & Tomography (11), Back Pain (10), Neuroscanning (10), Microfluidic Devices & Superhydrophobicity (9), Hospitality, Leisure, Sport & Tourism (9), Orthopedics (8), Urology & Nephrology - General (8), Gait & Posture (8), Social Reform (8), Brain Imaging (7), Prostate Cancer (7), Nutrition & Dietetics (7), Obstetrics & Gynecology (7), Virology - General (6), Strokes (6), Hearing Loss (6), Medical Ethics (6), Stem Cell Research (5), Cardiology - Circulation (5), Polymers & Macromolecules (5), Remote	IoT And Edge Computing (401), Protein Purification (64), Surgical Robotics (37), Deep Visual Recognition (34), Cardiac Electrophysiology (22), Stormwater Management (20), Occupational Safety (18), Cancer Modeling (13), Atrial Fibrillation Management (12), Mechanical Ventilation (11), Crowdsourcing And Crowdsensing (11), Appointment Scheduling (10), Diabetes Management (9), Microfluidics (9), Action Recognition (9), Urban Green Spaces (9), Open Data (8), Congenital Heart Disease (7), Synthetic Biology (7), Brain Computer Interface (7), Gait And Balance (7), Air Pollution (7), Coronavirus Research (6), Hearing Technologies (6), Digital Mental Health (6), Microwave Imaging (6), Spinal Disorders (5), Cocrystals (5), Bioinspired Adhesives (5), Light Pollution (5), Image Segmentation (5), EMF Bioeffects (5), Electron Microscopy (5), Electrical Impedance Tomography (5), MRI Advancements (4), Low Back Pain (4), Valve Interventions (4), Genomic Bioinformatics (4), Arterial Stiffness (4), Biosimilars (4), Oral Delivery (4), Environmental Justice (4), Atmospheric Aerosols (4), Stroke Management (3), Wall Shear Stress (3), Prostate Cancer (3), Procalcitonin (3), Evidence Based Medicine (3), Aortic Aneurysms (3), PET Imaging (3), Hypertrophic Cardiomyopathy (3), Bacterial Motility (3), Opioid Pain Management (3), Checkpoint Inhibition (3), Functional Connectivity (3), Percutaneous Coronary Intervention (3), Neonatal Hypoxia Effects (3), Cardiac Resynchronization Therapy (3),

