Review

Transformative Technologies and Anticipated Radical Technologies: Implications for Sustainable Value Production Networks

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ABSTRACT

Transformative Technologies (TTs) and Anticipated Radical Technologies (ARTs) are frequently discussed as drivers of sustainability transitions, but their conceptual boundaries and the evidence supporting their systemic effects remain inconsistent. This review examines how engineering and foresight literature characterizes these technologies and relates them to sustainable value production networks. TTs refer to the capacity for substantial socio-technical change, whereas ARTs emphasize the anticipation of radical developments whose trajectories and consequences remain uncertain. Maturity is treated as a separate analytical dimension. Drawing on the Finnish and Peruvian foresight frameworks, the study organizes the literature through seven attributes and a three-level ontology linking technological enablers, application domains, and sustainability outcomes. The initial Scopus search returned 211 records. Descriptive attribute frequencies are reported against that initial set, separately from the selection of studies for qualitative synthesis. A reference-linked catalogue presents 114 entries from the reference-linked classification, without treating those references as an independently verified inventory of 145 distinct technologies. The synthesis identifies three recurring themes: smart digitalization, advanced manufacturing, and energy sustainability. Technical performance and enabling conditions receive more attention in the reported coding than genericity and socio-regulatory impacts. An interpretive matrix relates selected applications to the 20 value production networks while identifying limits in their evidential coverage. The findings support a framework for examining potential network reconfiguration; they do not establish causal

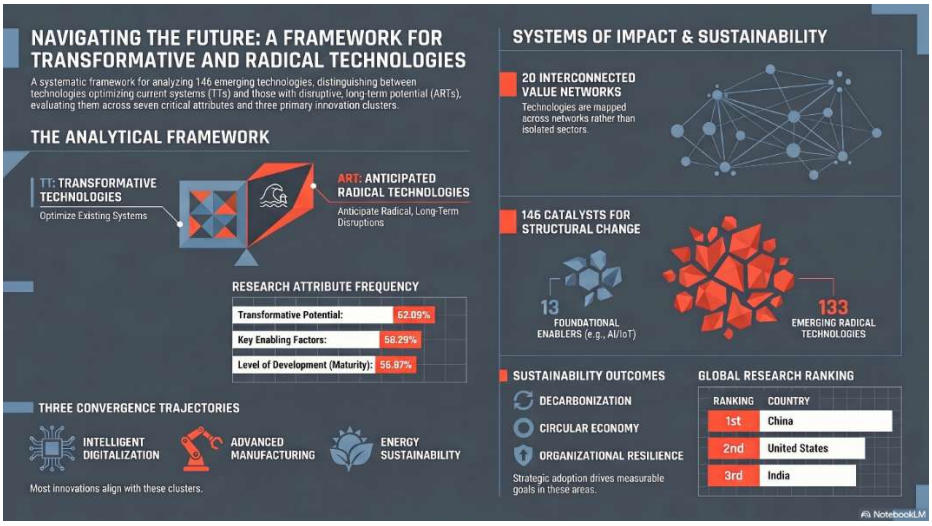
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sustainability effects or rank technologies by societal value. Policy recommendations therefore emphasize context-sensitive appraisal, transparent evidence, and governance that combines anticipation with learning during deployment.

KEYWORDS: transformative technologies; anticipated radical technologies; sustainability; value production networks; systematic literature review



Graphical Abstract

INTRODUCTION

Transformative Technologies (TTs) and Anticipated Radical Technologies (ARTs) are increasingly recognized as critical drivers of industrial transformation, economic competitiveness, and broader societal change. Rapid technological advancements in domains such as digital infrastructure, advanced manufacturing, artificial intelligence, biotechnology, and energy systems are reshaping production processes, business models, and patterns of value creation across multiple sectors. Consequently, understanding the characteristics, dynamics, and impacts of these technologies has become a central concern in research on innovation management, technology forecasting, and strategic planning.

In recent years, a growing body of literature has sought to conceptualize technological trajectories and identify categories of emerging or radical innovations through systematic literature reviews and foresight analyses. These studies have contributed to refining definitions, identifying application domains, and mapping the evolution of technological fields over time.

An alternative analytical perspective is presented in the report Social Transformation 2018–2037, developed by the Committee for the Future of Finland [1]. Rather than analyzing the economy through conventional industrial sectors, the report conceptualizes economic activity as a system

of twenty value-creation networks. These networks represent interconnected flows of specialization, knowledge exchange, and value generation across diverse domains of activity [1,2]. Within this framework, organizations and individuals may participate simultaneously in multiple networks, reflecting the increasingly interconnected and multidimensional nature of technological development and economic transformation [3].

From this perspective, technological change cannot be fully understood solely through sector-based classifications. Instead, technologies should be examined in terms of their capacity to influence multiple value-creation networks simultaneously. The report also identifies a range of rapidly evolving technologies expected to generate significant societal impacts, including innovations in consumer electronics such as organic light-emitting diode (OLED) displays, voice and motion interfaces, and increasingly accessible 3D printing technologies. Additional developments include cloud computing infrastructures, secure mobile devices, advanced data analytics capabilities, and emerging innovations in fields such as healthcare and energy systems [4].

Addressing this gap is relevant from both theoretical and practical perspectives. Theoretically, identifying and systematizing the attributes that characterize TTs and ARTs contributes to a more comprehensive understanding of technological evolution and its systemic effects. Practically, organizations and policymakers require robust analytical tools to anticipate technological change, evaluate emerging opportunities, and design effective innovation and competitiveness strategies. Based on the technological attributes identified in this review, the proposed framework offers strategic implications for innovation, policymaking, and future research. First, innovation strategies should be differentiated according to the degree of technological genericity, favoring ecosystem-based approaches for general-purpose technologies and sector-specific strategies for highly specialized technologies. Second, technology foresight and monitoring systems should incorporate attributes such as transformative potential, technological maturity, and systemic impact to improve the prioritization of emerging technologies. Third, innovation policies should be geared toward the governance of value production networks, promoting intersectoral coordination mechanisms and anticipatory governance frameworks for Anticipated Radical Technologies (ARTs). Furthermore, the framework provides guidance for human capital development, distinguishing between transversal digital skills and specialized technical capabilities according to the characteristics of each technology. There is a need to move toward empirical models that allow for the evaluation of the economic, organizational, and sustainability impact resulting from the interaction between technological attributes and adoption processes. These implications also offer practical applications for governments, regulators, businesses, and R&D leaders, facilitating policy design, strategic planning, and resource allocation.

Given their relevance, these recommendations are further developed and discussed in the Recommendations section of this article.

The Societal Transformation 2018–2037 report [1] identified 100 anticipated radical technologies (ARTs) and examined their potential impacts across 20 value-producing networks. This framework subsequently served as the basis for the technological surveillance study conducted by the authors [5] in Peru, which adapted the evaluation criteria to the Peruvian context. ARTs can be conceptualized as an anticipatory category for identifying technologies with transformative potential, as their identification is based on early signals of radical technological developments capable of generating profound impacts on socioeconomic structures, behaviors, and sociotechnical systems [6]. In this regard, an ART may exhibit transformative characteristics; however, not every ART will necessarily produce transformative effects in practice. Transformative innovations and technologies drive desirable and feasible socio-ecological changes [7], although their assessment faces challenges associated with uncertainty and data availability [8]. Furthermore, they transform the ways people interact, learn, and work [9], contribute to addressing major societal challenges [10] and promote personal and collective change [11].

TTs are characterized by their capacity to generate radical and systemic impacts that extend beyond incremental improvements and may reshape social and economic structures [12]. They also exhibit cross-sectoral applicability, as they can affect multiple domains and value-creation networks [13]. Furthermore, TTs can create new economic opportunities, transform occupations and skill requirements, and require adaptations in educational and regulatory systems. Their development often emerges from the integration of technological and social innovations, facilitating their application across diverse sectors. Additionally, TTs tend to exhibit accelerated development and maturation trajectories, driven by R&D investment and their potential for market adoption. Their transformative nature is ultimately reflected in their capacity to alter established sociotechnical regimes, affecting governance structures, production systems, and institutional arrangements [13–17].

The distinction therefore lies in the fact that the concept of ARTs emphasizes the anticipation of a radical technology with potential for future development and impact, whereas the concept of transformative technology emphasizes its capacity to generate profound or systemic changes across sectors, behaviors, structures, and sociotechnical systems. Accordingly, for the purposes of this study, ARTs are considered relevant as anticipatory signals of technologies that may acquire or materialize transformative characteristics. Generative artificial intelligence, for example, can illustrate the transition from an anticipated radical technology to a transformative technology. During the early stages of its development and diffusion, its prospective applications could be regarded as a signal of radical and uncertain technological change, consistent with

the concept of ART. Subsequently, as its applications expanded into areas such as education, research, software development, content production, and business processes, its potential to modify behaviors, economic activities, and sociotechnical systems supports its characterization as a technology with transformative capacity. Thus, the ART dimension is primarily associated with the anticipation of radical technological change, whereas the transformative dimension is associated with the magnitude and depth of the change generated or potentially generated.

In biotechnology, CRISPR-based gene-editing technology can illustrate the transition from an anticipated radical technology to a technology with transformative potential. During its early stages of development, CRISPR applications could be regarded as a radical technological development characterized by a broad horizon of potential applications and substantial uncertainty regarding its scope, features consistent with the concept of Anticipated Radical Technologies (ARTs). Subsequently, the expansion of its potential and experimental applications in fields such as medicine, agriculture, and biomanufacturing has demonstrated its capacity to modify fundamental biological processes and potentially transform production practices and healthcare systems. In this regard, the ART dimension of CRISPR is associated with the anticipation of its potential future developments and impacts, whereas its transformative dimension is related to its capacity to generate profound changes in biological, productive, and sociotechnical processes.

In the energy sector, green hydrogen can serve as an example of a technology exhibiting both ART characteristics and transformative potential. From a foresight perspective, its development and scale-up may be regarded as an anticipated radical technology because of the uncertainties surrounding its technological evolution, cost reductions, infrastructure, storage, distribution, and adoption across different sectors. Its transformative potential derives from its ability to reshape energy and industrial systems, particularly in hard-to-abate sectors that are difficult to electrify directly, such as steel production, certain chemical processes, and long-distance transportation. Thus, whereas the ART perspective emphasizes the anticipation of radical technological development and its potential future trajectories, the transformative perspective emphasizes the capacity of green hydrogen to contribute to structural changes in energy, industrial, and economic systems. Consequently, effective technology governance requires a bifurcated management logic that balances foresight-oriented exploration—focused on R&D, sustained funding mechanisms, collaborative ecosystems, and adaptive governance for ARTs—with adaptive efficiency based on cultural alignment, organizational leadership, and strategic appropriation.

To operationalize these dynamics, the study introduces an analytical framework comprising seven operational attributes—transformative potential, relationship with value networks, enabling factors, level of development, anticipated effectiveness, genericity, and socio-regulatory

impact—grounded in institutional foresight frameworks and the literature on sociotechnical change. Based on this framework, the manuscript is structured into six integrated sections. Section Introduction delineates the research problem, knowledge gap, guiding research questions, and objectives. Section Theoretical Framework addresses the institutional backgrounds of Finland and CONCYTEC, conceptualizes the TT–ART evolutionary continuum, and defines the seven attributes. Section Materials and Methods details the systematic literature review (SLR) protocol in accordance with the PRISMA 2020 statement. Section Results synthesizes the bibliometric mining conducted using VantagePoint, presents the inventory of enabling factors, and maps their co-occurrence across the 20 value-production networks. Section Discussion triangulates the findings with international benchmarks, evaluates network reconfiguration, analyzes the socioecological trade-offs associated with AI, and proposes a dual-governance interpretive framework. Finally, Section Conclusions, Limitations, and Recommendations synthesizes the main contributions, addresses methodological limitations independently, and outlines future research directions.

The present study addresses the lack of frameworks capable of determining how technological attributes shape the reconfiguration of value-production networks. To this end, it poses two research questions: RQ1, what operational attributes does the engineering literature employ to characterize TTs and ARTs? and RQ2, how does the interaction among these attributes contribute to the reconfiguration of the 20 value-production networks toward sustainability goals? The proposed inventory links technological attributes to their potential for network-level reconfiguration and provides a methodological basis for their analysis.

THEORETICAL FRAMEWORK

This section presents the theoretical foundations of Transformative Technologies (TTs) and Anticipated Radical Technologies (ARTs), drawing on the studies by [1,5], which establish criteria for their identification, classification, and assessment of their transformative potential. The literature indicates that TTs and ARTs remain conceptually fragmented and subject to ambiguity [6], and are associated with innovations capable of driving socioecological transformations [7], generating large-scale impacts, and involving substantial uncertainties in their assessment [8]. Likewise, TTs have been associated with disruptive changes in the ways people live, work, communicate, and address problems [9], as well as with efforts to address major societal challenges and transform everyday practices [10,11].

TTs and ARTs are characterized by their capacity to generate radical and systemic transformations that extend beyond technological change and affect social structures, business models, occupations, and ways of life [12]. Their main attributes include transformative impact, cross-sectoral applicability, value creation, interdisciplinarity, maturation potential, and

changes in operating models [13–17]. In addition, variables such as technological maturity, value potential, and impact on value-production networks enable comparative assessment of their transformative potential [1].

Background on Transformative Technologies and Anticipated Radical Technologies

Technological innovation has historically played a decisive role in shaping economic systems, social structures, and institutional arrangements. In recent decades, increasing attention has been directed toward a category of technologies capable of generating profound and systemic transformations across multiple sectors of society. These technologies are commonly referred to as TTs and in certain analytical frameworks, as ARTs.

One of the most comprehensive efforts to identify and analyze such technologies was undertaken by the Committee for the Future of the Parliament of Finland in the report Societal Transformation 2018–2037 [1]. This study examined one hundred emerging technologies and assessed their potential to generate large-scale societal transformations. The technologies were evaluated in relation to twenty value production networks, representing fundamental societal functions such as health, energy, mobility, food, and security.

Within this framework, the concept of ARTs was introduced to characterize technological developments with particularly high potential for systemic transformation. ARTs are not limited to individual technological artifacts; rather, they represent clusters of technological solutions that address similar societal needs. These clusters encompass multiple technical implementation pathways and potential applications, which may evolve as the technologies mature [1].

Building on this approach, the National Council for Science, Technology, and Technological Innovation of Peru (CONCYTEC) developed the Technology Watch Report: Transformative Technologies, which adapts the Finnish methodology to analyze emerging technologies with transformative potential in different contexts [5]. This report preserves the original analytical structure and evaluation criteria, particularly with regard to technological maturity, anticipated effectiveness, and the potential impact of technologies on value production networks.

While these institutional reports provide structured methodologies for identifying TTs, their primary emphasis lies in technological foresight and policy guidance rather than conceptual clarification. As a result, the academic literature continues to exhibit fragmented interpretations of what constitutes a Transformative Technology and how it differs from other forms of innovation.

Conceptual Approaches to Transformative Technologies

The concept of TTs overlaps with several related notions in the innovation literature, including transformative innovation, disruptive technologies, and socio-technical transitions. However, these concepts are not always applied consistently, contributing to a degree of conceptual ambiguity.

For instance, the concept of transformative innovation is inherently ambiguous and difficult to delimit, as it intersects with other forms of innovation, including incremental and disruptive innovations [6]. This ambiguity poses challenges for public policy design, since different types of innovation require distinct science and technology strategies.

From the perspective of sustainability transitions, transformative innovations are defined as those capable of enabling desirable and feasible socio-ecological transformations [7]. In this view, the transformative nature of a technology is determined not only by its technical novelty but also by its capacity to facilitate systemic transitions toward more sustainable socio-technical systems. Other contributions emphasize the methodological challenges associated with analyzing TTs. For instance, the limitations of applying Life Cycle Assessment (LCA) to emerging technologies have been highlighted [8]. Because these technologies are still evolving, their future applications, production systems, and environmental impacts remain uncertain. To address this issue, the authors propose a framework identifying ten factors that influence the evaluation of Transformative Technologies.

Additional studies focus on the broader societal implications of technological change. According to [9], technologies such as automobiles, smartphones, and digital communication platforms have fundamentally reshaped how individuals interact, work, learn, and conduct business. These examples illustrate the capacity of technological developments to redefine entire socio-economic systems.

Similarly, emphasize the role of technological innovation in addressing major societal challenges. Advances in artificial intelligence, big data, and digital technologies are rapidly transforming economic activities and decision-making processes across multiple sectors [10].

From a socio-cultural perspective, TTs also influence social awareness, collaboration, and creativity [11]. These technologies create new opportunities for innovation in areas such as agriculture, healthcare, manufacturing, and services, while simultaneously generating new social and institutional challenges. Taken together, these contributions suggest that TTs should not be understood merely as novel technological artifacts, but rather as drivers of systemic socio-technical change capable of reshaping economic structures, institutional arrangements, and everyday practices.

MATERIALS AND METHODS

To ensure traceability, reproducibility, and analytical rigor, the methodology was structured into three stages.