	Sensing (5), Biophotonics & Electromagnetic Field Safety (5), Nuclear Instruments (5), Pharmacology & Toxicology (4), Trauma & Emergency Surgery (4), Antibiotics & Antimicrobials (4), Wounds & Ulcers (4), Bacteriology (4), Immunology (4), Imaging & Tomography (4), Statistical Methods (4), Vascular, Cardiac & Thoracic Surgery (3), Medical Physics (3), Abdominal Surgery (3), Autonomic Regulation (3), Virology - Tropical Diseases (3), Anesthesiology (3), Nanoparticles (3), Food Science & Technology (3), Geometrical Optics (3), Agricultural Policy (3), Blood Disorders (2), Rheumatology (2), Molecular & Cell Biology - Cancer & Development (2), Liver & Colon Cancer (2), Soft Tissue, Bone & Nerve Cancers (2), Inflammatory Bowel Diseases & Infections (2), Fertility, Endometriosis & Hysterectomy (2), Virology - Identification & Sequencing (2), Genome Studies (2), Neuromuscular Disorders (2), Molecular & Cell Biology - Immunotherapy (2), Liver Diseases (2), Ultrasound In Medicine (2), Longevity (2), Dermatology - Skin Allergies (2), Dentistry & Oral Medicine (2), Neuroscience (2), Neurodegenerative Diseases (2), Blood Clotting (2), Reproductive Biology (2), Cell Biology (2), Nanofibers, Scaffolds & Fabrication (2), Nucleic Acids Chemistry (2), 2d Materials (2), Water Treatment (2), Phytochemicals (2), Smell & Taste Science (2), Contamination & Phytoremediation (2), Wireless Technology (2), Nuclear Physics (2), Social Psychology (2), Mechanics (2), Substance Abuse (1), Breast Cancer Scanning (1), Hepatitis (1), Pancreas & Gall Bladder Disorders (1), Healthcare Policy (1), Organ Donation & Transplantation (1), Sports Science (1), Cosmetic Surgery (1), Oncology (1), Psychiatry (1), Pelvic & Renal Disorders (1), Musculoskeletal Disorders (1), Lysosomal Storage Disorders (1), Dietary Stimulants (1), Radioactive Tracers (1), Ophthalmology (1), Allergy (1), Lipids (1), Molecular & Cell Biology - Physiology (1), Bone Diseases (1), Gastrointestinal & Esophageal Diseases (1), Protein Structure, Folding & Modelling (1), Mass Spectrometry (1), Nitroxides, Antioxidants & Free Radicals (1), Veterinary Sciences (1), Digital Signal Processing (1), Gender & Sexuality Studies (1), Electrical - Sensors & Monitoring (1), Nuclear Geology (1).	Transdermal Delivery (3), Entity Resolution (3), Pluripotent Stem Cells (2), Rheumatoid Arthritis (2), Glioma Research (2), Drug-induced Hepatotoxicity (2), Sarcoma Research (2), Disaster Medicine (2), Electronic Health Records (2), Particle Therapy (2), Genome-wide Association Studies (2), Multiple Sclerosis (2), Heart Rate Variability (2), Veterinary Education (2), Capsule Endoscopy (2), Ultrasound Imaging (2), Metabolic Syndrome (2), Triptolide Toxicity (2), Varicose Veins (2), Arthroplasty Innovations (2), Hip Fracture (2), Fracture Management (2), Echocardiography (2), Mechanical Circulatory Support (2), Dementia (2), Chronic Kidney Disease (2), Coronary CT Angiography (2), PCOS And Infertility (2), Arrhythmia Interventions (2), Hydroxyapatite Composites (2), DNA Nanotechnology (2), Fullerene Chemistry (2), Disinfection Byproducts (2), Non-thermal Food Processing (2), Sediment Metal Risks (2), WBAN (2), Neutron Detection (2), Laser Doppler Velocimetry (2), Diffuse Optical Tomography (2), X-ray Imaging (2), Dietary Sustainability (2), Nonlocal Thermoelasticity (2), Greenhouse Gas Dynamics (2), Adaptive Design (2), Alcoholic Liver Disease (1), Mesenchymal Stem Cells (1), Hepatocyte Growth Factor (1), Angiogenesis (1), GVHD (1), Hematopoietic Stem Cells (1), Wilms Tumor Genetics (1), Neural Crest (1), Hepatocellular Carcinoma (1), Colonoscopy (1), Advanced Neuroimaging (1), Cytochrome P450 (1), Non-animal Testing (1), Lymphedema (1), Inflammatory Bowel Disease (1), Gut Microbiota (1), NAFLD (1), Endometriosis (1), Myomectomy (1), Spinal Metastases (1), Virtopsy (1), Traumatic Brain Injury (1), KLFS In Cancer (1), Primary Care Models (1), Healthcare Policy (1), Multidisciplinary Oncology (1), Radiotherapy Innovations (1), Pancreatic Cancer (1), Intensive Care (1), Uncertainty Theory (1), Systemic Capillary Leak Syndrome (1), Off-label Prescribing (1), Community-based Participatory Research (1), Liver Transplantation (1), Poxvirus Immunology (1), Cytomegalovirus Infections (1), Thermoregulation (1), Maxillofacial Fractures (1), Head And Neck Cancer (1), Radioimmunotherapy (1), Phage Display (1), Factitious Disorders (1), Hernia Repair (1), Natural Orifice Transluminal Endoscopic Surgery (1), Abdominal Compartment Syndrome (1), Respiratory Control (1), Viral Hemorrhagic Fevers (1), Surgical Site Infection (1), MRSA And VRE (1), Outpatient Parenteral Antimicrobial Therapy (1), Naming Practices (1), Renal Cell Carcinoma (1), Microgravity Muscle Adaptation (1), Longevity Risk (1), Aging Mechanisms (1), Burns (1), Pressure Ulcer (1), Enzyme Replacement Therapy (1), Coffee And Caffeine (1), Pet Radiotracers (1), Heterotopic Ossification (1), Tendon Therapies (1), Vision Disorders (1), Heart Failure Management (1), Bacterial Gene Regulation (1), Physical Activity (1), Endodontics (1), Dental Implants (1), Astrocytes & Ketogenic Diet (1), Dopamine And Neuromodulation (1), Hypertension Management (1), Diuretic Medication (1), Adhesion Molecules (1), Asthma (1), Fat Crystallization (1), Pregnancy Medication Safety (1), Preeclampsia Factors (1), Childbirth Practices (1), Breastfeeding (1), Transglutaminase And Fibrin (1), Transfusion (1), Ion Channelopathies (1), Osteoporosis (1), Spinal Cord Injury (1), ECG Innovations (1), IBS & Functional Disorders (1), Cell Mechanics (1), Myosin (1), Protein Folding (1), Dry Powder Inhaler (1), Metabolomics (1), Irradiation Dosimetry (1), Magnetic Nanoparticles (1), Optical Gratings (1), SERS (1), Tea Polyphenols (1), Essential Oil (1), Health Claims (1), Electronic Nose (1), Equine Orthopedics (1), Cereal Starch Properties (1), Retinal Image Analysis (1), Phonocardiogram (1), Digital Holography (1), Climate Security (1), Family Fertility Dynamics (1), Food Sovereignty (1), Autobiographical Memory (1), Subjective Well-being (1), Surface Acoustic Wave (1), Radon Hazards (1), Fractional Calculus (1), Robust Estimation (1), Sampling Techniques (1)