Stage 1: Systematic literature review. A systematic literature review (SLR) was conducted following the guidelines of the PRISMA 2020 statement to ensure a transparent and reproducible document-selection process. Scopus was selected as the primary database for the identification, screening, and selection of the engineering literature corpus. The search strategy was based on the terms “transformative technology” and “anticipated radical technology” appearing in titles, abstracts, and keywords. The review focuses on examining how the engineering and foresight literature conceptualizes and operationally characterizes TTs and ARTs, rather than evaluating individual technologies in isolation. ScienceDirect, SciELO, and Google Scholar were used exclusively as complementary, non-systematic sources to support the theoretical framework and discussion. Consequently, documents retrieved from these sources were excluded from the quantitative PRISMA screening flow to preserve the statistical integrity and reproducibility of the primary Scopus corpus.

Stage 2: Bibliometric and attribute-based analysis. The study began with an SLR comprising 211 records, of which 145 studies constituted the final analytical corpus. Absolute and relative frequencies, as well as co-occurrence patterns, were analyzed for seven operational attributes used to characterize TTs and ARTs: transformative potential, enabling factors, level of development, relationship with value-production networks, anticipated effectiveness, socio-regulatory and labor impacts, and genericity. In addition, a three-level ontological architecture was proposed to link technological enablers, application domains or value-production networks, and sustainability outcomes. Subsequently, VantagePoint V15.2 was employed to analyze geographic, institutional, and collaboration dynamics. The analysis identified a concentration of scientific leadership in China, the United States, and India, as well as convergence trends among intelligent digitalization, advanced manufacturing, and energy sustainability, with sustainability emerging as a structuring axis. This methodology has previously been applied by the authors in other systematic literature reviews [18,19].

Stage 3: Interpretation and governance implications. The findings were interpreted in relation to the aforementioned theoretical frameworks, with particular attention to the role of the seven operational attributes and, especially, genericity. Based on this analysis, differentiated governance orientations for TTs and ARTs are proposed, emphasizing their capacity to systematically reconfigure value-production networks and contribute to sustainability.

ANALYSIS OF RESULTS

Conceptual and Taxonomic Framework for TTs and ARTs Based on the PRISMA Protocol

The SLR process was structured in accordance with the PRISMA 2020 protocol to establish a reproducible analytical corpus for the identification, classification, and assessment of TTs and ARTs in the literature. The results of the publication identification and screening, eligibility assessment, data extraction, and ontological validation phases are presented below and summarized in Figure 1.

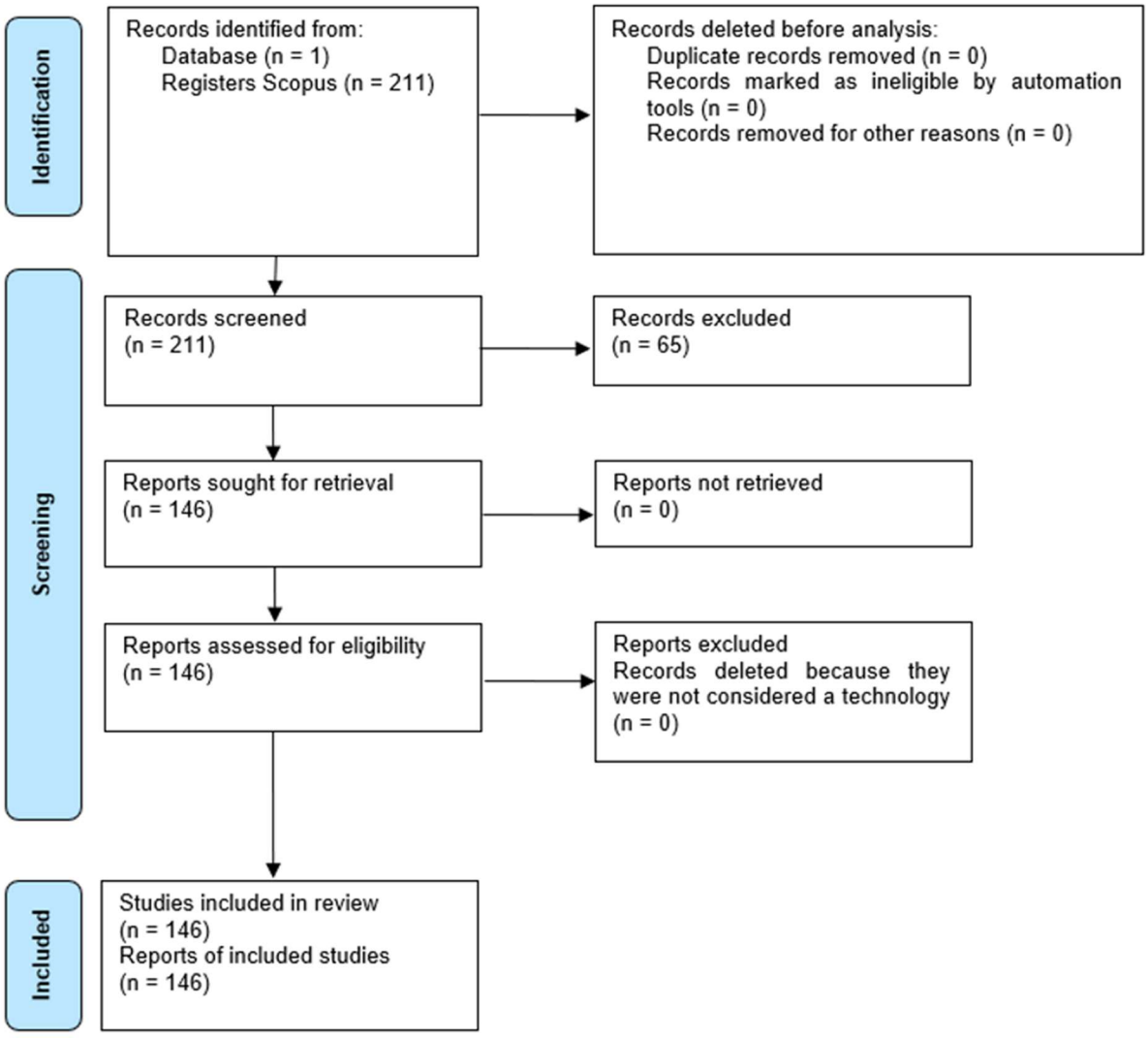


Figure 1. PRISMA phases.

Identification and screening of publications: The search equation applied to the Scopus database was TITLE-ABS-KEY (“transformative technolog*” OR “anticipated radical technolog*”) AND engi* AND (LIMIT-TO (DOCTYPE, “ar”)), which yielded a total of n = 211 records. During the screening phase, titles and abstracts were assessed according to the predefined inclusion and exclusion criteria. The inclusion criteria

comprised research articles addressing engineering-related topics and published in English or Spanish. Exclusion criteria comprised book chapters, conference proceedings, and studies lacking a clear focus on sustainability or technical applications. This screening process resulted in the exclusion of n = 65 records.

Eligibility assessment and inclusion: The remaining n = 145 articles were subjected to full-text assessment. Since all retrieved documents provided sufficient technical information to map at least one of the seven operational analytical attributes, no additional studies were excluded at this stage (n = 0). Accordingly, the final analytical corpus comprised n = 145 included studies.

Data extraction and ontological validation: Based on the systematic analysis of the retrieved records (N = 211), absolute and relative frequencies and co-occurrence patterns of the seven operational analytical attributes were examined. Each technological development identified in the final corpus was subsequently validated and structured according to a three-level ontology comprising technological enabler, application domain, and sustainability outcome. These elements were then mapped onto the 20 value-production networks defined within the Finnish foresight framework.

Identification of Analytical Evaluation Attributes

Based on the records retrieved through the SLR (n = 211), the absolute and relative frequencies and co-occurrence patterns of the seven operational analytical attributes were analyzed. Table 1 summarizes their presence in the engineering literature and enables technologies to be differentiated according to their level of development, maturity, and uncertainty, thereby avoiding the conflation of widely deployed technologies with emerging technological developments.

The results reveal a marked hierarchy in the engineering literature regarding the seven analytical attributes. The predominance of transformative potential (62.09%), enabling factors (58.29%), and technological development level (56.87%) indicates that research has focused primarily on understanding the capabilities that technologies can generate, the conditions that facilitate their development, and their degree of maturity. This pattern suggests a predominantly technological and operational orientation, in which transformation is interpreted in terms of technical capabilities, implementation conditions, and proximity to adoption. In contrast, the lower frequencies of socio-regulatory and labor impacts (35.07%) and genericity (30.33%) indicate comparatively limited attention to social and institutional implications and to the capacity of specific technologies to transcend individual sectors and application contexts.

Table 1. Number of documents by attributes.

Atribute	Operational attribute name	Papers (n)	% Included Corpus (n = 145)	Primary Analytical Focus & Operational Meaning
1	Transformative Potential	131	90.03%	Capacity to disrupt socio-technical regimes, introduce radical novelty, and reconfigure structural functions.
2	Key Enabling Factors	123	84.82%	Critical drivers, computational infrastructure, energy efficiency, data availability, and resources accelerating adoption.
3	Level of Development (Maturity)	120	82.75%	Degree of technological readiness, progressing from laboratory/simulation testing to functional prototypes and deployment.
4	Relationship with Value Production Networks	116	80.00%	Depth of integration and structural influence across the 20 cross-sectoral value creation networks.
5	Anticipated Effectiveness	113	77.93%	Probability and magnitude of achieving functional performance and driving sustainability goals (decarbonization/circularity).
6	Impacts on Professions, Regulation & Social Structures	74	51.03%	Workforce restructuring, reskilling needs, regulatory gaps, ethical considerations, and institutional adaptation.
7	Genericity	64	44.13%	Multi-purpose applicability across diverse industries (general-purpose technology capacity).

The relationship with value-production networks (54.98%) and anticipated effectiveness (53.55%) nevertheless indicates that a substantial proportion of studies moves beyond strictly technical assessment and considers the integration of technologies into productive systems. The joint presence of these attributes suggests that the literature recognizes functionality, scalability, and applicability as relevant dimensions for assessing transformative potential. However, the lower frequency of genericity indicates that the capacity of a technology to be integrated into and reused across multiple sectors remains comparatively underexamined, despite the cross-sectoral and integrative characteristics associated with technologies such as artificial intelligence (AI), machine learning, blockchain, and digital twins. Socio-regulatory and labor impacts likewise represent a less developed dimension within the corpus. Their lower frequency suggests that technology assessment continues to focus predominantly on technological capabilities and development conditions, whereas transformations affecting occupations, regulatory frameworks, and social structures receive comparatively less analytical attention. This difference is relevant because it points to a potential gap between the assessment of technological performance and the understanding of broader sociotechnical implications, particularly when technologies can extend across multiple domains of activity.

Finally, the fact that 80 of the 211 records (37.91%) did not present explicit coding for any of the seven attributes further supports this interpretation. These studies consisted primarily of case studies or technical applications that, although retrieved through the search strategy, did not explicitly operationalize the dimensions examined in this study. This finding also highlights the importance of distinguishing between the presence of a technology within the engineering literature and the explicit analytical characterization of its transformative attributes.

Corpus Operationalization: Classification by Analytical Attributes and Technological Focus

Once the values of the analytical attributes had been determined, Table 2 classifies the included studies according to the number of operational attributes addressed simultaneously, ranging from three to seven. This classification makes it possible to assess the analytical breadth of each study and to distinguish between multidimensional approaches, which integrate multiple attributes to characterize transformative technologies, and focused approaches, which concentrate on specific attributes or particular technological applications.

Table 2. Classification of the reviewed literature according to analytical attributes and technological approach.

Number of attributes	Dominant Focus and Scope	Authors/transformative technology
Seven atributes (Holistic and cross-sectoral assessment)	Comprehensive integration of technical feasibility, maturity, value network, effectiveness, genericity, and socio-regulatory/labor disruption.	AI-based digital twins for smart building optimization [20]. Future connectivity and innovations and challenges in 7G smart networks [21]. Blockchain-based secure vehicle-to-grid (V2G) models [22]. Building Information Modeling (BIM) for industrial safety improvement [23]. Intellectual property challenges in 3D printing [24]. Sustainable service consumption and technology-driven shopping experiences [25]. Technological trajectories in lithium battery manufacturing [26]. Global lithium supply chain optimization [27]. Emerging skills driven by Industry 4.0 in offsite construction [28]. Energy management for biological 3D printing [29]. Benchmarking IoT platforms through artificial intelligence assessment [30]. Research trends in telematics-based automobile insurance [31]. AI-based detection of Parkinson's disease using voice measurements [32]. Holographic communication in the metaverse [33]. Large language models for unmanned aerial vehicles (UAVs) [34]. User tracking using LEO satellites and reconfigurable intelligent surfaces (RIS) [35]. Explainable AI for Industry 5.0 [36]. Image preprocessing techniques for image classification [37]. UAV-based automated path generation for smart construction [38]. Automated agricultural monitoring and smart crop cultivation [39]. Reconfigurable intelligent surfaces for mobile radio [40]. Power modeling of RFID antennas [41]. Autonomous in-vehicle decision-making and driving-style reconfiguration [42]. Deep learning for indirect bridge-damage identification [43]. Adversarial AI and information privacy in data sharing [44]. Industrial IoT in 5G-and-beyond networks [45]. Computer-vision evaluation of powder flowability in metal additive manufacturing [46]. Performance and reliability of novel aircraft concepts [47]. Failure analysis of CNC machines due to human error [48]. Machine learning for marine sciences [49]. Biofoundries as hubs for industrial translation in synthetic biology [50]. Mixed-reality displays for guidance in cardiac mapping and ablation [51]. Probabilistic fracture-mechanics analysis of friction-stir-weld fatigue [52]. Impacts of connected and automated vehicles on greenhouse-gas emissions and urban NO_2 [53].
Six atributes (Advanced systemic assessment)	Studies linking technical feasibility and operational maturity with network efficiency and decarbonization, omitting only labor or genericity aspects.	An LLM-based decentralized vehicular network architecture for secure communications [54]. Real-time cell-distribution monitoring in 3D bioprinting using fluorescence imaging [55]. Metaheuristic optimization for wireless coverage enhancement with RIS [56]. Machine-learning prediction of tensile strength in 3D-printed PLA parts [57]. Biodegradable silk bioelectronics for long-term biosignal monitoring [58]. Intelligent roads integrating sensing and communication in mobile networks [59]. Deep-learning-powered tactile perception using graphene electronic skin [60]. Generative AI in computer programming and its relationship to learning and motivation [61]. Effects of geometry on dissolution of additively manufactured tablets [62]. Cloud service quality optimization through resource scheduling [63]. Discrete-

		event system specification for IoT applications [64]. Feature fusion in a steady-state visually evoked potential brain–computer interface [65]. Digital twins for transportation asset-data management [66]. Concept-design choices and trade-offs [67]. Investments needed to achieve net-zero construction in the UK by 2050 [68]. Data-driven condition monitoring of power-electronics systems using an edge–cloud framework [69]. Carbon-fiber composite laminates for ultralight aeronautical applications [70]. A twin-traction method for high-capacity elevators [71]. Design and implementation of ESP32-based IoT devices [72]. Optimized metaheuristic load balancing for cloud computing [73]. Assessment of BIM maturity in Malaysian public projects [74]. Packet offloading in P4 switches integrated with virtual network-function servers [75]. Digital twins in the aerospace industry [76]. Technology-strategy-based organizational transformation [77]. Additive manufacturing applications in the energy sector [78]. Microneedle applications, materials, and fabrication methods [79]. Deep-learning-based tensile-strength prediction in fused deposition modeling [80]. Augmented-reality interfaces for assistive robotic grasping [81]. Ironmaking technology designed to reduce energy consumption and CO_2 emissions [82]. Microstructure and corrosion resistance of additively manufactured 316L stainless steel [83].
Five atributes (Intermediate operational assessment)	Research focused on experimental validation, functional performance, scalability, and integration into specific value chains.	Self-powered photodetectors based on vertically stacked van der Waals heterostructures [84]. A bio-inspired PDA@MoS_2 electrode with high conductivity and antibacterial properties [85]. A CRISPR-AapCas12b platform for sensitive and specific detection [86]. Experimental evaluation of a reconfigurable intelligent surface for wireless applications [87]. An IoT data-security model using elliptic-curve Diffie–Hellman and AES [88]. Energy consumption of lightweight ciphers under ISO/IEC 29192-2 [89]. Distributed channel estimation and optimization for 6D movable antennas [90]. Deep reinforcement learning for resource allocation in wireless VR communications [91]. An additively manufactured multi-material radio-frequency quadrupole prototype [92]. Cryptocurrency adoption in India [93]. Cognitive RIS-NOMA networks [94]. Modeling concentrators for solar photovoltaic systems [95]. IoT drivers in supply chains in the oil, gas, and electric-power industries [96]. Distributed-ledger technology integration in the Nigerian construction industry [97]. Resource allocation and energy efficiency in IRS-aided MIMO wireless communications [98]. Challenges, applications, and measurements in 5G channel models [99]. Multilegged walking robots for interaction with different terrains [100]. Machine learning to predict sensor-related accident severity in autonomous vehicles [101]. Residential built-environment effects on modal preferences and auto ownership [102]. Reducing casting defects through 3D sand-printed mold designs [103]. Effects of zinc coating on weld-brazed automotive steel [104]. Raman-scattering-based distributed temperature sensors [105]. Fuzzy axiomatic design for evaluating blockchain deployment projects [106]. Mesoporous carbon catalysts with single-atom metal sites for electrochemical CO_2 reduction [107]. Laser deposition of graded γ-TiAl/Ti_2AlNb alloys [108]. Cooperative beam routing for multi-IRS-aided communications [109]. Thermodynamic calculation methods for supercritical CO_2 coal-fired boiler systems [110]. IoT security through wireless-channel-based key generation [111]. Improving reproducibility in synthetic biology [112]. Flexible photodetectors for wearable optoelectronics [113]. Technologies for safely managed sanitation [114]. Estimating the reliability of autonomous vehicles [115]. Optimal unsteady convection under dynamic thermal loads [116].
Four atributes (Focused assessment)	Works oriented toward solving targeted technical problems, protocol optimization, and defect detection in materials.	Plasma-jet-printed AgNP electrodes for high-performance fabric triboelectric generators and adaptive sensing [117]. Energy-assisted protocols in wireless sensor networks [118]. Improving abrasive-flow-machining uniformity in channels fabricated by selective laser melting [119]. Ethical and privacy concerns arising from advances in artificial intelligence, with proposed solutions [120]. Convolutional neural networks for industrial defect detection [121].
Three atributes (Niche technical assessment)	Laboratory-based experimental research limited to specific physical or mechanical parameters, or particular algorithms.	Effects of annealing on 3D-printed graphene-reinforced PLA composites [122]. Power-measurement-based channel estimation for IRS-enhanced wireless coverage [123]. Comparison of centralized and distributed SDN environments for IoT networks [124]. Strategic directions and multidisciplinary collaboration for advanced automation and control systems at IFAC [125]. Deep learning for 3D object detection in autonomous driving [126]. Vision-based omnidirectional robots for autonomous navigation and localization in manufacturing [127]. Energy harvesting technologies and applications for IoT and wireless sensor networks [128]. Transformative design methods for public spaces, applied to the ancient Yangzhou Canal in China [129]. Stability and regulation of flexible-joint robots under input/output communication delays [130].

TTs and ARTs share the potential to generate significant technological change, but differ in terms of maturity, temporal horizon, and degree of disruption. Whereas TTs tend to support the progressive improvement of processes and competitiveness, ARTs anticipate radical long-term

transformations and are associated with greater technological, regulatory and social uncertainties [131]. This distinction suggests a dual approach to innovation management that combines adaptive efficiency with foresight-oriented exploration, thereby addressing both current needs and emerging future challenges [132–137].

Regarding the technologies identified across the value-production networks, the literature provides evidence of their contribution to structural transformations associated with research, development, and innovation across diverse domains of activity. Within this corpus, 80 articles did not explicitly address the analytical attributes examined in this study but presented case studies or specific technological applications. The identified value-production networks include passenger transportation, logistics, goods manufacturing, energy supply, materials, the built environment, work automation, healthcare, security, and collaboration and trust, among others [138–146].

For example, studies addressing the passenger transportation value-production network indicate a transition toward more autonomous and sustainable mobility systems. Innovations in materials and intelligent driving, including brazing technologies applied to automotive steels and driver-emotion recognition, contribute to enhanced structural safety and human–machine interaction. Likewise, secure and decentralized vehicular communications enabled by technologies such as BlockLLM and vehicle-to-everything (V2X) systems support the development of autonomous mobility systems [147].

The authors agree that safety, efficiency, and public trust are central to the transition to smart transportation. Meanwhile, the logistics value chain is evolving toward autonomous systems and intelligent cargo robotics. The role of IoT, RFID, and blockchain optimizes traceability and communication in the supply chain. The common thread in these studies is their emphasis on data efficiency and security, which enables the consolidation of a more reliable logistics ecosystem.

In the goods manufacturing network, the transition to robotic and decentralized manufacturing relies on technologies such as bioprinting, multimaterial 3D printing, ultralight materials, and computer vision for quality control. Research agrees that these innovations reduce costs, improve quality, decentralize production, and promote sustainability.

The livelihood value production network integrates urban agriculture and robotic food production. Smart farming systems with sensors, IoT in beekeeping, and biofoundries for standardized biological processes strengthen productivity and traceability. These developments share a common focus on sustainability and the connection between technological innovation and food security.

In the energy supply network, the transition to renewable and decentralized energy is driven by distributed sensors, advanced storage, and blockchain. Catalysts for CO_2 reduction, lithium batteries, and advanced solar technologies highlight the importance of efficiency and

sustainability. These findings suggest that decentralization and innovation in energy storage are essential for a sustainable energy transition.

The materials production network incorporates circular economy approaches and renewable materials. Advances in topological photonics, materials computing, zinc coatings, and emissions reduction technologies are transforming energy-intensive industries [148]. These proposals share the common goal of promoting efficiency and sustainability, which is aligned with global decarbonization targets.

Across all value production networks, the studies reviewed highlight several common patterns. First, decentralization and digitalization are recurring enablers of transformation, allowing networks to operate more autonomously and resiliently. Second, sustainability and efficiency emerge as central objectives, linking technological innovation directly to environmental and social outcomes. Third, integration of emerging technologies—ranging from AI, IoT, blockchain, and digital twins to advanced materials and biofabrication—strengthens both operational performance and adaptability across networks.

Overall, these findings illustrate that technological transformation within value production networks is multidimensional, encompassing improvements in safety, efficiency, sustainability, and adaptability. They also indicate that successful innovation relies not only on the technology itself but on the ability to embed it within interconnected sociotechnical systems, creating value through enhanced coordination, automation, and responsiveness. The literature thus underscores the importance of viewing technological change as a systemic process that reshapes entire networks rather than isolated sectors.

This analysis reinforces the relevance of the Value Production Networks attribute as a lens for understanding how transformative technologies influence industrial, urban, and socio-environmental systems, highlighting both sector-specific effects and cross-cutting patterns of structural change.

Currently, TTs are driving the digitalization and automation of construction [149]. From BIM to digital twins and smart surfaces, the emphasis is on design optimization, real-time monitoring, and sustainability. These trends highlight the transition to smart infrastructure, which improves operational efficiency and urban quality.

The exchange network is moving toward schemes based on reputation, economics, and e-commerce. The consumption of green and digital services enhances consumer experience in P2P and C2B2C environments. The common emphasis is on the transformation of consumption models through sustainable technologies. Meanwhile, the remote impact network integrates virtual reality, augmented reality, and holographic communication to expand interactions beyond traditional media. Advanced connectivity through 5G, 6G networks, and artificial intelligence reinforces immersive experiences and telepresence. These convergences

highlight the need to redefine communication and collaboration in hybrid environments.

Work automation networks are advancing from centralized processes to decentralized robotics based on AI and collective collaboration. The IoT, XAI, and digital twins stand out for their roles in productive efficiency and transparency. The convergence of studies highlights technical governance, sustainability, and industrial resilience.

In healthcare networks, systems are evolving toward self-diagnosis, gamification, and personalized nutrition. Advances in image preprocessing, microneedles, portable spectroscopy, mixed reality, and bioelectronics have optimized diagnoses and personalized care. These developments are transforming care into more accessible, accurate, and sustainable models.

The disability care network incorporates robotics, AI, and artificial organs to promote autonomy and mobility. From AR-enabled robotic grasping systems to multipod robots, the inclusion and quality of life are being enhanced. The findings highlight human-robot integration and inclusive design as key to sustainable solutions.

In the information acquisition network, technologies such as cloud load balancing, optical communication, and blockchain strengthen the efficiency and security of distributed systems [150]. The authors also emphasize the importance of resource optimization and quality of service in cloud and IoT.

Other relevant networks include the skills and validation network, which is evolving toward AI-supported flipped and independent learning. The metaverse and generative AI in programming personalize teaching and validate practical skills. The shared insights highlight the roles of autonomous learning and immersive interaction as transformative elements.

The experience production network integrates games, shared VR/AR, and digital tourism experiences. Advances in deep learning for resource allocation, metaverse adoption studies, and digital cultural tourism have strengthened this network [151]. These studies concur in emphasizing immersion and interaction as central factors in the creation of value.

Similarly, security networks are gaining relevance as they evolve toward decentralized and collaborative approaches. Key generation via wireless channels and SDN network security are driving new forms of digital protection [152]. The shared insights lie in decentralization and collaboration as the principles of trust and digital resilience.

Within the network of collaboration and trust, digital platforms foster transparency in data-sharing. The analysis of privacy versus AI highlights the risks and promotes governance practices oriented towards peer trust. These findings underscore the need to balance data utility and privacy protection.

Finally, models based on subsidiarity and redistribution emerge within the network of power structures. Strategy-oriented technology

management strengthens institutional legitimacy and transparency. The authors concur that technology governance redefines contemporary global power dynamics.

Structuring a Technology Ontology

Overall, the 145 technologies identified can be interpreted as potential catalysts for structural transformations across the economic, social, and environmental dimensions, highlighting the need for integrated technology governance strategies and interdisciplinary collaboration. From the perspective of the Radical Technology Inquirer (RTI), Anticipated Radical Technologies (ARTs) are characterized by their transformative potential, their relationship with value-production networks, and their potential impacts on occupations, regulatory frameworks, and social structures. These attributes are complemented by anticipated effectiveness, key enabling factors, level of development, and genericity, which together provide a basis for assessing the likelihood, scope, and conditions under which such transformative potential may materialize.

This conceptualization is grounded in studies that define ARTs as technological innovations whose transformative potential has not yet materialized but that may generate significant changes in socioeconomic structures [12]. Accordingly, Table 3 classifies the technologies analyzed according to their correspondence with the Transformative Technology (TT) and ART categories, considering their technological domains, applications, attributes, and potential impacts across value-production networks.

Table 3. Classification of TTs and ARTs according to technological enablers, application domains, and sustainability outcomes.

Technology Category	TT References	ART References	Application Domains	Associated Sustainability Outcomes
AI and Advanced Analytics	[20,33,37,38,45,46, 51,59,78,82,93,103, 124,128]	[35,40,62,63, 129,130]	Mobility, manufacturing, education, construction, marine sciences	Efficiency, safety, resource optimization, emissions reduction
IoT and Cyber-Physical Systems	[31,41,43,47,61,66, 74,98,107,108,114, 121,127]	[67,131]	Industry, agriculture, smart cities, supply chains, healthcare	Energy efficiency, monitoring, resource optimization, resilience
Advanced Connectivity and Telecommunications	[36,47,65,71,75,77, 100,101,112,126]	[42,58,89,92, 96]	Telecommunications, IoT, mobility, energy systems	Energy efficiency, connectivity, consumption reduction
Blockchain and Digital Trust	[46,90,91,99,108, 109]	[22,95]	Construction, energy, IoT, digital transactions	Traceability, security, transparency, efficiency
Extended Reality and Metaverse	[74,76,93]	[21,27,34,53, 83]	Education, tourism, healthcare, industry	Novel educational models, process efficiency, inclusion
Advanced Manufacturing	[24,29,30,39,50,54, 57,59,64,76,78,80,82,	[24]	Manufacturing, construction, healthcare, energy	Circular economy, production efficiency, waste reduction

	85,94,105,111,122, 124,125]			
Advanced Materials and Nanotechnology	[54,72,85,87,106,111, 116,120,125]	[60,62]	Manufacturing, energy, sensors, electronics	Material savings, efficiency, novel sustainable materials
Biotechnology and Digital Health	[57,64,81,107,117, 120]	[52,53,60,88, 115]	Healthcare, biofabrication, synthetic biology	Health and well-being, bioeconomy, biodegradable materials
Energy and Sustainability	[26,30,48,70,80,84, 97,110,113,119,121]	[69]	Energy, manufacturing, mobility	Decarbonization, energy efficiency, CO_2 reduction
Robotics and Autonomous Systems	[39,44,49,55,68,73, 103,118,128]	[35,40,83,102, 129,130,133]	Mobility, construction, manufacturing, services	Automation, safety, efficiency, and resilience

These technologies are structured within a three-level technical ontology, which facilitates the analysis of their interactions with socioeconomic systems and their potential impacts on sustainability. The proposed ontological model integrates three fundamental dimensions.

Hierarchical Three-Level Ontological Architecture: Enabler, Domain, and Sustainability Outcome

Technological enabler (technology): Represents the technical or scientific component driving innovation. Examples include artificial intelligence, quantum computing, blockchain, and bioengineering. These enablers form the foundational capabilities that enable transformative or radical applications across sectors. When describing the technical ontology, it is emphasized that the Technological Enabler level does not correspond to a fixed technological category, but can represent an ARTs or a TTs, depending on its level of technological maturity (Attribute 4: Level of Development) and its anticipated effectiveness (Attribute 5: Anticipated Effectiveness). This distinction reinforces the evolutionary nature of the ontology and the dynamic nature of the transition from emerging technologies to technologies with transformative capacity.

Application domain (value network): Corresponds to the socioeconomic system in which the technology is implemented. The study identifies 20 distinct value production networks, including transport, health, energy, manufacturing, information, and logistics. This dimension emphasizes the cross-sectoral relevance and interconnectivity of emerging technologies.

Sustainability outcome (impact): Defines the anticipated ultimate effect of the technology in terms of economic, environmental, or social transformation. Examples include decarbonization, material circularity, and enhanced organizational resilience. This dimension links technological adoption to measurable contributions toward sustainability objectives.

This hierarchical ontology enables a structured mapping of technologies, from their scientific or technical foundation to the socioeconomic systems they influence and the sustainability outcomes

they generate. By integrating these dimensions, the model provides a comprehensive framework for assessing the systemic implications of TTs and ARTs, supporting both technological foresight and policy formulation.

The proposed three-level ontological model comprises three systematically interconnected levels (Table 4). The Technological Enabler represents the core scientific and technical driver, such as Artificial Intelligence (AI), blockchain, or biochar. The Application Domain identifies the socioeconomic value-creation network in which the technology is implemented, such as healthcare, energy, or agriculture. Finally, the Sustainability Outcome specifies the expected socioecological impact, such as decarbonization, circularity, or soil regeneration. This structure establishes a direct link between technological adoption and measurable sustainability goals.

Table 4. Classification of technologies according to the proposed ontology.

Technological Enabler	Application Domain	Sustainability Outcome	Classification (ART–TT)
Digital twins	Construction/Manufacturing	Infrastructure lifecycle optimization	TT
CRISPR/Gene editing	Healthcare/Agri-food	Personalized medicine and food security	ART
4D printing	Materials production	Waste reduction and structural adaptability	ART
Blockchain	Transaction networks	Supply chain transparency and traceability	TT
Vehicle-to-Grid (V2G) systems	Energy/Transport	Grid integration and energy resilience	TT
Quantum computing	Cybersecurity/Automation	Complex problem solving	ART
Nanomaterials	Materials production	Energy efficiency and weight reduction	TT
Microneedles and portable spectroscopy	Healthcare	Decentralized diagnostics	TT
Generative AI/LLMs	Education/Creative industries	Personalized learning and content generation	TT
Biochar	Agriculture	Carbon sequestration and soil regeneration	TT

A comparative analysis identified synonyms and conceptual convergences, which are essential for technology intelligence and terminological standardization. These convergences include natural language processing; the Internet of Things (IoT) with ubiquitous environments; BIM with digital construction; UAVs and drones with quadcopters; additive manufacturing with 3D printing and metamaterials; blockchain with smart contracts and P2P solutions; and nanotechnology with graphene and nanoparticles.

The sectoral analysis demonstrates that the convergence of digital, biological, and material technologies is reshaping multiple socioeconomic systems:

The transport sector is being transformed through the integration of artificial intelligence, advanced sensors, and V2X communication,

enabling autonomous vehicles and mobility-as-a-service (MaaS). The logistics sector benefits from the convergence of IoT, RFID, and blockchain to improve traceability, transparency, and supply chain efficiency. The healthcare sector leverages technologies such as microneedles, bioelectronics, and portable spectroscopy to support self-diagnosis, preventive care, and personalized medicine. The energy sector is advancing through smart grids and vehicle-to-grid (V2G) systems, enabling consumers to become active energy prosumers and fostering decentralized energy management. Finally, the construction sector adopts Building Information Modeling (BIM) and digital twins to support the transition from static design to predictive infrastructure monitoring and maintenance. Overall, these sectoral transformations underscore the emergence of a convergent technological ecosystem in which digitalization, automation, and biotechnology are shaping new productive architectures oriented toward sustainability, resilience, and long-term global competitiveness. Unlike the institutional foresight approaches developed by the Committee for the Future of the Parliament of Finland [1] and adapted by CONCYTEC [5], this research proposes a three-level ontological architecture to organize and track Transformative Technologies (TT) and Anticipated Radical Technologies (ART). The model connects the technological enabler with its application domain and sustainability outcomes, making it possible to represent the innovation trajectory from its technical foundation to its potential systemic effects.

Application of the Conceptual Criteria and Attributes Derived from the RTI Framework Explicit

This section clarifies that ARTs are primarily characterized by their transformative potential, their relationship with value-production networks, and their potential impacts on occupations, regulatory frameworks, and social structures. Anticipated effectiveness complements this characterization by considering the potential materialization of the identified transformative potential, whereas enabling factors, level of development, and genericity operate as supporting and descriptive attributes. This organization establishes a more transparent link between the conceptual distinction between ARTs and TTs and the analytical and classification procedures applied in the study.