Supplementary Information for extended Table 2

WoS Index (Number of Studies)	Citation Topics Micro (Number of Studies)
SCI-EXPANDED (8647)	SDG-9 (2993), SDG-12 (2698), SDG-11 (1512), SDG-3 (947), SDG-7 (589), SDG-13 (441), SDG-17 (319), SDG-15 (171), SDG-6 (163), SDG-14 (108), SDG-2 (90), SDG-4 (18), SDG-5 (9), SDG-16 (7), SDG-8 (5), SDG-10 (4)
ESCI (1441)	SDG-9 (602), SDG-12 (516), SDG-11 (182), SDG-3 (119), SDG-7 (70), SDG-13 (67), SDG-17 (91), SDG-15 (29), SDG-6 (25), SDG-14 (17), SDG-2 (16), SDG-4 (13), SDG-5 (1), SDG-16 (2), SDG-8 (2), SDG-10 (1), SDG-1 (1)
SSCI (539)	SDG-9 (306), SDG-12 (275), SDG-11 (114), SDG-13 (53), SDG-17 (39), SDG-7 (35), SDG-3 (34), SDG-15 (22), SDG-2 (17), SDG-14 (15), SDG-6 (9), SDG-8 (5), SDG-4 (4), SDG-1 (1), SDG-5 (1), SDG-10 (1)
CPCI-S Digital Twin (45)	SDG-9 (18), SDG-12 (17), SDG-11 (8), SDG-7 (6), SDG-2 (2), SDG-3 (2), SDG-13 (2), SDG-14 (1), SDG-15 (1)
BKCI-S Digital Twin (41)	SDG-9 (20), SDG-12 (19), SDG-3 (11), SDG-11 (2), SDG-17 (2), SDG-4 (1), SDG-6 (1), SDG-8 (1), SDG-13 (1), SDG-16 (1)
A&HCI Digital Twin (34)	SDG-15 (9), SDG-9 (6), SDG-11 (6), SDG-12 (3), SDG-17 (3), SDG-14 (2), SDG-3 (1)
BKCI-SSH Digital Twin (7)	SDG-9 (4), SDG-12 (4), SDG-4 (1), SDG-11 (1), SDG-17 (1)
CPCI-SSH Digital Twin (1)	SDG-4 (1)

Supplementary Information for extended Table 3

	Topics id - Concatenate (Term)	Locally using Ollama			Remotely using OpenRouter		
		laguna-xs.2:latest	llama3	mistral	NVIDIA: Nemotron 3 Nano Omni	inclusionAI: Ling-2.6-1T	OpenAI: gpt-oss-120b
SDG-9 - Industry Innovation And Infrastructure	topic_0 model, digital, system, performance, prediction, accuracy, learning, detection, results	9.5 / 0.85	9.5 / 1.0	9.5 / 0.8	9.5/0.90	9.5/0.95	9.5/0.88
	topic_1 healthcare, health, digital, patient, medical, personalized, medicine, patients, treatment	SDG-3 (cross) / 0.30	3.8 / 0.9	not_related / -	9.5/0.85	9.b/0.75	9.b/0.80
	topic_2 digital, model, method, system, process, technology, intelligent, physical, control	9.5 / 0.80	9.4 / 0.8	9.5 / 0.7	9.4/0.80	9.4/0.70	9.4/0.78
	topic_3 digital, industry, research, technologies, technology, analysis, review, literature, challenges	9.5 / 0.90	9.5 / 0.7	not_related / -	9.5/0.90	9.5/0.85	9.5/0.86
	topic_4 digital, framework, systems, real-time, challenges, integration, technology, monitoring, management	9.1 / 0.75	9.1 / 0.6	9.2 / 0.6	9.4/0.80	9.1/0.80	9.4/0.82
	topic_5 network, networks, security, resource, service, cloud, computing, allocation, services	9.c / 0.85	9.c / 0.8	9.a / 0.6	9.1/0.85	9.c/0.90	9.c/0.84
	topic_6 urban, cities, smart, planning, water, management, infrastructure, digital, transportation	9.a / 0.75	11.2 / 0.7	11.2 / 0.7	9.4/0.80	9.1/0.75	9.1/0.79
	topic_7 manufacturing, production, system, smart, process, systems, industry, simulation, product	9.2 / 0.80	9.4 / 0.8	9.2 / 0.8	9.4/0.85	9.2/0.90	9.4/0.83
	topic_8 digital, twins, systems, physical, models, system, development, design, which	9.5 / 0.80	9.5 / 0.6	not_related / -	9.5/0.80	9.4/0.75	9.5/0.80
	topic_9 energy, power, consumption, carbon, waste, operation, plant, emissions, electric	9.4 / 0.80	7.2 / 0.7	12.c / 0.6	9.4/0.85	9.4/0.70	9.4/0.81
	topic_10 virtual, system, robot, human, robotic, reality, robots, control, environment	9.5 / 0.75	9.4 / 0.6	not_related / -	9.5/0.80	9.4/0.75	9.5/0.77
	topic_11 process, manufacturing, quality, additive, machining, material, parts, machine, parameters	9.2 / 0.75	9.4 / 0.8	not_related / -	9.4/0.85	9.2/0.80	9.4/0.80
	topic_12 agriculture, agricultural, farming, maritime, twins, fruit, product, forest, marine	SDG-2 (cross) / 0.30	2.4 / 0.5	not_related / -	9.5/0.80	2.4/0.80	9.b/0.74
	topic_13 construction, building, information, management, model, safety, buildings, maintenance, project	9.1 / 0.70	11.a / 0.6	not_related / -	9.4/0.80	9.1/0.80	9.1/0.79