The Table 5 was developed to differentiate technologies according to their anticipatory character, level of development, and transformative potential. This classification avoids treating technologies with different degrees of maturity and radicality as analytically equivalent. Accordingly, the revised framework establishes a clearer distinction between technologies that are already widely deployed, such as AI, IoT, 3D printing, and BIM, and emerging or higher-uncertainty developments, such as Hyperloop, fusion energy, and quantum computing. This revision improves the internal consistency of the classification and strengthens the

alignment between the conceptual framework, the analytical attributes, and the empirical evidence presented in the manuscript.

Table 5. Technologies according to their anticipatory character.

Transformative Technologies (TTs)	Anticipated Radical Technologies (ARTs)
Smart buildings + digital twins + AI	Metaverse in education
Blockchain for V2G	Holographic communication in the metaverse
BIM for industrial safety	LLMs in drones
3D printing and intellectual property	Emotional intelligence in autonomous vehicles
Sustainable shopping experiences	Reconfigurable surfaces for telecommunications
Lithium batteries	Biofoundries in synthetic biology
Global lithium supply chain	Mixed reality in surgery
Industry 4.0 competencies	Decentralized vehicle architecture + LLMs
Energy system for 3D bioprinting	Reconfigurable surfaces for wireless coverage
IoT and AI platforms	Biodegradable bioelectronics
Telematics for insurance	Electronic skin + deep learning
AI-based voice detection	Generative AI in education
LEO + RIS for tracking	Brain-computer interface
Explainable AI in Industry 5.0	Fusion energy
AI-based image processing	Augmented reality + robotics
Drones in construction	CRISPR-AapCas12b
Smart agriculture	Reconfigurable intelligent surfaces
RFID antennas	6D movable antennas
Adaptive vehicles	Cryptocurrencies
Deep learning for structural damage assessment	Cognitive RIS-NOMA
Adversarial data protection	Multi-terrain robots
IIoT + 5G	Synthetic biology
Carbon neutrality	
Innovative aircraft	
CNC failures	
Machine learning in marine sciences	
Welded joints	
Environmental impact of automated vehicles	
3D bioprinting monitoring	
ML for 3D printing	
Smart roads	
3D printing of pharmaceuticals	
Cloud service optimization	
Discrete-event systems + IoT	
Digital twins in transportation	
Investments for net-zero emissions	
Edge-cloud computing for power systems	
Ultralight carbon composites	
High-capacity elevators	
IoT-based educational prototyping	
Cloud load balancing	
BIM maturity	
P4 + NFV	
AI for defect detection in additive manufacturing	
Organizational technology strategy	
Additive manufacturing in the energy sector	
Microneedles	
Deep learning in additive manufacturing	
Energy and emissions reduction in iron production	
Additively manufactured stainless steel	

Self-powered photodetectors
Bioinspired PDA@MoS_2 electrode
IoT security using ECDH/AES
Lightweight encryption
Deep reinforcement learning for VR
Multi-material additive manufacturing
Solar concentrators
IoT in supply chains
Blockchain in construction
MIMO energy efficiency
5G channel models
ML for autonomous vehicle accidents
Residential environment and mobility
3D molds
Zinc coating on automotive steel
Raman sensors
Evaluation of blockchain projects
Catalysts for CO_2 reduction
Laser-fabricated gradient alloys
IRS-assisted cooperative routing
Supercritical boilers
IoT security through key generation
Flexible photodetectors
Technologies for safe sanitation
Autonomous vehicle reliability
Unsteady thermal convection
AgNP electrodes + adaptive sensors
Energy-efficient protocols in wireless networks
Abrasive flow machining + SLM
CNNs for industrial defect detection
Graphene + PLA via 3D printing
IRS-assisted channel estimation
SDN for IoT
Automation and control systems
Transformative design of public spaces

VantagePoint Software Results

Computational analysis using VantagePoint (v.15.2) is instrumental in examining the evolutionary dynamics of Transformative Technologies (TTs) and Anticipated Radical Technologies (ARTs), as well as in assessing how their systemic potential is associated with the structure of the scientific and geopolitical ecosystem underlying their development. Based on the search equation applied to Scopus, co-occurrence density analysis and the identification of emerging topics enable the characterization of key actors involved in sociotechnical transitions, as well as the identification of gaps in interinstitutional collaboration that may warrant attention from a public policy perspective. Within this analytical framework, the syntactic normalization of institutional affiliations and the subsequent bibliometric analysis reveal a highly asymmetric geographical distribution of scientific output, with research on TTs and ARTs concentrated predominantly in global leaders such as China, the United States, and India (Figure 2).

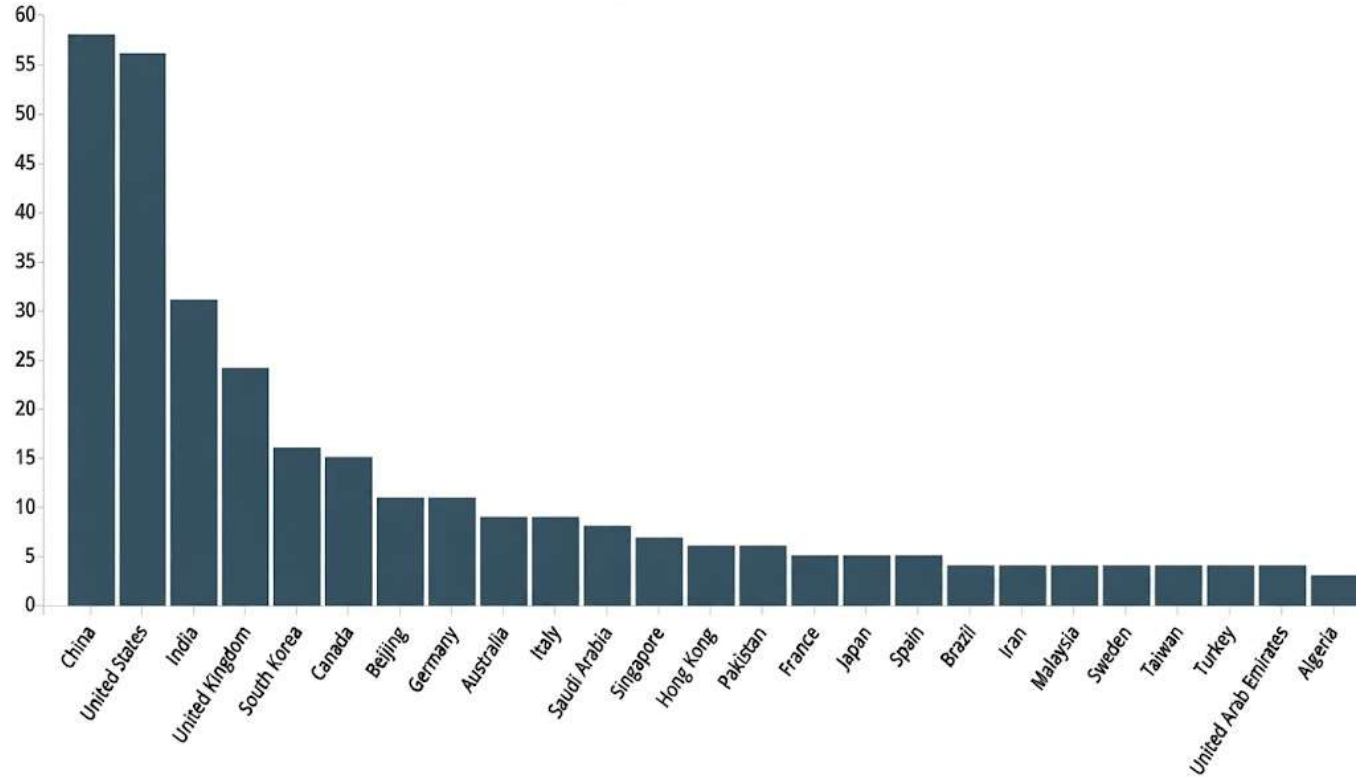


Figure 2. Data on countries that lead in the number of publications.

The concentration of scientific output in China, the United States, and India indicates a pronounced geographical specialization of technological knowledge, whereby each country directs part of its R&D capabilities toward strategic technological enablers. The co-occurrence patterns suggest that this specialization is associated with distinct domains of transformation: China exhibits a strong presence in artificial intelligence (AI) and the Internet of Things (IoT), whereas the United States shows greater representation in biotechnology and quantum computing. These findings suggest that national technological capabilities may contribute to shaping differentiated patterns of value-production network reconfiguration and sociotechnical transitions.

Figure 3 presents a frequency matrix linking technologies and countries. The bubble chart visualizes the intensity of these associations, facilitating the identification of technology areas with the highest representation within each country.

The previous figure reveals marked geographical heterogeneity and patterns of technological specialization. The United States exhibits the highest intensity of activity, particularly in Additive Manufacturing, whereas India stands out in Machine Learning and also shows activity in Additive Manufacturing, Deep Learning, and Blockchain. Germany, the United Kingdom, China, and South Korea display more diversified and specialized profiles, with China and India showing a notable concentration in 3D Printing and Digital Twin. Overall, the results indicate that global technological development is structured around specialized

hubs associated with the distinctive scientific and industrial capabilities of each country.

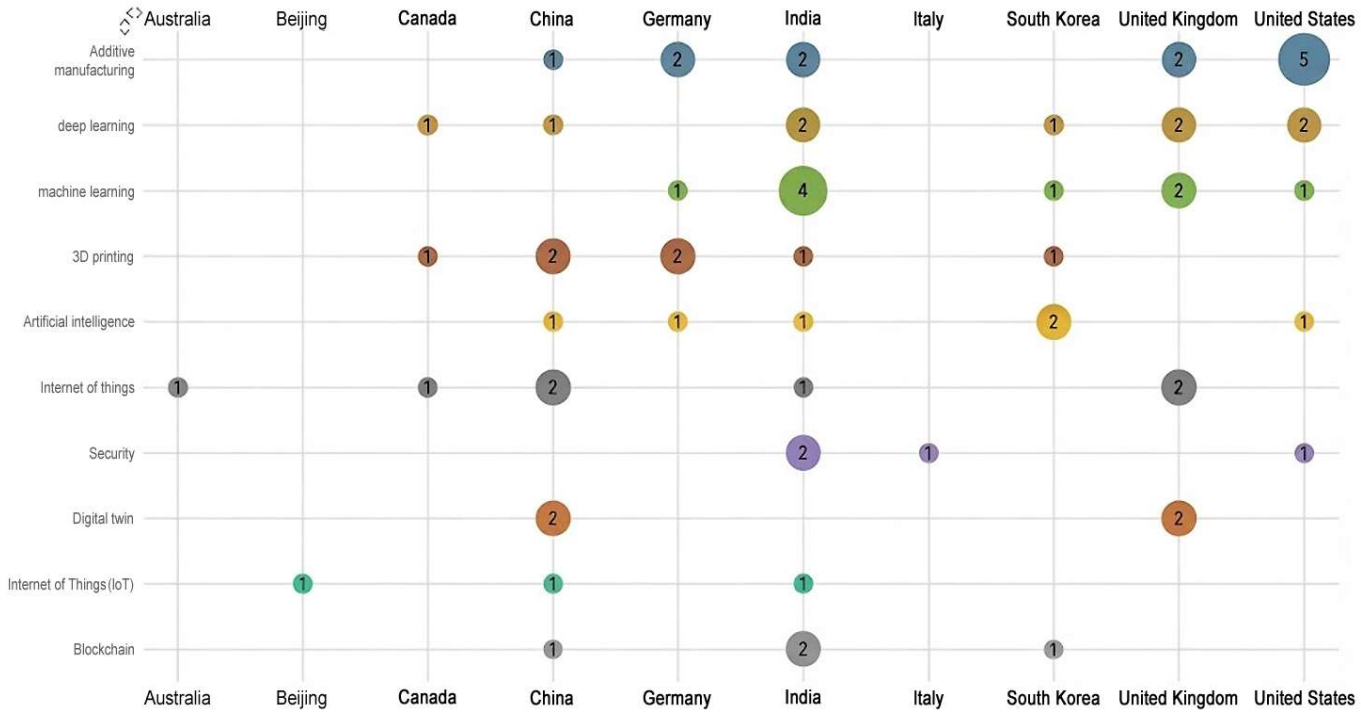


Figure 3. Technologies associated with each country.

Figure 4 presents a co-occurrence network linking authors and technological topics. The data were normalized and clustered to identify thematic and collaborative relationships, represented by nodes and links whose size and intensity reflect, respectively, the frequency and strength of these relationships.

The co-occurrence network reveals an interconnected research structure in which central authors articulate the clusters of intelligent digitalization, advanced manufacturing, and energy sustainability. The presence of IoT and digital twins as prominent technological enablers, together with AI and advanced materials, indicates convergence across different technological domains. This configuration suggests that the development of TTs and ARTs depends on interactions among technologies, authors, and fields of knowledge, while peripheral nodes extend the network toward specialized niches. In this regard, the core–periphery structure supports the interpretation of value-production network reconfiguration as a process of technological and interdisciplinary integration rather than as the isolated evolution of individual technologies.

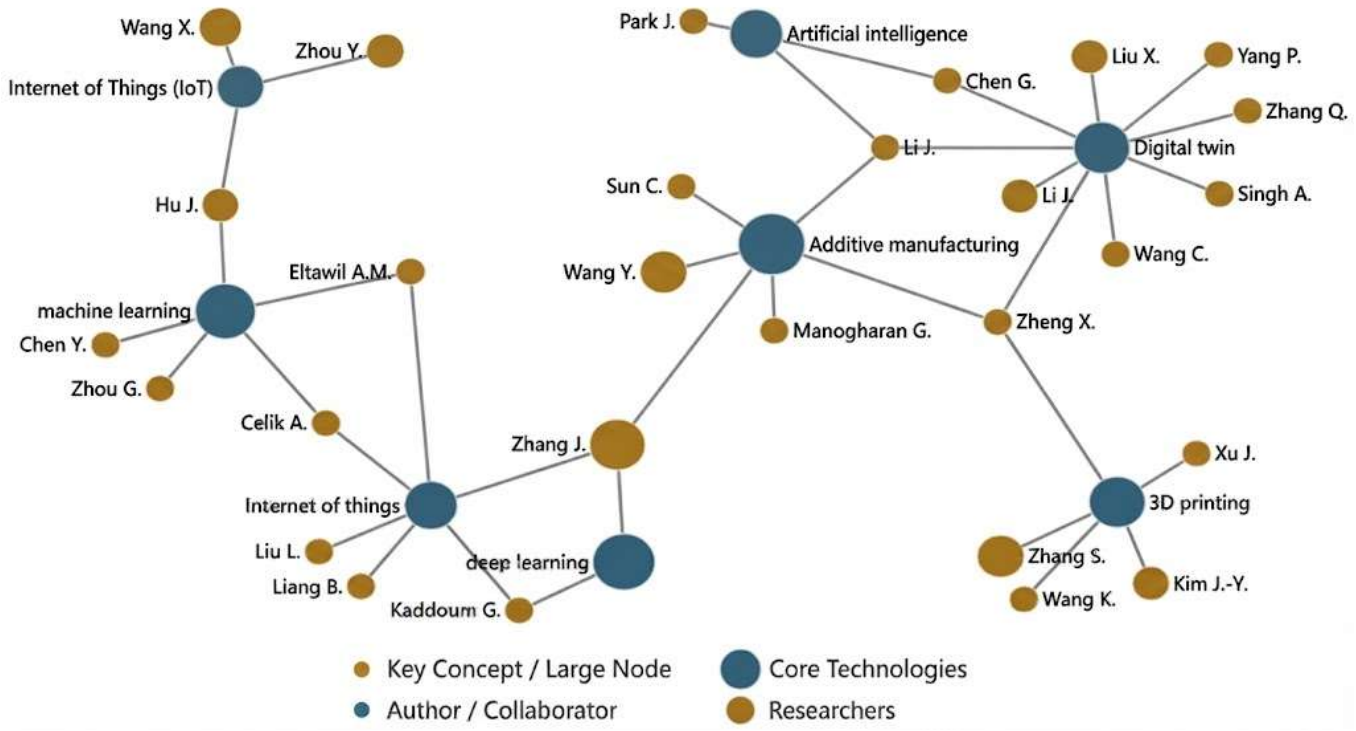


Figure 4. Co-occurrence networks.

Figure 5 presents a cluster map of authors generated using VantagePoint V15.2, showing co-occurrence patterns that highlight collaborative networks and thematic proximities within the field of transformative technologies. The analysis reveals a decentralized yet structured configuration, comprising multiple interconnected clusters that represent groups of authors working on related topics.

As shown in the previous figure, the cluster map reveals a decentralized yet interconnected scientific structure in which different groups develop complementary technological research lines. The coexistence of a core of authors with higher scientific output and a periphery oriented toward emerging applications suggests a dynamic of knowledge concentration and diversification. This configuration indicates that knowledge generation on TTs and ARTs is supported by interactions among specialized clusters, facilitating the integration of diverse technological perspectives and domains in the development of sustainable value-production networks.

As shown in Figure 6, the emergence report indicates that sustainability constitutes the principal thematic driver of the technological trajectories identified. Its high emergence intensity suggests that sustainability functions as an integrating axis linking technological convergence with different application domains, particularly energy, manufacturing, healthcare, and urban infrastructure. Likewise, the position of the Chinese Academy of Sciences highlights the institutional concentration of scientific output associated with these emerging trajectories. Overall, this pattern suggests that technological emergence is shaped by the interaction among

sustainability, technological convergence, and institutional R&D capabilities, with implications for the evolution of value-production networks.

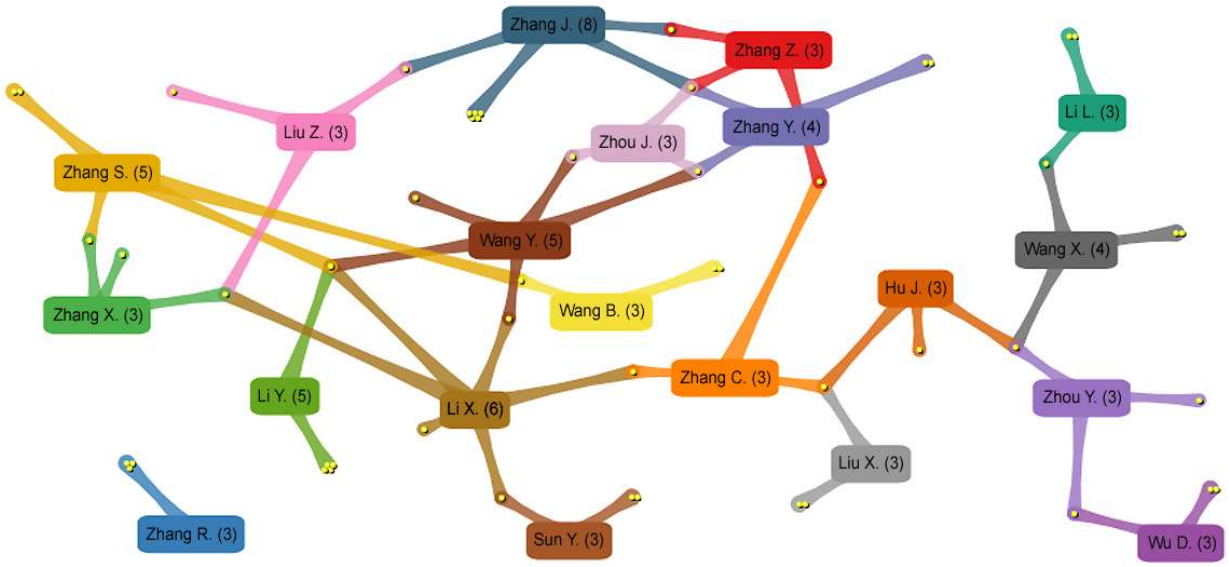


Figure 5. Cluster map of authors.

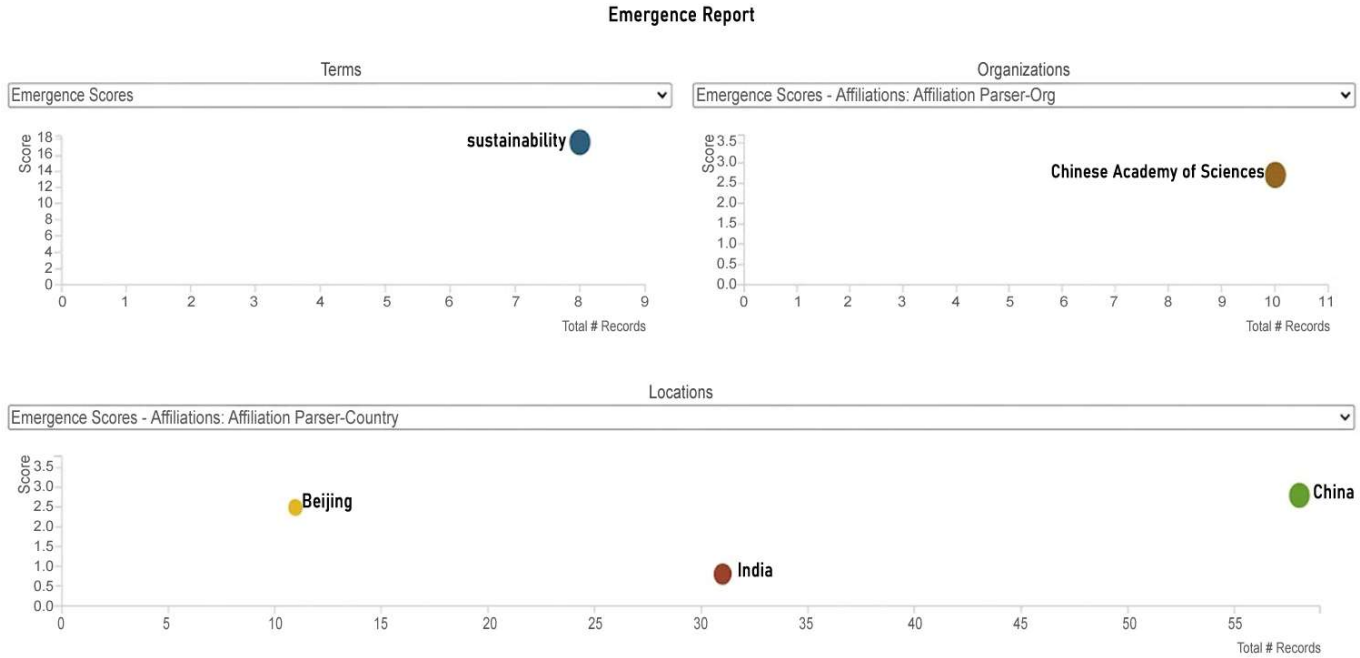


Figure 6. Emergence analysis report.

As illustrated by the word cloud (Figure 7) generated through natural language processing, text mining applied to titles, abstracts, and keywords provides a mapping of the frequencies of key terms within the corpus. However, moving beyond mere visual prominence requires qualitative contextualization of the studies to elucidate the underlying technological domains. This content analysis reveals that the literature converges around three main interrelated trajectories: (i) intelligent digitalization, centered on AI, IoT, digital twins, and cyber-physical integration; (ii)

advanced manufacturing, driven by additive manufacturing, smart sensors, and process customization; and (iii) energy sustainability, focused on energy storage, decarbonization, and resource efficiency. Overall, these clusters demonstrate how cross-cutting technological enablers can function as systemic drivers that simultaneously reconfigure industrial architectures, digital infrastructures, and sustainable value-creation networks.

The qualitative content analysis demonstrates that the identified technologies converge around three sociotechnical trajectories: intelligent digitalization, advanced manufacturing, and energy sustainability. These trajectories encompass Artificial Intelligence (AI), digital twins, the metaverse (AR/VR), autonomous vehicles, 3D printing, energy storage, and environmental solutions, which function as systemic enablers of industrial production, digital connectivity, and sustainable development. They also exhibit conceptual overlaps with the framework reported in [1] and articulate cross-cutting concepts such as scalability and efficiency, with applications in healthcare, security, and smart cities. Their integration can support resource optimization, cost reduction, and the pursuit of economic, environmental, and social objectives. However, their adoption faces barriers associated with technological maturity, regulation, social acceptance, ethics, interoperability, infrastructure, costs, governance, and data privacy.

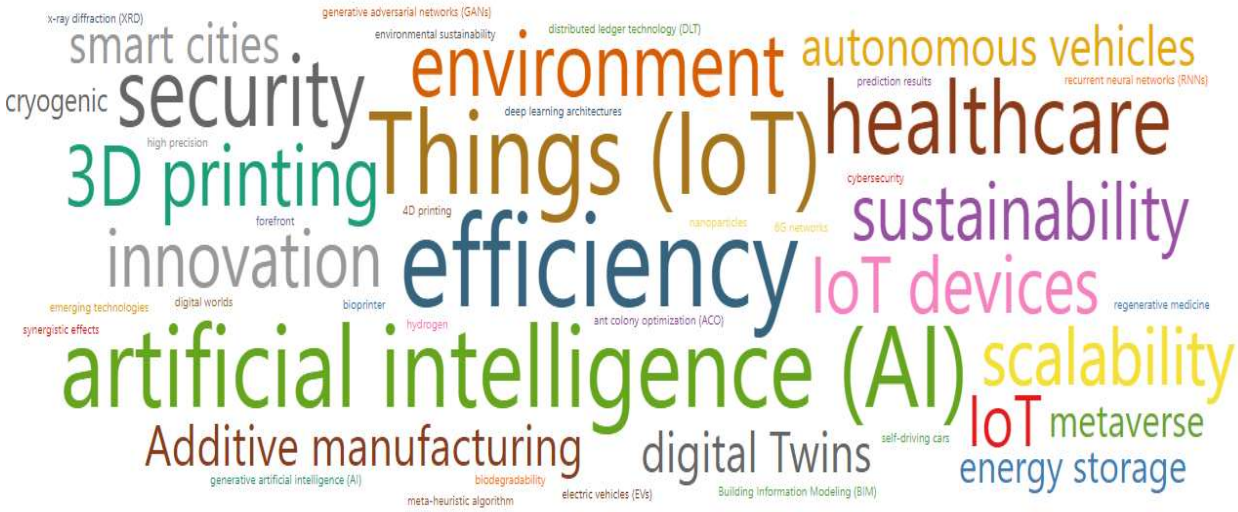


Figure 7. Word Cloud of Transformative Technologies.

The integration of these technologies expands their potential applications, including the combination of AI, IoT, and digital twins for smart cities; the integration of the metaverse/AR–VR with digital twins for urban simulations; and the combination of autonomous vehicles with IoT, AI, sensor networks, and energy-storage technologies. In this context, their management requires integrated strategies that address technological innovation, governance, regulation, social participation, ethical oversight, standardization, and sustainability.

Based on the identification of foundational technologies and the need to overcome interoperability, regulatory, and governance barriers through multitechnological integration—such as the synergies among AI, IoT, digital twins, and smart grids—it is essential to examine the bibliometric prominence with which these enablers emerge in the scientific literature. The analysis indicates that the successful management of TTs requires the integration of technological innovation with governance, public policies, social acceptance, standards, ethics, and sustainability, while also addressing challenges related to emerging environmental measurement objectives, automation, citizen participation, internationalization, and the transformation of measurement services.

In this context, Figure 8 synthesizes the frequency distribution of the most recurrent TTs and ARTs, illustrating how technical novelty, strategic alignment with sustainability, organizational leadership, and the geographical concentration of knowledge help delineate the emerging frontiers of innovation.

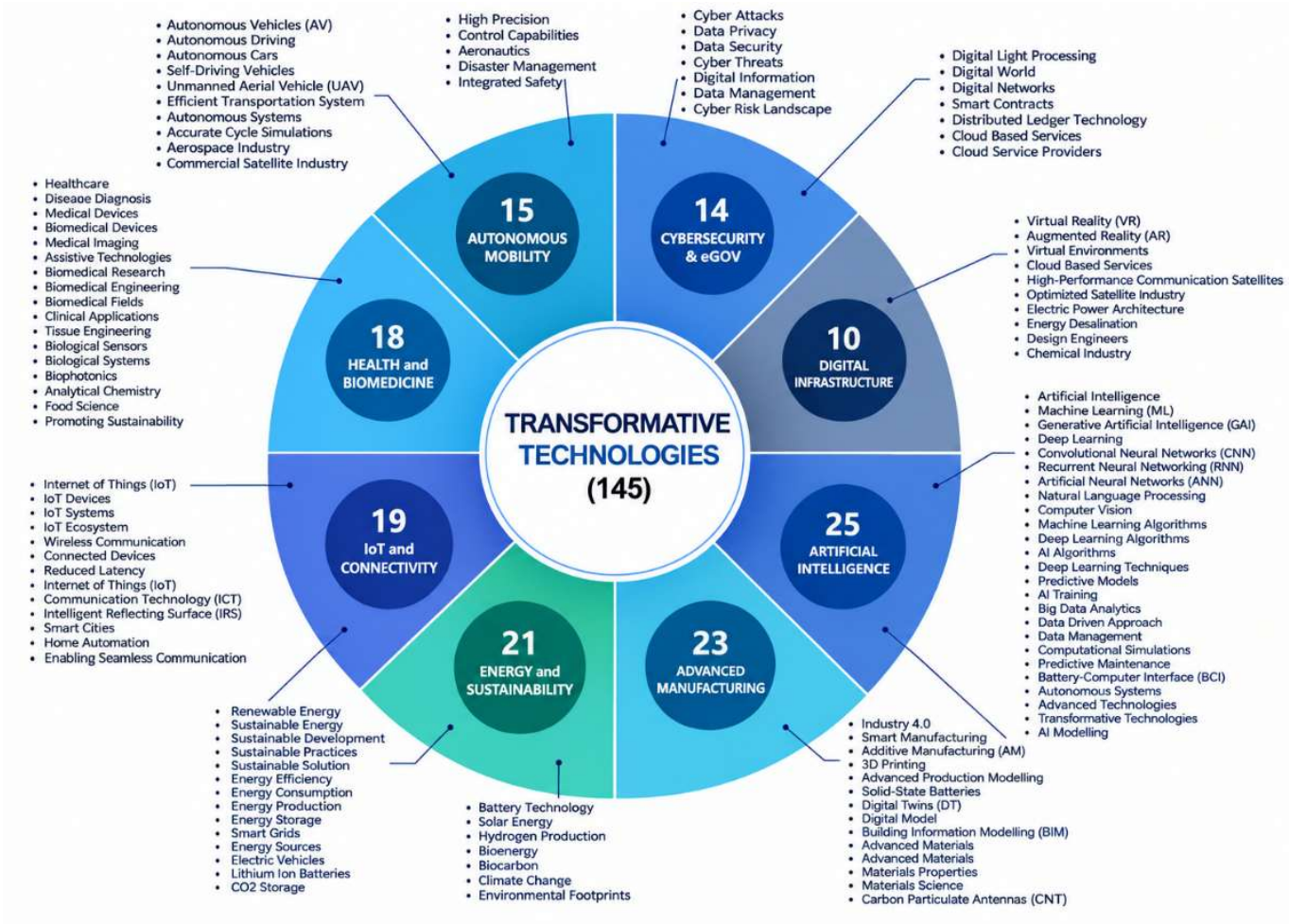


Figure 8. Most frequent TT and ARTs.

The figure above shows the 13 technologies that coincide with the Finland 2037 study. It also lists 132 new technologies identified in this literature review, including renewable energy, 4D printing, cyberattacks,

and IoT ecosystems. The 145 technologies become inputs for scientific, technological, and commercial surveillance studies and for new prospective studies with more concrete applications at the level of value production networks. Furthermore, the table suggests that, in order to take advantage of these technologies, not only technical advances are needed, but also integrated governance strategies, proactive public policies, ethics, specialized training, public-private partnerships, and assessment of social, economic, and environmental impacts.

The Triangulation of the Seven Analytical Attributes

The triangulation of the seven analytical attributes alongside the observed technological patterns identified in the word cloud (Figure 3) reveals not only the presence of transformative technologies but also systematic differences in the way the literature conceptualizes technological change. Rather than appearing with similar intensity, the attributes exhibit a clear hierarchy in the reviewed studies, reflecting the analytical priorities of engineering-oriented research.

The most frequent attribute is Transformative Potential, which appears in 62.09% of the reviewed articles. This predominance suggests that the engineering literature tends to emphasize technological novelty and the disruptive capacity of emerging technologies such as artificial intelligence, the Internet of Things (IoT), blockchain, additive manufacturing, and digital twins. These technologies are often presented as drivers of structural change in production systems, healthcare services, urban infrastructures, and digital economies. However, the analysis also reveals that the notion of transformation varies depending on the sector analyzed. In some cases, the transformation is primarily technological, as occurs with advanced materials or additive manufacturing. In others, it involves broader socioeconomic changes, such as the emergence of digital platforms, decentralized governance models enabled by blockchain, or new immersive environments associated with the metaverse.

The second most frequent attribute is Key Factors (58.29%), which generally refers to enabling conditions such as data availability, energy efficiency, computational infrastructure, or cybersecurity. The prominence of this attribute indicates that engineering research often frames technological transformation as dependent on specific enabling infrastructures, including digital connectivity, high-performance computing, or advanced materials. In this sense, the literature highlights the importance of systemic technological ecosystems rather than isolated innovations.

Similarly, the attribute Level of Development (56.87%) reflects the strong emphasis that engineering publications place on technological maturity. Most studies assess transformative technologies through experimental validation, simulation environments, or prototype development. Technologies that demonstrate interoperability with existing systems or integration into value chains are typically considered

to have greater transformative potential. This suggests that the literature implicitly links technological transformation to progress along the innovation maturity continuum, from laboratory experimentation to deployment in real-world environments.