Supplementary Information for extended Table 4

	Topics id - Concatenate(Term)	Locally using Ollama			Remotely using OpenRouter		
		laguna-xs.2:latest	llama3	mistral	NVIDIA: Nemotron 3 Nano Omni	inclusionAI: Ling-2.6-1T	OpenAI: gpt-oss-120b
SDG-12 - Responsible Consumption And Production	topic_0 digital, model, system, method, process, manufacturing, physical, intelligent, technology	12.2 / 0.85	12.1 / 0.6	not_related / 0.0	12.2/0.85	12.2/0.80	12.2/0.84
	topic_1 supply, chain, sustainable, sustainability, management, environmental, logistics, waste, impact	12.3 / 0.90	12.2 / 0.8	12.3 / 0.75	12.2/0.90	12.2/0.85	12.5/0.89
	topic_2 model, process, machining, machine, method, digital, prediction, control, performance	12.2 / 0.80	12.3 / 0.7	12.4 / 0.65	12.2/0.80	12.2/0.75	12.2/0.78
	topic_3 energy, power, consumption, carbon, operation, plant, electric, systems, efficiency	12.2 / 0.85	9.4 / 0.5	12.5 / 0.8	12.2/0.90	12.2/0.80	12.2/0.86
	topic_4 robot, human, system, robotic, virtual, reality, collaborative, robots, collaboration	12.2 / 0.75	9.1 / 0.8	not_related / 0.3	12.2/0.80	12.2/0.70	12.1/0.66
	topic_5 production, manufacturing, scheduling, system, optimization, dynamic, simulation, planning, process	12.2 / 0.80	9.3 / 0.7	not_related / 0.2	12.2/0.85	12.2/0.80	12.2/0.81
	topic_6 maintenance, digital, monitoring, model, fault, health, equipment, system, safety	12.5 / 0.80	12.4 / 0.9	not_related / 0.4	12.2/0.85	12.2/0.70	12.5/0.80
	topic_7 healthcare, health, patient, digital, medical, personalized, patients, medicine, treatment	SDG-3 (cross) / 0.30	3.8 / 0.4	not_related / 0.35	12.2/0.85	3.8/0.85	not_related/0.33
	topic_8 digital, industry, twins, research, technologies, manufacturing, technology, challenges, development	12.2 / 0.80	9.5 / 0.6	not_related / 0.3	12.2/0.85	9.4/0.80	12.1/0.82
	topic_9 digital, framework, real-time, systems, smart, system, approach, network, physical	12.2 / 0.75	12.1 / 0.7	not_related / 0.35	12.2/0.80	12.2/0.70	12.1/0.78

	topic_10 water, digital, temperature, agriculture, sensor, farming, pipeline, agricultural, twins	SDG-6 (cross) / 0.40	6.1 / 0.5	not_related / 0.35	12.2/0.85	2.4/0.85	12.2/0.84 (->SDG-6)
	topic_11 urban, digital, cities, building, management, infrastructure, planning, smart, traffic	12.2 / 0.70	11.1 / 0.8	not_related / 0.35	12.2/0.85	11.6/0.80	12.2/0.75
	topic_12 process, material, surface, quality, grinding, materials, metal, parameters, furnace	12.2 / 0.75	9.1 / 0.6	not_related / 0.4	12.2/0.80	12.2/0.75	12.2/0.80
	topic_13 digital, twins, systems, system, models, physical, design, model, process	12.2 / 0.80	9.5 / 0.7	not_related / 0.4	12.2/0.85	9.4/0.80	12.1/0.81

Supplementary Information for extended Table 5

	Topics id - Concatenate(Term)	Locally using Ollama			Remotely using OpenRouter		
		laguna-xs.2:latest	llama3	mistral	NVIDIA: Nemotron 3 Nano Omni	inclusionAI: Ling-2.6-1T	OpenAI: gpt-oss-120b
SDG-11 - Sustainable Cities And Communities	topic_0 energy, building, buildings, thermal, consumption, carbon, emissions, model, digital	11.6 / 0.85	9.4 / 0.8	9.5 / 0.8	11.6/0.90	11.6/0.80	11.6/0.86
	topic_1 system, control, digital, simulation, model, design, which, systems, controller	SDG-9 (cross) / 0.35	9.5 / 0.7	not_related / -	11.3/0.85	not_related/0.35	11.3/0.78
	topic_2 model, digital, models, method, prediction, accuracy, learning, results, real-time	SDG-9 (cross) / 0.30	3.1 / 0.6	9.5 / 0.7	11.3/0.80	not_related/0.35	11.3/0.75
	topic_3 metaverse, virtual, design, transport, reality, social, users, semantic, experience	11.2 / 0.70	not_related / 0.2	not_related / -	11.2/0.80	11.2/0.65	11.2/0.80
	topic_4 urban, cities, planning, water, resilience, areas, disaster, community, sustainable	11.3 / 0.80	11.1 / 0.9	9.2 / 0.6	11.5/0.85	11.5/0.90	11.5/0.88
	topic_5 digital, computing, network, problem, networks, offloading, resource, algorithm, optimization	SDG-9 (cross) / 0.40	9.3 / 0.8	9.a / 0.6	11.3/0.80	not_related/0.35	11.b/0.70
	topic_6 security, attacks, blockchain, against, layer, control, secure, nuclear, resilient	11.b / 0.75	9.1 / 0.7	11.2 / 0.7	11.6/0.75	11.6/0.60	11.b/0.68
	topic_7 structural, model, damage, bridge, digital, structure, monitoring, structures, analysis	SDG-9 (cross) / 0.60	11.3 / 0.6	9.2 / 0.8	11.2/0.80	11.1/0.80	11.1/0.84
	topic_8 traffic, vehicle, vehicles, driving, autonomous, control, system, transportation, safety	11.2 / 0.90	9.2 / 0.8	not_related / -	11.2/0.95	11.2/0.95	11.2/0.85
	topic_9 digital, management, smart, systems, research, system, framework, technology, twins	11.6 / 0.65	9.5 / 0.7	12.c / 0.6	11.3/0.80	11.6/0.75	11.3/0.76
	topic_10: human, logistics, content, graph, video, recognition, streaming, spatial-temporal, users	SDG-9 (cross) / 0.25	not_related / 0.2	not_related / -	11.2/0.70	not_related/0.30	11.a/0.71
	topic_11 circular, construction, economy, waste, product, sustainable, industry, supply, manufacturing	11.3 / 0.75	12.5 / 0.9	not_related / -	11.6/0.85	12.5/0.80	11.6/0.83
	topic_12 point, method, construction, image, tunnel, images, cloud, scene, registration	SDG-9 (cross) / 0.40	9.4 / 0.7	not_related / -	11.2/0.80	11.1/0.70	11.3/0.72
	topic_13 battery, batteries, electric, charging, lithium-ion, process, degradation, estimation, capacity	11.2 / 0.80	9.4 / 0.8	not_related / -	11.2/0.90	7.2/0.75	11.6/0.78