The attribute Relationship with Value Production Networks (54.98%) confirms that many transformative technologies are analyzed within the context of sectoral value chains. The literature shows how technologies such as IoT, digital twins, and blockchain are increasingly integrated into production networks, logistics systems, energy infrastructures, and urban services. These findings reinforce the idea that technological transformation rarely occurs in isolation; rather, it emerges through the reconfiguration of interconnected sociotechnical networks.

The attribute Anticipated Effectiveness (53.55%) reflects the expectation that these technologies will generate measurable improvements in efficiency, sustainability, or service quality. In most cases, this effectiveness is associated with three convergent elements: functional validation, applicability to real-world problems, and the potential for scalability within existing value networks. Technologies such as smart grids, autonomous systems, and artificial intelligence–based diagnostic tools exemplify this pattern.

In contrast, two attributes appear with significantly lower frequency: Impacts on Professions, Regulation, and Social Structures (35.07%) and Genericity (30.33%). The relatively low presence of these attributes may reflect an important characteristic of the engineering literature. Many studies focus primarily on technical feasibility and performance, while social, institutional, or labor implications receive comparatively less attention. This imbalance suggests that the social consequences of transformative technologies—such as the transformation of work, regulatory adaptation, or ethical challenges—remain underexplored in engineering-oriented research. Consequently, future studies could benefit from greater interdisciplinary integration that incorporates perspectives from the social sciences, public policy studies, and innovation governance.

The relatively low frequency of the attribute Genericity indicates that many studies examine technologies within specific sectoral contexts rather than emphasizing their cross-sector applicability. Nevertheless, several digital technologies—particularly artificial intelligence, machine learning, blockchain, and the Internet of Things—clearly function as general-purpose technologies capable of simultaneously transforming multiple industries.

Overall, the distribution of attributes suggests that the literature on transformative technologies and anticipated radical technologies is strongly oriented toward technological capability, maturity, and operational performance, while broader social and institutional implications receive comparatively less attention. This pattern highlights the need for more integrative research approaches capable of connecting technological innovation with broader socioeconomic transformation.

DISCUSSION

The present discussion contrasts the empirical findings with the literature on sociotechnical transitions, technological foresight, and innovation governance. The analysis is structured around six triangulation axes that enable the findings to be interpreted in relation to existing theoretical and empirical references.

Triangulation with foresight and transformative innovation frameworks. The triangulation with foresight frameworks and transformative innovation literature indicates that the analysis of emerging technologies should move beyond sectoral classifications and focus on interactions among technologies, application domains, and value-production networks. Consistent with the approaches developed by CONCYTEC–Peru and Finland 2037, the proposed ontology—Technological Enabler–Application Domain–Sustainability Outcome—increases analytical resolution by disaggregating broad categories into specific enablers such as BIM, XAI, 4D printing, biochar, and advanced cybersecurity. This approach responds to Xu et al., who emphasize the need to operationally delimit transformative innovation, and is consistent with [7,8], which argue that transformative character depends not solely on technological novelty but also on the capacity to contribute to socioecological transitions and generate effects across the life cycle.

Distribution of analytical attributes. The distribution of the seven attributes reveals a clear orientation of the engineering literature toward technical capabilities and implementation conditions, reflected in the predominance of Transformative Potential (89.73%), Key Enabling Factors (84.25%), and Level of Development/Maturity (82.19%). In contrast, the lower representation of Genericity (43.84%) and Socio-regulatory and Labor Impacts (50.68%) indicates comparatively less attention to cross-sectoral diffusion and the institutional implications of technologies. Consistent with Gruetzemacher, Whittlestone, and Phillips, these results suggest a gap between technical characterization and the understanding of broader sociotechnical consequences, reinforcing the relevance of interdisciplinary approaches to technology assessment.

Differentiation between TTs and ARTs. The differentiation between TTs and ARTs indicates that technological enablers exhibit different levels of maturity, uncertainty, and adoption conditions; therefore, treating them as equivalent categories may introduce analytical bias. The use of Technology Readiness Levels (TRLs) provides a basis for distinguishing between TTs (TRL 7–9), associated with relatively mature technologies oriented toward the optimization and integration of existing processes, and ARTs (TRL 1–6), characterized by greater technical and regulatory uncertainty and by transformative potential that has not yet fully materialized. This differentiation is consistent with Linturi et al. and is also related to the approaches of Maine and Garnsey and Daim et al. Accordingly, the distinction between TT and ART depends not solely on the

technological artifact itself, but also on its level of maturity and its coupling with processes of value transformation.

Reconfiguration of value-production networks. The reconfiguration of value-production networks indicates that technologies do not operate in isolation but are interconnected transversally through processes of technological convergence. The VantagePoint analysis identifies three sociotechnical trajectories: intelligent digitalization, advanced manufacturing, and energy sustainability. These trajectories are articulated, respectively, by AI, IoT, and digital twins; additive manufacturing, biomimetic sensors, and collaborative robotics; and advanced energy storage, decarbonization, and renewable-energy integration. This configuration suggests that systemic transformation is associated with interactions among technologies, as illustrated by combinations such as V2G and blockchain in energy networks and AI and sensors in precision agriculture. These findings are consistent with the propositions of Laakkonen et al. (2023) and Luhas et al. (2019) concerning transformations in sustainable value-creation logics [2,3].

Socioecological implications of AI. Recent empirical evidence further deepens the analysis of the role of Artificial Intelligence (AI) in sustainability, indicating that its effects on resilience and energy transition are neither linear nor homogeneous [153]. On the one hand, AI can strengthen energy security, intelligent management, and cyber-physical protection against geopolitical risks, while supporting decision-making and facilitating renewable-energy adoption under conditions influenced by financial development [154]. On the other hand, its deployment involves critical socioecological and distributive trade-offs: it may generate tensions with energy equity and has been associated with an Environmental Kuznets Curve (EKC)-type trajectory [155], in which early adoption may increase energy consumption and environmental pressures before technological maturation enables reductions in carbon intensity and improvements in efficiency [156]. Taken together, these findings indicate that the genericity of AI (Attribute 6) does not ensure homogeneous outcomes across application contexts, since its effectiveness is also conditioned by technological development and maturity (Attribute 4), cybersecurity risk mitigation, and institutional capacities for equitable access (Attribute 7).

Differentiated governance implications. Based on the theoretical and empirical triangulation, a differentiated governance approach is proposed according to technological maturity and uncertainty. For ARTs, anticipatory governance is supported by foresight, technology intelligence, and interdisciplinary assessment, with the objective of exploring alternative trajectories and potential implications before widespread adoption. For TTs, adaptive governance emphasizes controlled testing environments, including regulatory sandboxes, the updating of standards, and the development of workforce capabilities, given their closer interaction with existing infrastructures, institutions, and markets.

Recommendations: Strategic and Governance Considerations

Based on the technological attributes identified in the review, several differentiated strategic and research recommendations can be proposed.

First, innovation strategies should be differentiated according to the degree of technological genericity. For highly generic technologies—such as artificial intelligence, digital infrastructures, and data-driven platforms—innovation strategies should prioritize ecosystem-based innovation models. These include platform-based innovation architectures, open innovation systems, and modular technology integration strategies that enable complementary innovations across multiple sectors. Because such technologies function as enabling infrastructures, organizations should focus on interoperability standards, data governance frameworks, and scalable digital architectures that facilitate cross-sector diffusion.

Second, technologies characterized by lower genericity but high impact on professional structures require sector-specific capability development strategies. In these cases, the main challenge is not technological diffusion but the restructuring of specialized professional competencies and regulatory frameworks. Innovation models for these technologies should therefore emphasize sectoral technology integration programs, including professional reskilling initiatives, regulatory adaptation mechanisms, and industry-specific testing environments such as regulatory sandboxes or pilot infrastructures. Examples include medical robotics, advanced manufacturing systems, and specialized biotechnology platforms, where adoption depends strongly on professional accreditation systems and regulatory oversight.

Third, technology monitoring and foresight systems should incorporate attribute-based evaluation criteria. Rather than identifying emerging technologies solely through publication or patent trends, foresight systems should assess technologies according to attributes such as transformative potential, maturity level, genericity, and systemic impact. Integrating these dimensions into monitoring frameworks would allow organizations and policymakers to prioritize technologies with the highest capacity to restructure value production networks.

Fourth, innovation policy should focus on the governance of value production networks rather than individual industries. The review shows that transformative technologies often operate across interconnected sectors—such as mobility, logistics, manufacturing, energy systems, digital services, and healthcare. Policy instruments should therefore encourage cross-sector experimentation platforms, technology testbeds, and collaborative innovation infrastructures capable of coordinating technological development across multiple value networks.

Fifth, differentiated human capital strategies should be developed according to the technological attributes identified. For highly generic technologies, workforce strategies should prioritize digital literacy, data competencies, and interdisciplinary technological capabilities that allow

professionals to operate within digitally integrated systems. In contrast, for specialized technologies with strong professional impact, training policies should focus on advanced technical specialization, certification mechanisms, and continuous professional updating programs linked to sector-specific technological standards.

Future research should advance toward quantitative evaluation models capable of measuring the economic, environmental, and organizational impacts of early ART adoption. In particular, empirical studies are needed to examine how the interaction between technological attributes—such as genericity, maturity, and systemic impact—affects adoption dynamics, productivity gains, and sustainability outcomes across different sectors.

By linking innovation strategies to the specific attributes that characterize transformative technologies, future research and policy design can move beyond generic innovation recommendations toward more precise frameworks for managing technological disruption and sustainability-oriented transformation.

The innovation policy should focus on the governance of value production networks rather than individual industries. The review shows that transformative technologies often operate across interconnected sectors such as mobility, logistics, manufacturing, energy systems, digital services, and healthcare. Policy instruments should therefore encourage cross-sector experimentation platforms, technology testbeds, and collaborative innovation infrastructures capable of coordinating technological development across multiple value networks. In this context, recent frameworks emphasize that adaptive governance and regulatory sandboxes must integrate real-time feedback loops to balance rapid technological deployment with institutional stability. Furthermore, strategic foresight models in 2026 highlight the necessity of cross-sectoral policy alignment to prevent regulatory fragmentation in complex value creation ecosystems.

This study presents several limitations that should be considered when interpreting its findings. First, the SLR used Scopus as the sole primary database and employed a search strategy centered on the labels “transformative technolog*” and “anticipated radical technolog*,” which may have excluded studies addressing disruptive or emerging technologies that do not explicitly use these categories. Second, no formal evidence-quality assessment or standardized classification based on Technology Readiness Levels (TRLs) was applied; therefore, the assessment of technological maturity relied on the characterization reported in the included studies. Third, although the coding of the seven attributes was conducted through independent review and discrepancy resolution, no formal inter-rater reliability coefficient was calculated. Finally, the concentration of evidence in particular regions and the linguistic restrictions of the corpus may limit the representativeness of the findings, particularly with respect to TT and ART dynamics in the Global

South. These limitations delimit the scope of the findings and suggest the need for future reviews to incorporate multiple databases, formal quality-assessment procedures, inter-rater agreement metrics, and greater geographical and linguistic diversity.

CONCLUSIONS

This study contributes to the emerging literature on Anticipated Radical Technologies (ARTs) and Transformative Technologies (TTs) by identifying and systematizing 145 technologies extracted from 211 Scopus-indexed publications through a structured systematic literature review supported by bibliometric analysis using VantagePoint. The main conceptual contribution of the study lies in the identification of seven analytical attributes that characterize these technologies: transformative potential, integration within value production networks, critical enabling factors, level of technological maturity, anticipated effectiveness, degree of genericity, and impact on professions, regulation, and social structures.

The results indicate that ARTs should not be understood as isolated technological breakthroughs but as components of convergent technological ecosystems in which multiple domains—such as artificial intelligence, robotics, biotechnology, advanced materials, and digital infrastructures—interact to generate systemic change. Their transformative capacity emerges primarily from their ability to reconfigure value production networks, affecting several sectors simultaneously rather than producing isolated industry-specific disruptions.

Furthermore, the findings demonstrate that bridging the gap between Anticipated Radical Technologies (ARTs) and Transformative Technologies (TTs) requires a paradigm shift from traditional, sector-isolated policy approaches toward integrated network governance. Because ARTs operate under high technological uncertainty while TTs demand rapid organizational adaptation, institutional frameworks must pursue dual-track implementation strategies: employing anticipatory governance with continuous foresight for emerging ARTs, and flexible, adaptive regulatory sandboxes for deploying TTs across value production networks. Ultimately, the systemic transformation of these 20 value-creation networks relies not merely on the technical superiority of individual innovations, but on the strategic alignment of technological attributes—such as genericity, maturity, and cross-sectoral applicability—with overarching sustainability and decarbonization imperatives.

Another important finding concerns the role of ARTs in enabling sustainability-oriented transformations of value production systems. Several of the technologies identified in the review—particularly those related to smart energy systems, advanced materials, digital monitoring platforms, and precision agriculture—support improvements in resource efficiency, circular production systems, and environmental monitoring capabilities. In this sense, ARTs increasingly function as technological

enablers of sustainability transitions, particularly when integrated into circular economy models and digitally coordinated production networks.

DATA AVAILABILITY

The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

JZS: Conceptualization, Methodology, Formal analysis, Investigation, Writing—original draft, Project administration. LHB: Formal analysis, Methodology, Investigation, Validation, Data curation. LGC: Conceptualization, Formal analysis, Writing—review and editing, Validation. MLP: Project administration, Supervision, Validation, Visualization, Writing—review and editing. JT: Investigation, Data curation, Visualization, Software, Writing—review and editing, Supervision. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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REFERENCES

1. Linturi R, Kuusi O. Societal transformation 2018–2037: 100 anticipated radical technologies, 20 regimes, case Finland. Helsinki (Finland): Parliament of Finland, Committee for the Future; 2018.
2. Laakkonen A, Rusanen K, Hujala T, Gabrielsson M, Pykäläinen J. Implications of the sustainability transition on the industry value creation logic–case of Finnish pulp and paper industry. Silva Fenn. 2023;57(3):23024. doi: 10.14214/sf.23024
3. Luhas J, Mikkilä M, Uusitalo V, Linnanen L. Product diversification in sustainability transition: the forest-based bioeconomy in Finland. Sustainability. 2019;11(12):3293. doi: 10.3390/su11123293
4. Zarkogianni K, Litsa E, Mitsis K, Wu PY, Kaddi CD, Cheng CW, et al. A review of emerging technologies for the management of diabetes mellitus. IEEE Trans Biomed Eng. 2015;62(12):2735-49. doi: 10.1109/TBME.2015.2470521
5. Peralta Delgado CS, Cárdenas Velásquez JI. Informe de vigilancia tecnológica: Tecnologías transformadoras. 2020. Available from: https://repositorio.concytec.gob.pe/entities/publication/501ac860-8b6d-406c-bd8f-931798acf6db. Accessed on 2026 Feb 7.

6. Xu H, Pang H, Winnink J, Luo R, Wang C. Disambiguating the definitions of the concept 'transformative innovation'. J Inf Sci. 2023;49(4):932-51. doi: 10.1177/01655515211061865
7. Novy A, Barlow N, Fankhauser J. Innovación transformadora. Manual de política ambiental crítica. Cheltenham (UK): Edward Elgar Publishing; 2022. p. 593-610. doi: 10.4337/9781839100673.00053
8. Miller SA, Keoleian GA. Framework for analyzing transformative technologies in life cycle assessment. Environ Sci Technol. 2015;49(5):3067-75. doi: 10.1021/es505217a
9. Jarvenpaa SL, Ives B. Introducing transformational information technologies: the case of the World Wide Web technology. Int J Electron Commer. 1996;1(1):95-126. doi: 10.1080/10864415.1996.11518278
10. Assimakopoulos DG, Oshri I, Pandza K. Management of emerging technologies for economic and social impact: an introduction. Managing Emerging Technologies for Socio-Economic Impact. 2015:1-22. doi: 10.4337/9781782547884.00007
11. Karmokar S. Transformative technologies and social change: an introduction. Proceedings of the 14th European Conference on Innovation and Entrepreneurship; 2019 Sep 19-20; Kalamata, Greece.
12. Linturi R, Höyssä M, Kuusi O, Vähämäki V. Radical Technology Inquirer: a methodology for holistic, transparent and participatory technology foresight. Eur J Futures Res. 2022;10(1):18. doi: 10.1186/s40309-022-00206-6
13. Gruetzmacher R, Whittlestone J. The transformative potential of artificial intelligence. Futures. 2022;135:102884. doi: 10.1016/j.futures.2021.102884
14. Maine E, Garnsey E. Commercializing generic technology: the case of advanced materials ventures. Res Policy. 2006;35(3):375-93. doi: 10.1016/j.respol.2005.12.006
15. Daim TU, Rueda G, Martin H, Gerdsri P. Forecasting emerging technologies: use of bibliometrics and patent analysis. Technol Forecast Soc Change. 2006;73(8):981-1012. doi: 10.1016/j.techfore.2006.04.004
16. Phillips PW. Governing transformative technological innovation: who's in charge? Governing Transformative Technological Innovation. Cheltenham (UK): Edward Elgar Publishing; 2007.
17. Fazey I, Schäpke N, Caniglia G, Patterson J, Hultman J, Van Mierlo B, et al. Ten essentials for action-oriented and second order energy transitions, transformations and climate change research. Energy Res Soc Sci. 2018;40:54-70. doi: 10.1016/j.erss.2017.11.026
18. Campuzano LR, Hincapie Llanos GA, Zartha Sossa JW, Orozco Mendoza GL, Palacio JC, Herrera M. Barriers to the adoption of innovations for sustainable development in the agricultural sector—systematic literature review (SLR). Sustainability. 2023;15(5):4374. doi: 10.3390/su15054374
19. Betancourt Morales CM, Zartha Sossa JW. Circular economy in Latin America: a systematic literature review. Bus Strategy Environ. 2020;29(6):2479-97. doi: 10.1002/bse.2515

20. Oulefki A, Kheddar H, Amira A, Kurugollu F, Himeur Y, Bounceur A. Innovative AI strategies for enhancing smart building operations through digital twins: a survey. Energy Build. 2025;335:115567. doi: 10.1016/j.enbuild.2025.115567
21. Chamola V, Peelam MS, Guiana M, Niyati D. Future of connectivity: a comprehensive review of innovations and challenges in 7g smart networks. IEEE Open J Commun Soc. 2025;6:3555-613. doi: 10.1109/OJCOMS.2025.3560035
22. Sasirega R, Prakash S. Secure and incentivized V2G participation with blockchain and game theory. J Inf Secur Appl. 2025;89:103975. doi: 10.1016/j.jisa.2025.103975
23. Manzoor B, Charef R, Antwi-Afari MF, Alotaibi KS, Harirchian E. Revolutionizing construction safety: unveiling the digital potential of Building Information Modeling (BIM). Buildings. 2025;15(5):1154. doi: 10.3390/buildings15051154
24. Kantaros A. Intellectual property challenges in the age of 3D printing: navigating the digital copycat dilemma. Appl Sci. 2024;14(23):11448. doi: 10.3390/app142311448
25. Nair AJ, Manohar S. Green service consumption: unlocking customer expectations on technological transformations enhancing purchase experience in retail store. Int J Inf Manage Data Insights. 2024;4(2):100277. doi: 10.1016/j.jjimei.2024.100277
26. Zhao X, Wu W, Wu D. Technological trajectory analysis in lithium battery manufacturing: based on patent claims perspective. J Energy Storage. 2024;98:112894. doi: 10.1016/j.est.2024.112894
27. Jones EC Jr. Lithium supply chain optimization: a global analysis of critical minerals for batteries. Energies. 2024;17(11):2685. doi: 10.3390/en17112685
28. Ginigaddara B, Perera S, Feng Y, Rahnamayiezekavat P, Kagioglou M. Industry 4.0 driven emerging skills of offsite construction: a multi-case study-based analysis. Constr Innov. 2024;24(3):747-69. doi: 10.1108/CI-04-2022-0081
29. Wang K, Xu J, Zhang S, Tan J. Energy management system for biological 3D printing based on manifold model morphing and semi-supervised machine learning. J Clean Prod. 2024;448:141520. doi: 10.1016/j.jclepro.2024.141520
30. Crăciun RA, Pietraru RN, Moisescu MA. Internet of things platform benchmark: an artificial intelligence assessment. Rev Roum Sci Tech Sér Électrotech Énergét. 2024;69(1):97-102. doi: 10.59277/RRST-EE.2024.1.17
31. Chauhan V, Yadav J. Bibliometric review of telematics-based automobile insurance: mapping the landscape of research and knowledge. Accid Anal Prev. 2024;196:107428. doi: 10.1016/j.aap.2023.107428
32. Pradeep Reddy G, Rohan D, Kumar YVP, Prakash KP, Srikanth M. Artificial intelligence-based effective detection of Parkinson's disease using voice measurements. Eng Proc. 2024;82(1):28. doi: 10.3390/ecsa-11-20481
33. Shvetsov AV, Alsamhi SH. When holographic communication meets metaverse: applications, challenges and future trends. IEEE Access. 2024;12:197488-515. doi: 10.1109/ACCESS.2024.3514576

34. Javaid S, Fahim H, He B, Saeed N. Large language models for UAVs: current state and pathways to the future. IEEE Open J Veh Technol. 2024;5:1166-92. doi: 10.1109/OJVT.2024.3446799
35. Zheng P, Liu X, Al-Naffouri TY. LEO-and RIS-empowered user tracking: a Riemannian manifold approach. IEEE J Sel Areas Commun. 2024;42(12):3445-61. doi: 10.1109/JSAC.2024.3459074
36. Trivedi C, Bhattacharya P, Prasad VK, Patel V, Singh A, Tanwar S, et al. Explainable AI for industry 5.0: vision, architecture, and potential directions. IEEE Open J Ind Appl. 2024;5:177-208. doi: 10.1109/OJIA.2024.3399057
37. Dehbozorgi P, Ryabchykov O, Bocklitz T. A systematic investigation of image pre-processing on image classification. IEEE Access. 2024;12:64913-26. doi: 10.1109/ACCESS.2024.3395063
38. Kim HJ, Kim JY, Kim JW, Kim SK, Na WS. Unmanned aerial vehicle-based automated path generation of rollers for smart construction. Electronics. 2024;13(1):138. doi: 10.3390/electronics13010138
39. Rahman MB, Chakma JD, Momin A, Islam S, Uddin MA, Islam MA, et al. Smart crop cultivation system using automated agriculture monitoring environment in the context of Bangladesh agriculture. Sensors. 2023;23(20):8472. doi: 10.3390/s23208472
40. Casetti C. Spotlight on reconfigurable intelligent surfaces [Mobile radio]. IEEE Veh Technol Mag. 2023;18(3):8-14.
41. Wei L, Lau WC. Modelling the power of RFID antennas by enabling connectivity beyond limits. Natl J Antennas Propag. 2023;5(2):43-8. doi: 10.31838/NJAP/05.02.07
42. Panagiotopoulos I, Dimitrakopoulos G. Intelligent, in-vehicle autonomous decision-making functionality for driving style reconfigurations. Electronics. 2023;12(6):1370. doi: 10.3390/electronics12061370
43. Hajializadeh D. Deep learning-based indirect bridge damage identification system. Struct Health Monit. 2023;22(2):897-912. doi: 10.1177/14759217221087147
44. Majeed A, Hwang SO. When AI meets information privacy: the adversarial role of AI in data sharing scenario. IEEE Access. 2023;11:76177-95. doi: 10.1109/ACCESS.2023.3297646
45. Mahmood A, Beltramelli L, Abedin SF, Zeb S, Mowla NI, Hassan SA, et al. Industrial IoT in 5G-and-beyond networks: vision, architecture, and design trends. IEEE Trans Ind Inform. 2021;18(6):4122-37. doi: 10.1109/TII.2021.3115697
46. Zhang J, Habibnejad-korayem M, Liu Z, Lyu T, Sun Q, Zou Y. A computer vision approach to evaluate powder flowability for metal additive manufacturing. Integr Mater Manuf Innov. 2021;10(3):429-43. doi: 10.1007/s40192-021-00226-3
47. Bendarkar MV, Sarojini D, Mavris DN. Off-nominal performance and reliability of novel aircraft concepts during early design. J Aircr. 2022;59(2):400-14. doi: 10.2514/1.C036395

48. Boral S, Chakraborty S. Failure analysis of CNC machines due to human errors: an integrated IT2F-MCDM-based FMEA approach. Eng Fail Anal. 2021;130:105768. doi: 10.1016/j.engfailanal.2021.105768
49. Ryazanov I, Nylund AT, Basu D, Hassellöv IM, Schliep A. Deep learning for deep waters: an expert-in-the-loop machine learning framework for marine sciences. J Mar Sci Eng. 2021;9(2):169. doi: 10.3390/jmse9020169
50. Farzaneh T, Freemont PS. Biofoundries are a nucleating hub for industrial translation. Synth Biol.2021;6(1):ysab013. doi: 10.1093/synbio/ysab013
51. Southworth MK, Silva JNA, Blume WM, Van Hare GF, Dalal AS, Silva JR. Performance evaluation of mixed reality display for guidance during transcatheter cardiac mapping and ablation. IEEE J Transl Eng Health Med. 2020;8:1-10. doi: 10.1109/JTEHM.2020.3007031
52. Ranjan R, Walbridge S, Shah L, Gerlich A. Probabilistic fracture mechanics analysis of friction stir weld fatigue performance. Kei Kinzoku Yosetsu. 2020;58(Suppl):72s-6s. doi: 10.11283/jlwa.58.72s
53. Tu R, Alfaseeh L, Djavadian S, Farooq B, Hatzopoulou M. Quantifying the impacts of dynamic control in connected and automated vehicles on greenhouse gas emissions and urban NO2 concentrations. Transp Res Part D Transp Environ. 2019;73:142-51. doi: 10.1016/j.trd.2019.06.008
54. Arshad U, Halim Z. BlockLLM: a futuristic LLM-based decentralized vehicular network architecture for secure communications. Comput Electr Eng. 2025;123(Part A):110027. doi: 10.1016/j.compeleceng.2024.110027
55. Margarita A, Gugliandolo SG, Santoni S, Moscatelli D, Colosimo BM. A novel solution for real-time in-situ cell distribution monitoring in 3D bioprinting via fluorescence imaging. Biofabrication. 2025;17(2):021001. doi: 10.1088/1758-5090/adb891
56. Panuganti N, Ranjan P, Shukla A. Impact of metaheuristic optimization algorithms on wireless network coverage enhancement with reconfigurable intelligent surfaces. Int J Commun Syst. 2025;38(5):e70026. doi: 10.1002/dac.70026
57. Nikzad MH, Heidari-Rarani M, Rasti R, Sareh P. Machine learning-driven prediction of tensile strength in 3D-printed PLA parts. Expert Syst Appl. 2025;264:125836. doi: 10.1016/j.eswa.2024.125836
58. Mirbakht SS, Golparvar A, Umar M, Kuzubasoglu BA, Irani FS, Yapici MK. Highly self-adhesive and biodegradable silk bioelectronics for all-in-one imperceptible long-term electrophysiological biosignals monitoring. Adv Sci. 2025;12(8):advs.202405988. doi: 10.1002/advs.202405988
59. Matricardi E, Favarelli E, Pucci L, Xu W, Paolini E, Giorgetti A. Toward intelligent roads: uniting sensing and communication in mobile networks. Sensors. 2025;25(3):778. doi: 10.3390/s25030778
60. Heo G, Yoon J, Jeong J, Kwon YW, Hong SW. Deep learning-powered robust tactile perception: bridging graphene electronic skin and dynamic decoding. Adv Intell Syst. 2025;7(6):2400909. doi: 10.1002/aisy.202400909

61. Cubillos C, Mellado R, Cabrera-Paniagua D, Urra E. Generative artificial intelligence in computer programming: does it enhance learning, motivation, and the learning environment? IEEE Access. 2025;13:40438-55. doi: 10.1109/ACCESS.2025.3532883
62. Afkhami S, Abdi M, Baserinia R. Effect of geometry on the dissolution behaviour of complex additively manufactured tablets. J Manuf Mater Process. 2025;9(1):11. doi: 10.3390/jmmp9010011
63. Tamilarasu P, Singaravel G, Manoharan P, Selvarajan S. QoS transformation in the cloud: advancing service quality through innovative resource scheduling. IET Commun. 2025;19(1):e70040. doi: 10.1049/cmu2.70040
64. Alavi Fazel I, Wainer G. Discrete event system specification for iot applications. Sensors. 2024;24(23):7784. doi: 10.3390/s24237784
65. Krishnappa M, Anandaraju M. A novel steady-state visually evoked potential-based brain-computer interfaces using trans-subject feature fusion approach. Indones J Electr Eng Comput Sci. 2024;36(1):392-400. doi: 10.11591/ijeecs.v36.i1.pp392-400
66. Ammar A, Maier F, Pratt WS, Richard E, Dadi G. Practical application of digital twins for transportation asset data management: case example of a safety hardware asset. Transp Res Rec. 2024;2678(10):114-30. doi: 10.1177/03611981241231804
67. Waldon C, Muldrew SI, Keep J, Verhoeven R, Thompson T, Kisbey-Ascott M. Concept design overview: a question of choices and compromise. Philos Trans A Math Phys Eng Sci. 2024;382(2280):20230414. doi: 10.1098/rsta.2023.0414
68. Dunant CF, Allwood JM. What investments in material production are needed to achieve net-zero construction in the UK by 2050. J Clean Prod. 2024;464:142709. doi: 10.1016/j.jclepro.2024.142709
69. Bhoi SK, Chakraborty S, Verbrugge B, Helsen S, Robyns S, El Baghdadi M, Hegazy O. Intelligent data-driven condition monitoring of power electronics systems using smart edge-cloud framework. Internet Things. 2024;26:101158. doi: 10.1016/j.iot.2024.101158
70. Fantuzzi N, Dib A, Babamohammadi S, Campigli S, Benedetti D, Agnelli J. Mechanical analysis of a carbon fibre composite woven composite laminate for ultra-light applications in aeronautics. Compos Part C Open Access. 2024;14:100447. doi: 10.1016/j.jcomc.2024.100447
71. Kim GY, Jang SH. Elevating innovation: unveiling the twin traction method for a 50-ton load capacity elevator in building and construction applications. Buildings. 2024;14(5):1244. doi: 10.3390/buildings14051244
72. Hercog D, Lerher T, Truntič M, Težak O. Design and implementation of ESP32-based IoT devices. Sensors. 2023;23(15):6739. doi: 10.3390/s23156739
73. Rao DC, Sharma S, Nayak SK, Srichandan SK, Dash A. A novel modified and optimized meta-heuristic load-balancing technique for cloud computing system. Int J Intell Syst Appl Eng. 2023;11(9s):598-611.
74. Yusoff SNS, Brahim J, Mohd Nordin R, Preece C. Assessing building information modelling (BIM) maturity level in design and build public projects: case studies of public projects in Malaysia. Int J Sustain Constr Eng Technol. 2023;14(5):241-51.

75. Neha FF, Lai YC, Hossain MS, Lin YD. Offloading in P4 switch integrated with multiple virtual network function servers. J Commun Softw Syst. 2023;19(4):278-88. doi: 10.24138/jcomss-2023-0125
76. Li L, Aslam S, Wileman A, Perinpanayagam S. Digital twin in aerospace industry: a gentle introduction. IEEE Access. 2021;10:9543-62. doi: 10.1109/ACCESS.2021.3136458
77. Luman RR, Galpin TJ, Krill JA. Becoming a strategy-driven technology organization: a case study. IEEE Eng Manag Rev. 2023;51(2):104-19. doi: 10.1109/EMR.2023.3246431
78. Sun C, Wang Y, McMurtrey MD, Jerred ND, Liou F, Li J. Additive manufacturing for energy: a review. Appl Energy. 2021;282:116048. doi: 10.1016/j.apenergy.2020.116041
79. Rad ZF, Prewett PD, Davies GJ. An overview of microneedle applications, materials, and fabrication methods. Beilstein J Nanotechnol. 2021;12(1):1034-46. doi: 10.3762/bjnano.12.77
80. Zhang J, Wang P, Gao RX. Deep learning-based tensile strength prediction in fused deposition modeling. Comput Ind. 2019;107:11-21. doi: 10.1016/j.compind.2019.01.011
81. Weisz J, Allen PK, Barszap AG, Joshi SS. Assistive grasping with an augmented reality user interface. Int J Robot Res. 2017;36(5-7):543-62. doi: 10.1177/0278364917707024
82. Sohn HY, Mohassab Y. Development of a novel flash ironmaking technology with greatly reduced energy consumption and CO_2 emissions. J Sustain Metall. 2016;2(3):216-27. doi: 10.1007/s40831-016-0054-8
83. Trelewicz JR, Halada GP, Donaldson OK, Manogharan G. Microstructure and corrosion resistance of laser additively manufactured 316L stainless steel. JOM. 2016;68(3):850-9. doi: 10.1007/s11837-016-1822-4
84. Ding EX, Karakassides A, Zhou Y, Fang R, Ali F, Kauppinen EI, Lipsanen H. High-performance, self-powered photodetectors based on vertically stacked van der Waals heterostructures toward bifacial photovoltaics. Nano Energy. 2025;111:111062. doi: 10.1016/j.nanoen.2025.111062
85. Zhang S, Deng S, Bo T, Li Y, Zhao J, Wang Y, Liu Y. A bio-inspired PDA@MoS2 electrode with high conductivity and excellent antibacterial properties for selective and efficient uranium recovery via capacitive deionization. Chem Eng J. 2025;494:163199. doi: 10.1016/j.cej.2025.163199
86. Zhou J, Wu Z, Yu L, Huang X, Xiao F, Zhang Y, Wang Y. A one-pot, one-step CRISPR-AapCas12b-based platform for sensitive and specific detection of Klebsiella pneumoniae. Sens Bio-Sens Res. 2025;47:100797. doi: 10.1016/j.sbsr.2025.100797
87. ALRikabi HTS, Sallomi AH, Khazaal HF, Magdy A. Design and experimental evaluation of a reconfigurable intelligent surface for wireless applications. Results Eng. 2025;26:104694. doi: 10.1016/j.rineng.2025.104694
88. Alviana S, Azizi MF, Hirawan D. Internet of things data security model using elliptic curve Diffie-Hellman and advanced encryption standard. J Eng Sci Technol. 2025;20(2):47-54.