Supplementary Information for extended Table 6

	Topics id - Concatenate(Term)	Locally using Ollama			Remotely using OpenRouter		
		laguna-xs.2:latest	llama3	mistral	NVIDIA: Nemotron 3 Nano Omni	inclusionAI: Ling-2.6-1T	OpenAI: gpt-oss-120b
SDG-3 Good Health And Well-Bein	topic_0 model, digital, which, models, results, approach, different, system, parameters	not_related / 0.30	3.b / 0.80	not_related / 0.2	3.3/0.70	not_related/0.30	not_related/0.30
	topic_1 cardiac, heart, clinical, atrial, models, ablation, ventricular, digital, patients	3.4 / 0.80	3.4 / 0.70	3.4 / 0.9	3.4/0.85	3.4/0.85	3.b/0.85
	topic_2 digital, network, computing, offloading, resource, problem, networks, algorithm, learning	3.4 / 0.80	3.d / 0.60	9.5 / 0.8	3.8/0.80	not_related/0.30	not_related/0.28
	topic_3 mechanical, element, finite, biomechanical, tissue, forces, implant, patient-specific, design	SDG-9 (cross) / 0.80	3.8 / 0.90	3.1 / 0.9	3.8/0.80	3.4/0.80	3.b/0.80
	topic_4 system, robot, control, virtual, robotic, digital, safety, reality, interaction	3.8 / 0.80	3.7 / 0.50	3.6 / 0.8	3.8/0.75	3.4/0.75	not_related/0.32
	topic_5 acoustic, images, structures, electron, platform, child, radiation, devices, sound	3.8 / 0.70	3.6 / 0.70	not_related / 0.1	3.8/0.70	3.4/0.80	3.b/0.78
	topic_6 learning, model, digital, detection, models, accuracy, performance, network, water	3.8 / 0.70	3.1 / 0.40	3.4 / 0.8	3.3/0.75	3.3/0.75	3.d/0.74 (cross->SDG-6)
	topic_7 cells, pandemic, these, covid-19, modeling, immune, spread, sars-cov-2, mechanisms	3.3 / 0.90	3.3 / 0.80	3.4 / 0.9	3.3/0.95	3.3/0.90	3.3/0.92
	topic_8 patients, clinical, digital, patient, treatment, personalized, cancer, outcomes, disease	3.4 / 0.80	3.c / 0.60	3.4 / 0.9	3.8/0.85	3.4/0.85	3.b/0.81
	topic_9 pressure, ventilation, respiratory, mechanical, particle, workers, virtual, breathing, volume	3.4 / 0.70	3.6 / 0.80	not_related / 0.2	3.8/0.80	3.4/0.80	3.9/0.77
	topic_10 process, control, digital, production, manufacturing, development, operation, continuous, processes	not_related / 0.30	3.8 / 0.70	not_related / 0.2	not_related/0.35	not_related/0.30	not_related/0.30
	topic_11 digital, smart, systems, management, technologies, technology, challenges, twins, research	3.c / 0.60	3.b / 0.90	not_related / 0.2	3.8/0.85	not_related/0.35	not_related/0.29
	topic_12 liver, model, stimulation, insulin, fentanyl, glucose, therapy, blood, metabolic	3.4 / 0.80	3.4 / 0.60	not_related / 0.2	3.8/0.80	3.4/0.80	3.b/0.84
	topic_13 cognitive, design, space, brain, health, emergency, information, urban, participants	3.4 / 0.70	not_related / 0.20	not_related / 0.2	3.8/0.80	3.4/0.75	3.d/0.72 (cross->SDG-11)

Araştırma Makalesi

Mapping The Sustainable Development Goals in Digital Twin Research: Low Code Topic Modeling and LLM-Based Evaluation Framework

Dijital İkiz Araştırmalarında Sürdürülebilir Kalkınma Hedeflerinin Haritalandırılması: Düşük Kodlu Konu Modellemesi ve LLM Tabanlı Bir Değerlendirme Çerçevesi

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Genişletilmiş Özet

2015 yılında Birleşmiş Milletler Genel Kurulu tarafından kabul edilen “2030 Sürdürülebilir Kalkınma Gündemi”, 17 Sürdürülebilir Kalkınma Hedefi (SKH) ve bunlara bağlı 169 alt hedef belirlemiştir. Hedef yılı olan 2030’a yaklaşılırken, bilim, teknoloji ve inovasyonun bu hedeflere ulaşmadaki rolü giderek daha kritik hale gelmektedir. Dijital ikiz teknolojileri, fiziksel ve dijital sistemleri gerçek zamanlı olarak bütünleştirme kapasitesi sayesinde sürdürülebilir kalkınma için umut vadeden araçlardan biri olarak öne çıkmaktadır. Bununla birlikte, mevcut literatürde dijital ikiz araştırmalarının hangi SKH’lerle, hangi alt hedeflerle ve hangi teknolojik alt alanlarla ilişkili olduğuna dair sistematik ve ölçeklenebilir kanıtlar sınırlıdır. Bu çalışma, Web of Science (WoS) Core Collection’da indekslenen 10.306 dijital ikiz yayınını kullanarak, konu modelleme ve büyük dil modelleri (LLM) destekli bir değerlendirme çerçevesi ile dijital ikiz araştırmalarının SKH’lerle ilişkisini sistematik bir şekilde haritalandırmayı amaçlamaktadır. Ayrıca, bu haritalama üzerinden bilim, teknoloji ve inovasyon politikalarına yönelik stratejik çıkarımlar sunmakta ve gelecek araştırmalar için sürdürülebilirlik odaklı bir yol haritası oluşturmaktadır.

Çalışma kuramsal olarak iki temele dayanmaktadır. Birincisi, misyon odaklı inovasyon teorisidir; bu teoriye göre toplumsal zorlukların çözümü, çok paydaşlı ve hedef odaklı inovasyon süreçleri gerektirir. Dijital ikizler bu bağlamda yalnızca operasyonel verimlilik aracı değil, aynı zamanda SKH’lerle uyumlu misyonların gerçekleştirilmesi için stratejik koordinasyon ve simülasyon altyapısı olarak konumlandırılmaktadır. İkincisi, sosyo-teknik sistemler teorisidir (Geels, 2004); bu kuram, dijital sistemlerin teknolojinin yanı sıra insan, kurum, politika ve çevre etkileşiminin ürünü olduğunu vurgular. Dijital ikizlerin SKH’lere katkısı, yalnızca teknik kapasitelerine değil, içinde çalıştıkları sosyo-teknik sistemin uyum ve dönüşüm kapasitesine bağlıdır.

Yöntemsel olarak çalışma, hibrit bir bibliyometrik ve semantik analiz çerçevesi benimsemektedir. Veri toplama aşamasında, 4 Ağustos 2025’te WoS’ta “TS=”digital twin””, belge türü “makale”, dil “İngilizce” sorgusu ile 10.306 yayına ulaşılmıştır. Bibliyografik meta veriler (başlık, özet, anahtar

kelimeler) .xls formatından .csv'ye dönüştürülmüş ve temizlenmiştir. Analiz, en sık ilişkilendirilen SKH-9 (Sanayi, Yenilikçilik ve Altyapı; n=3.703), SKH-12 (Sorumlu Üretim ve Tüketim; n=3.321), SKH-11 (Sürdürülebilir Şehirler ve Topluluklar; n=1.739) ve SKH-3 (Sağlık ve Kaliteli Yaşam; n=1.081) olmak üzere 4 SKH üzerinde yoğunlaşılmıştır.

Konu modelleme, low-code olarak KNIME Analytics Platform üzerinde gerçekleştirilmiştir. Metin ön işleme adımları (tokenizasyon, durdurma kelimelerinin çıkarılması, kök bulma) uygulandıktan sonra, MALLET kütüphanesindeki SparseLDA algoritması ile paralel LDA çalıştırılmıştır. Bu yöntem, Yao, Mimno ve McCallum (2009) tarafından önerilen hızlı örnekleme yöntemlerine kıyasla iki kata kadar hız artışı ve önemli ölçüde daha az bellek kullanımı sağlamıştır. Her SKH için 5 ila 20 konu aralığı test edilmiş ve her bir SKH için 14 gizli konu ile her konuyu temsil eden 9 en baskın terim belirlenmiştir.