89. Aslan B. Energy consumption analysis of ISO/IEC 29192-2 standard lightweight ciphers. Appl Sci. 2025;15(7):3928. doi: 10.3390/app15073928
90. Shao X, Zhang R, Jiang Q, Park J, Quek TQS, Schober R. Distributed channel estimation and optimization for 6D movable antenna: unveiling directional sparsity. IEEE J Sel Top Signal Process. 2025;19:353908. doi: 10.1109/JSTSP.2025.353908
91. Kougioumtzidis G, Poulkov VK, Lazaridis PI, Zaharis ZD. Deep reinforcement learning-based resource allocation for QoE enhancement in wireless VR communications. IEEE Access. 2025;13:3538546. doi: 10.1109/ACCESS.2025.3538546
92. Brenner S, Dickmann M, Helm R, Mitteneder J, Schlick G, Lehmann M, et al. A radio-frequency quadrupole prototype additively manufactured as a multi-material component. Prog Addit Manuf. 2025;10(6):3951-61. doi: 10.1007/s40964-025-01120-6
93. Sharma A, Panse C, Gupta N, Dawar S, Kudal P, Sharma M. Adoption of cryptocurrency in India: an extended technology adoption model. Int J Saf Secur Eng. 2024;14(6):140602. doi: 10.18280/ijsse.140615
94. Thien HT, Le AT, Minh BV, Rejfek L, Koo I. Performance analysis of a cognitive RIS-NOMA in wireless sensor network. Appl Sci. 2024;14(13):5865. doi: 10.3390/app14135865
95. Machado da Costa AF, Marques Lameirinhas RA, Pinho Correia Valério Bernardo C, Neto Torres JP, Santos M. The modeling of concentrators for solar photovoltaic systems. Energies. 2024;17(13):3201. doi: 10.3390/en17133201
96. Hasheminasab Z, Mazroui Nasrabadi E, Sadeqi Arani Z. Presenting the model of internet of things drivers in Iran's oil, gas, and electric power industry supply chain with a fuzzy total interpretive structural modeling approach. Energy Eng Manag. 2024;14(1):90-107. doi: 10.22052/eem.2024.253818.1036
97. Aliu J, Oke AE, Ehiosun LU. Distributed ledger technology integration in Nigerian construction industry: key drivers. Int J Build Pathol Adapt. 2025;43(7):1706-24. doi: 10.1108/IJBPA-02-2024-0044
98. Baskar N, Selvaprabhu P, Kumaravelu VB, Chinnadurai S, Rajamani V, Menon V. A survey on resource allocation and energy efficient maximization for IRS-aided MIMO wireless communication. IEEE Access. 2024;12:85423-54. doi: 10.1109/ACCESS.2024.3415374
99. Shoaib M, Husnain G, Sayed N, Lim S. Unveiling the 5G frontier: navigating challenges, applications, and measurements in channel models and implementations. IEEE Access. 2024;12:59533-60. doi: 10.1109/ACCESS.2024.3392761
100. Robson N, Audrey V, Dwivedi A, Kunzmann D. Robust multilegged walking robots for interactions with different terrains. J Mech Robot. 2024;16(1):4062134. doi: 10.1115/1.4062303
101. Shafique R, Rustam F, Murtala S, Jurcut AD, Choi GS. Advancing autonomous vehicle safety: machine learning to predict sensor-related accident severity. IEEE Access. 2024;12:25933-48. doi: 10.1109/ACCESS.2024.3366990

102. Mondal A, Bhat CR. Investigating residential built environment effects on rank-based modal preferences and auto-ownership. Transp Res Rec. 2023;2677(10):777-96. doi: 10.1177/03611981231163861
103. Martinez D, King P, Sama SR, Sim J, Toykoc H, Manogharan G. Effect of freezing range on reducing casting defects through 3D sand-printed mold designs. Int J Adv Manuf Technol. 2023;126(1):569-81. doi: 10.1007/s00170-023-11112-x
104. Khan MS, Cho YH, Zhang S, Goodwin F, Biro E, Zhou YN. The effect of zinc coating type on the morphology, joint geometry, and mechanical properties of weld-brazed thin-gauge automotive steel. Metall Mater Trans A. 2023;54(1):179-95. doi: 10.1007/s11661-022-06857-1
105. Silva LC, Segatto ME, Castellani CE. Raman scattering-based distributed temperature sensors: a comprehensive literature review over the past 37 years and towards new avenues. Opt Fiber Technol. 2022;74:103091. doi: 10.1016/j.yofte.2022.103091
106. Gölcük İ. An interval type-2 fuzzy axiomatic design method: a case study for evaluating blockchain deployment projects in supply chain. Inf Sci. 2022;602:159-83. doi: 10.1016/j.ins.2022.04.034
107. Luo Z, Yin Z, Yu J, Yan Y, Hu B, Nie R, et al. General synthetic strategy to ordered mesoporous carbon catalysts with single-atom metal sites for electrochemical CO_2 reduction. Small. 2022;18(16):2107799. doi: 10.1002/smll.202107799
108. Chen H, Liu Z, Cheng X, Zou Y. Laser deposition of graded γ-TiAl/Ti2AlNb alloys: microstructure and nanomechanical characterization of the transition zone. J Alloys Compd. 2021;875:159946. doi: 10.1016/j.jallcom.2021.159946
109. Mei W, Zhang R. Cooperative beam routing for multi-IRS aided communication. IEEE Wirel Commun Lett. 2021;10(2):426-30. doi: 10.1109/LWC.2020.3034370
110. Zhou J, Zhu M, Su S, Chen L, Xu J, Hu S, et al. Numerical analysis and modified thermodynamic calculation methods for the furnace in the 1000 MW supercritical CO_2 coal-fired boiler. Energy. 2020;212:118735. doi: 10.1016/j.energy.2020.118735
111. Zhang J, Li G, Marshall A, Hu A, Hanzo L. A new frontier for IoT security emerging from three decades of key generation relying on wireless channels. IEEE Access. 2020;8:138406-46. doi: 10.1109/ACCESS.2020.3012006
112. Jessop-Fabre MM, Sonnenschein N. Improving reproducibility in synthetic biology. Front Bioeng Biotechnol. 2019;7:18. doi: 10.3389/fbioe.2019.00018
113. An J, Le TSD, Lim CHJ, Tran VT, Zhan Z, Gao Y, et al. Single-step selective laser writing of flexible photodetectors for wearable optoelectronics. Adv Sci. 2018;5(8):1800496. doi: 10.1002/advs.201800496
114. Sohail M, Cavill S, Afolabi OO. Transformative technologies for safely managed sanitation. Proc Inst Civ Eng Munic Eng. 2018;171(2):78-85. doi: 10.1680/jmuen.16.00026

115. Kalra N, Paddock SM. Driving to safety: how many miles of driving would it take to demonstrate autonomous vehicle reliability? Transp Res Part A Policy Pract. 2016;94:182-93. doi: 10.1016/j.tra.2016.09.010
116. Fakoor-Pakdaman M, Ahmadi M, Andisheh-Tadbir M, Bahrami M. Optimal unsteady convection over a duty cycle for arbitrary unsteady flow under dynamic thermal load. Int J Heat Mass Transf. 2014;78:1187-98. doi: 10.1016/j.ijheatmasstransfer.2014.07.058
117. Aliyana AK, Jalajamony HM, De S, Bairagi S, Mulvihill DM, Fernandez RE, Stylios GK. Plasma jet printed AgNP electrodes for high-performance fabric TENGs and adaptive sensing applications. Chem Eng J. 2025;504:158791. doi: 10.1016/j.cej.2024.158791
118. Qureshi KU, Almutairi HS. Empirical evaluation of energy-assisted protocols for wireless sensor networks. Indones J Electr Eng Inform. 2024;12(4):991-1004. doi: 10.52549/ijeei.v12i4.5814
119. Peng C, Xu Q, Ding L, Zhou T, Gao H, Wang X. Novel insights into abrasive flow machining uniformity for SLM channels. Int J Mech Sci. 2024;262:108726. doi: 10.1016/j.ijmecsci.2023.108726
120. Furizal F, Ramelan A, Adriyanto F, Maghfiroh H, Ma'arif A, Kariyamin K, Fawait AB. Concerns of ethical and privacy in the rapid advancement of artificial intelligence: directions, challenges, and solutions. J Robot Control. 2024;5(6):2015-26. doi: 10.18196/jrc.v5i6.24090
121. Khanam R, Hussain M, Hill R, Allen P. A comprehensive review of convolutional neural networks for defect detection in industrial applications. IEEE Access. 2024;12:94250-95. doi: 10.1109/ACCESS.2024.3425166
122. Liesenfeld J, Jablonski JJ, da Silva JRF, Buenos AA, Scheuer CJ. Impact of annealing on the characteristics of 3D-printed graphene-reinforced PLA composite. J Manuf Process. 2024;128:133-57. doi: 10.1016/j.jmapro.2024.08.025
123. Sun H, Zhu L, Mei W, Zhang R. Power measurement based channel estimation for IRS-enhanced wireless coverage. IEEE Trans Wirel Commun. 2024;23(12):19183-98. doi: 10.1109/TWC.2024.3480314
124. Yalda K, Hamad DJ, Tapus N. Comparative analysis of centralized and distributed SDN environments for IoT networks. J Control Eng Appl Inform. 2024;26(3):84-91. doi: 10.61416/ceai.v26i3.9164
125. Stapleton L, Wang FY, Netto M, Jia QS, Visioli A, Kopacek P. Shaping the future of advanced automation and control systems for society strategic directions and multidisciplinary collaborations of IFAC's social systems coordinating committee. Annu Rev Control. 2024;58:100967. doi: 10.1016/j.arcontrol.2024.100967
126. Pravallika A, Hashmi MF, Gupta A. Deep learning frontiers in 3D object detection: a comprehensive review for autonomous driving. IEEE Access. 2024;12: 173936-80. doi: 10.1109/ACCESS.2024.3456893

127. Patruno C, Renò V, Nitti M, Mosca N, Summa M, Stella E. Vision-based omnidirectional indoor robots for autonomous navigation and localization in manufacturing industry. Heliyon. 2024;10:e26042. doi: 10.1016/j.heliyon.2024.e26042
128. Naifar S, Kanoun O, Trigona C. Energy harvesting technologies and applications for the internet of things and wireless sensor networks. Sensors. 2024;24(14):4688. doi: 10.3390/s24144688
129. Fanzini D, Miao S, Casoni G. Methods and instruments for the transformative design of the public space: insight from the ancient canal of Yangzhou in China. Front Built Environ. 2024;10:1408827. doi: 10.3389/fbuil.2024.1408827
130. Liu YC, Chopra N. On stability and regulation performance for flexible-joint robots with input/output communication delays. Automatica. 2014;50(6):1698-705. doi: 10.1016/j.automatica.2014.04.022
131. Chirombo BF, Pangapanga-Phiri I. Adaptive practices and governance structures for building climate resilient agrifood systems value chains in Sub-Saharan Africa. Discov Sustain. 2025;6:879. doi: 10.1007/s43621-025-01837-y
132. Acemoglu D, Lensman T. Regulating transformative technologies. NBER Work Pap. 2023; 359-76. doi: 10.3386/w31461
133. Fuentes-Peñailillo F, Gutter K, Vega R, Silva GC. Transformative technologies in digital agriculture: leveraging IoT, remote sensing, and artificial intelligence for smart crop management. J Sens Actuator Netw. 2024;13(4):39. doi: 10.3390/jsan13040039
134. Cisternas Irarrazabal C, Vallejos-Romero A, Cordova-Sánchez M, Sáez-Ardra F. Risk governance of emerging technologies: the case of synthetic biology in Latin America. Sociol Tecno. 2025;1:74-99. doi: 10.24197/st.1.2025.74-99
135. Huo X, Wang S, Zheng B, Wu X. R&D subsidies and radical innovation: innovative mindset and competition matter. Systems. 2025;13(4):282. doi: 10.3390/systems13040282
136. Vissa AA, Sekhar JA. Technical trends, radical innovation, and the economics of sustainable, industrial-scale electric heating for energy efficiency and water savings. Sustainability. 2025;17(13):5916. doi: 10.3390/su17135916
137. Isaza Domínguez LG. Digital twins in Industry 5.0–a systematic literatura review. Eur Public Soc Innov Rev. 2024;9:1-21. doi: 10.31637/epsir-2024-641
138. Singh G, Rajesh R, Misra SC, Singh S. Analyzing the role of digital twins in developing a resilient sustainable manufacturing supply chain: a grey influence analysis (GINA) approach. Technol Forecast Soc Change. 2024;209:123763. doi: 10.1016/j.techfore.2024.123763
139. Rachmawati R, Rahmah AA, Reinhart H, Sensus DI, Sunindyo WD. Metaverse, digital twins, and smart sustainable urban development concepts for Nusantara capital city, Indonesia. Int J Sustain Dev Plan. 2024;19(12):4613. doi: 10.18280/ijsdp.191210
140. Myllylä Y, Kaivo-oja J. A hybrid foresight study of the environmental reference laboratory system in Finland: a foresight study for the government of Finland. Eur J Futures Res. 2024;12:2. doi: 10.1186/s40309-023-00223-z

141. Bahroun Z, Anane C, Ahmed V, Zacca A. Transforming education: a comprehensive review of generative artificial intelligence in educational settings through bibliometric and content analysis. Sustainability. 2023;15(17):12983. doi: 10.3390/su151712983
142. Babashahi L, Barbosa CE, Lima Y, Lyra A, Salazar H, Argôlo M, et al. AI in the workplace: a systematic review of skill transformation in the industry. Adm Sci. 2024;14(6):127. doi: 10.3390/admsci14060127
143. Jeremiah SR, El Azzaoui A, Xiong NN, Park JH. A comprehensive survey of digital twins: applications, technologies and security challenges. J Syst Archit. 2024;151:103120. doi: 10.1016/j.sysarc.2024.103120
144. Sakr M, Sadhu A. Recent progress and future outlook of digital twins in structural health monitoring of civil infrastructure. Smart Mater Struct. 2024;33(3):033001. doi: 10.1088/1361-665X/ad2bd7
145. Mayer A, Greif L, Haeussermann TM, Otto S, Kastner K, El Bobbou S, et al. Digital twins, extended reality, and artificial intelligence in manufacturing reconfiguration: a systematic literature review. Sustainability. 2025;17(5):2318. doi: 10.3390/su17052318
146. Zribi H, Ben Abid T, Elloumi A, Hani Y, Bechir Graba B, Elmhamedi A. Industry 4.0: digital twins characteristics, applications, and challenges in-built environments. Prod Manuf Res. 2025;13(1):2456277. doi: 10.1080/21693277.2025.2456277
147. Khalid I, Maglogiannis V, Naudts D, Shahid A, Moerman I. Intra-technology enhancements for multi-service multi-priority short-range V2X communication. Sensors. 2025;25(8):2564. doi: 10.3390/s25082564
148. Blanco de Paz M, Devescovi C, Giedke G, Saenz JJ, Vergniory MG, Bradlyn B, et al. Tutorial: computing topological invariants in 2D photonic crystals. Adv Quantum Technol. 2020;3(2):1900117. doi: 10.1002/qute.201900117
149. Chowdhury T, Adain J, Wilkinson S. Review of digital technologies to improve productivity of New Zealand construction industry. J Inf Technol Constr. 2019;24: 569-87. doi: 10.36680/j.itcon.2019.032
150. Celik A, Romdhane I, Kadoun G, Entail AM. A top-down survey on optical wireless communications for the internet of things. IEEE Commun Surv Tutor. 2022;25(1):1-45. doi: 10.1109/COMST.2022.3220504
151. Koziel AM, Shen CW, Djailani I, Chang YL. Beyond social norms: psychological and hedonic drivers of metaverse adoption among generation Y. IEEE Access. 2025;13:78441-60. doi: 10.1109/ACCESS.2025.3563758
152. Yzzogh H, Benaboud H. Enhancing SDN security with a feature-based approach using multiple k-means, Word2Vec, and neural network. Bull Electr Eng Inform. 2025;14(2):1456-67. doi: 10.11591/eei.v14i2.8834
153. Zhang C, Li R, Wang Q. Geopolitical risks and energy resilience: the moderating role of artificial intelligence in the global energy transition. Renew Sustain Energy Rev. 2027;244:117465. doi: 10.1016/j.rser.2026.117465
154. Wang Q, Liu T, Li R. Artificial intelligence and environmental sustainability: investigating the AI-EKC nexus for SDG 7 and SDG 13. Sustain Dev. 2026;34(1):1141-66. doi: 10.1002/sd.70294

155. Liu T, Li R, Wang Q. Artificial intelligence innovation and the global energy trilemma: a cross-country panel analysis of conditional associations. Sustain Dev. 2026;1-27. doi: 10.1002/sd.71385
156. Zhang C, Li R, Wang Q. Artificial intelligence and energy resilience: dynamic evolution, developmental heterogeneity, and the moderating roles of geopolitical risk and clean energy. Sustain Dev. 2026;1-22. doi: 10.1002/sd.71366

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