Alt SKH eşlemesi için çoklu LLM orkestrasyonu kurulmuştur. Yerel olarak Ubuntu 24.04.3 LTS işletim sisteminde Ollama platformu kurulmuş; Mistral, Llama3 ve laguna-xs.2 (23 GB) modelleri çalıştırılmıştır. Uzaktan erişim için OpenRouter API kullanılmış; NVIDIA Nemotron 3 Nano Omni, inclusionAI Ling-2.6-1T ve OpenAI gpt-oss-120b modellerine (tümü ücretsiz ve "en popüler" kategorisinden) erişilmiştir. Tüm modellere aynı yapılandırılmış prompt şablonu (subSDGprompt.txt) verilmiş ve JSON şeması ile alt SKH etiketi, güven puanı (confidence score) ve çapraz SKH bayrakları üretilmiştir. Ayrıca her yayın, Clarivate'ın Atıf Konuları taksonomisine göre mezo düzey (ör. Tasarım ve Üretim, Telekomünikasyon) ve mikro düzey (ör. Endüstri 4.0, Nesnelerin İnterneti, Döngüsel Ekonomi) kodlarla etiketlenmiş; VOSviewer kullanılarak anahtar kelime birlikte oluşum ağları görselleştirilmiştir. Tüm veri, kod ve çıktılar GitHub'da (github.com/HuseyinPARMAKSIZ/DigitalTwinSDGs) kamuya açık olarak verilmiştir.

Bulgular, SCI-Expanded indeksindeki 8.647 dijital ikiz çalışmasının çoğunluğunun SKH-9 (2.993) ve SKH-12 (2.698) ile ilişkili olduğunu göstermektedir. Bu eğilim ESCI, SSCI ve diğer alt indekslerde de tutarlıdır. Buna karşılık, SKH-01 (Yoksulluk), SKH-05 (Toplumsal Cinsiyet Eşitliği) ve SKH-10 (Eşitsizliklerin Azaltılması) gibi sosyal boyutlu hedeflere yönelik yayın sayısı tüm indekslerde oldukça düşüktür. Mezo ve mikro düzey kodlama (Tablo 1) SKH-9'da en baskın mezo kategorinin "Tasarım ve Üretim" (3.362), en baskın mikro kategorinin "Endüstri 4.0" (2.951) olduğunu; SKH-12'de de benzer şekilde "Tasarım ve Üretim" ile "Endüstri 4.0"ın öne çıktığını ancak "Tedarik Zinciri ve Lojistik" ile "İleri İşleme" gibi mikro alanların da belirgin olduğunu ortaya koymuştur. SDG-11'de "Telekomünikasyon" (503) ana mezo kategori olup mikro ölçekte "IoT ve Uç Bilişim" (401), "Hasar Tespiti" (175) ve "Bina Enerji Verimliliği" (165) ilk sıralardadır. SKH-3'te ise "Telekomünikasyon" (401) yine ilk sırada yer alırken mikro kategorilerde "IoT ve Uç Bilişim" (401), "Protein Saflaştırma" (64) ve "Cerrahi Robotik" (37) bulunmaktadır.

LLM'lerin alt SKH sınıflandırmasında karşılaştırmalı değerlendirmesi, doğruluğun ötesine geçen anlamlı performans farklılıkları ortaya koymuştur. Uzaktan erişilen modeller (Nemotron, gpt-oss-120b) üstün yapısal ve anlamsal uyum sergilemiş, güven puanları sürekli olarak 0,80'in üzerinde olmuştur. Bu performans avantajı, kapsamlı talimat ayarlamasından ve heterojen teknik külliyata maruz kalmaktan kaynaklanmaktadır. Yerel modeller arasında laguna-xs.2, çapraz SKH bayraklarını sistematik kullanarak SKH-9, SKH-11, SKH-12 ve SKH-3 arasında en tutarlı performansı göstermiştir. Bu yetenek, kavramsal örtüşmeyi tanıyarak analitik aşırı indirgemeciliği hafifletmekte ve dijital ikiz araştırmasının çok boyutlu doğasını korumaktadır. Llama3 ise bağlamsal olarak değerli olmakla birlikte alana özgü güçlü yönler sergilemiş, en iyi uyumu yalnızca sağlık sınıflandırmalarında göstermiştir. Buna karşın Mistral'ın belirgin muhafazakârlığı, anlamsal olarak makul eşlemelere rağmen sık sık "not_related" sonucu üretmesi, onu katı alt SKH taksonomisi atamaları için yetersiz kılmaktadır. Bu sınıflandırma farklılıkları yalnızca teknik tutarsızlıklar olarak değil, sürdürülebilirlik biliminin doğasında bulunan kavramsal akışkanlığın epistemolojik yansımaları olarak yorumlanmalıdır. Örneğin, laguna-xs.2'nin sağlık dijitalleşmesini yenilik hedeflerine (SKH-9.5) bağlama eğilimi ile Llama3'ün hizmet sunum çerçevelerini (SKH-3.8) tercih etmesi arasındaki fark, teknolojik kolaylaştırıcılar ile kalkınma çıktıları arasındaki yapısal gerilimi gözler önüne sermektedir. Bununla birlikte, büyük uzaktan modellerin bütünleştirici genişliği normatif riskler de taşımaktadır: dağıtımsal etkiler, katılımcı yönetişim veya kurumsal hazırbulunuşluk gibi unsurları açıkça dikkate almadan yapılan aşırı güvenli hedef atamaları, eşitlik, erişilebilirlik ve dönüştürücü SKH uygulaması için gerekli sistemik koşullar gibi kritik sosyo-teknik soruları gölgeleyebilir.

VOSviewer birlikte oluşum ağları bulguları zenginleştirmektedir. SKH-12 ağı döngüsel ekonomi, akıllı üretim ve dijital etkinleştiriciler olmak üzere üç ana küme sergilemekte; "digital twin" düğümü yüksek merkezilikle tüm kümelere güçlü bağlantılar sunmaktadır. SKH-09 ağında "inovasyon ekosistemleri" ve "teknoloji transferi"nin belirginliği, SKH-9.5 ile doğrudan örtüşmektedir. SKH-11 ağı, akıllı şehir altyapısını kentsel direnç, sürdürülebilir hareketlilik ve afet risk azaltma arasında bağlantı noktası olarak resmetmektedir. SKH-03 ağı ise kişiselleştirilmiş bakım, hastaya özel modelleme, teletıp etrafında klinik olarak merkezlenmiş; "yapay zekâ", "derin öğrenme" ve "gerçek zamanlı sistemler"in yüksek birlikte oluşumu, LLM tabanlı yüksek güvenli atamaların (SKH-3.4 ve SKH-3.8) geçerliliğini güçlendirmektedir.

Sonuç olarak, dijital ikiz literatürü en güçlü odağını SKH-9 ve SKH-12 üzerinde yoğunlaştırmakta; SKH-11 ve SKH-3 önemli ancak daha sınırlı bir araştırma birikimine sahiptir. Dijital ikizlerin ilk olarak imalat sanayinde ortaya çıkması (Boschert & Rosen, 2016) ve teknolojik altyapı gerektirmesi bu dağılımı kısmen açıklamaktadır. SKH'ler arasındaki güçlü bağlantılar nedeniyle (Nilsson v.d., 2016) bir SKH'ye yönelik çabalar dolaylı olarak diğerlerine de katkıda bulunabilir. Ancak çalışma, dijital ikiz araştırmalarının sosyal boyutlu SKH'ler (yoksulluk, toplumsal cinsiyet eşitliği, eşitsizliklerin azaltılması) ile kesişiminin çok sınırlı olduğunu ve bunun ciddi bir boşluk teşkil ettiğini ortaya koymaktadır. Bu nedenle dijital ikizlerin yalnızca operasyonel verimlilik araçları değil, aynı zamanda sosyal, etik ve kurumsal bağlamları bütünleştiren sosyo-teknik sistemler olarak yeniden kavramsallaştırılması önerilmektedir. Politika yapıcılar için: teknoloji odaklı SKH'lerin (SKH-09, SKH-11) sosyal ve kurumsal SKH'lerle (SKH-10, SKH-16) bütünleştirildiği bütüncül bir SKH yönetişimi; kamu sektöründe insan merkezli ve katılımcı tasarım; kapasite geliştirme, düzenleyici hazırbulunuşluk ve organizasyonel öğrenmeye yatırım önerilmektedir. Çalışmanın sınırlılıkları: yalnızca WoS kullanılması, yerel donanım kısıtları nedeniyle alana özel ince ayar yapılamaması, ProQuest gibi tez veri tabanlarının dışlanmasıdır. Çalışmanın sınırlılıkları: yalnızca WoS kullanılması, yerel donanım kısıtları nedeniyle alana özel ince ayar yapılamaması, ProQuest gibi tez veri tabanlarının dışlanmasıdır. Ayrıca, çoklu LLM'lerin alt SKH eşlemesinde gözlemlenen modeller arası düşük uyum önemli bir yöntemsel sınırlılık olarak belirlenmiştir. Altı model üzerinde hesaplanan Fleiss' κ ve Krippendorff's α değerleri SKH-9'da sırasıyla 0,234 ve 0,236; SKH-11'de 0,077 ve 0,079; SKH-3'te 0,102 ve 0,104; SKH-12'de -0,040 ve -0,038 olarak gerçekleşmiştir. Krippendorff'un önerdiği kabul edilebilir eşik ($\alpha \geq 0{,}667$) dikkate alındığında bu değerler yetersiz güvenilirliğe işaret etmektedir. Bu durum; modellerin mimari farklılıklarından, SKH sınıflandırmasının doğasında var olan öznellikten ve her SKH için yalnızca 14 konu ile sınırlı kategori uzayından kaynaklanmaktadır. Bu nedenle, uzlaşıya dayalı eşlemeler (Tablo 3-6) kesin sınıflandırmalar değil, keşifsel hipotezler olarak yorumlanmalıdır. Bu sınırlılığı azaltmak için çalışmada muhafazakâr bir raporlama eşiği (çoğunluk oyu ≥4/6 model) benimsenmiş ve tüm ham model çıktıları kamuya açık hâle getirilmiştir. Gelecek araştırmalarda insan uzman doğrulaması, topluluk yöntemleri veya alana özel ince ayarlı LLM'ler ile güvenilirliğin artırılması önerilmektedir. Gelecek araştırmalar, dijital ikizlerin sosyal boyutlarını disiplinler arası ekiplerle incelemeli, geliştirilen LLM çerçevesini yapay zekâ, blok zinciri, yeşil hidrojen gibi diğer yükselen teknolojilere uyarlamalıdır. Son olarak, sunulan metodoloji, herhangi bir teknolojik inovasyonun sürdürülebilirlik etkilerini değerlendirmek için aktarılabilir bir referans modeli oluşturmakta, teknolojik ilerlemeyi küresel sürdürülebilirlik hedefleriyle uyumlu hale getirmek için ölçeklenebilir ve sistematik bir yaklaşım sunmaktadır.