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Editorial

Technological Development as a Cyclic Foundation for Achieving Sustainable Development Goals: Towards a Synthesis of Virtual Economics

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Abstract. The contemporary stage of technological development is characterised by a transition from the digital economy to a cognitive–virtual phase, in which technology serves as a key instrument for achieving the Sustainable Development Goals (SDGs). In a broad context, this paper conceptualises technological development as a cyclical process that reflects the regularities of successive technological paradigms, economic waves, and industrial revolutions. Particular attention is given to the integration of approaches from economics, management, mathematics, information technology, and the social sciences to enable a systemic analysis of sustainable development phenomena. The literature review demonstrates that, despite extensive research on technological paradigms and digital transformation, the interrelation between technological cycles and SDGs across micro-, meso-, macro-, and mega-levels remains insufficiently examined. Moreover, a coherent conceptual model explaining how the wave structure of technological progress contributes to the resilience of economic and social systems has not yet been fully developed. The objective of this study is to establish a conceptual framework that unites the theory of economic cycles, the evolution of technological paradigms, and the sustainable development agenda within the paradigm of Virtual Economics. Methodologically, the study adopts an interdisciplinary approach combining elements of mathematical modelling, systems analysis, and comparative–historical methods. The findings suggest that technological cycles not only reflect the internal dynamics of innovation but also shape the conditions for achieving SDGs through digitalisation, cognitive technologies, and the development of virtual ecosystems. The study concludes that Virtual Economics represents a new integrative platform combining economic, technological, and socio-cultural dimensions of sustainable development. Future research perspectives involve examining the role of the metaverse as a cognitive-economic domain of the seventh technological paradigm and developing mathematical models to forecast its impact on global processes.

Keywords: technological cycles; sustainable development; SDGs; virtual economics; digital transformation; cognitive technologies; metaverse.

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1. Introduction

The contemporary stage of global development is characterised by rapid technological progress, which has become not merely a factor of economic growth but a system-forming principle in the evolution of human societies. In an era of accelerating digitalisation and increasing interconnectivity of global processes, technology functions as a universal instrument for transforming economic, social, and cultural systems. Consequently, within the framework of the United Nations' Sustainable Development Goals (SDGs), technological development is regarded as a key driver in achieving ecological balance, social justice, and economic resilience. Despite the abundance of strategies, concepts, and national programmes of digital transformation, no comprehensive model has yet been proposed that fully accounts for the cyclical nature of technological progress, its multi-level structure, and its interrelation with the global sustainability agenda. Development should not be perceived as a linear process; rather, it unfolds in waves or oscillations that reflect the rhythmic interaction of innovation, production, and social change. These waves – whether those of Kitchin, Juglar, Kuznets, or Kondratieff – mark the recurrent pulsation of economic activity and structural transformation. Each wave signifies the emergence of a new technological paradigm, accompanied by an industrial revolution that reshapes both economic structures and social organisation.

From the standpoint of systems dynamics, technological development can be conceptualised as a sequence of phase transitions through which dominant technological paradigms and corresponding industrial revolutions succeed one another. Historically, these processes have been closely interconnected:

- The first technological paradigm, emerging in the 1770s, coincided with the First Industrial Revolution, founded on the mechanisation of production and the use of water and steam power;
- The second paradigm, developing from the 1820s, reflected the Age of Coal and Steam and the Second Industrial Revolution, marked by the expansion of railways and steam engines;
- The third paradigm, established by the 1870s, corresponded to the Age of Steel and Electricity, characterised by mass production and the introduction of the Bessemer process;
- The fourth paradigm, beginning in the early twentieth century, was aligned with the Third Industrial Revolution—the age of oil, assembly lines, and motorisation;
- The fifth paradigm, developing since the 1970s, embodied the Fourth Industrial Revolution, the digital age, driven by computers, microelectronics, and telecommunications;
- The sixth paradigm, emerging in the early twenty-first century, is associated with the Era of Nanotechnologies, Bioengineering, and Intelligent Systems;
- The seventh paradigm, currently in formation, is linked to the Cognitive Revolution, where artificial intelligence, neurotechnologies, the metaverse, and the fusion of physical and digital realities play a central role.

Thus, technological paradigms and industrial revolutions form a synchronous structure in which each new wave of innovation generates not only technological but also socio-economic transformations in the world system.

The relevance of this study lies in the need to integrate approaches from various disciplines – economics, management, mathematics, information technology, and socio-cultural studies – to construct a comprehensive understanding of technological development within the context of sustainable progress. Mathematical modelling, in particular, enables the identification of deep regularities in cyclicity, the quantitative description of technological waves, the detection of bifurcation points, and the forecasting of paradigm transitions. The synthesis of humanistic, technological, and mathematical knowledge provides a conceptual foundation for understanding development patterns in the era of digital and cognitive transformation.

The transition from the sixth to the seventh technological paradigm marks the beginning of a new cognitive-virtual phase, in which physical, digital, and social spaces converge into a single ecosystem – the metaverse. In this context, the metaverse is not a transient technological trend but rather a structural manifestation of the next stage of techno-economic evolution, where virtual interactions, artificial intelligence, and data constitute the foundation of a new economic reality.

Within this transformation, the concept of the Virtual Economy acquires particular significance as the nucleus of the emerging post-industrial development paradigm. In this study, the Virtual Economy is understood not merely as the aggregate of economic processes occurring in digital environments but as a new paradigm of socio-economic interaction based on the integration of real and virtual spaces, data, and cognitive technologies. It represents a system of interconnected digital, informational, and network ecosystems in which both material and immaterial resources—data, knowledge, algorithms, images, and meanings—are created, distributed, and consumed. Unlike the traditional digital economy, primarily focused on technological infrastructure, the Virtual Economy reflects a new economic ontology in which the boundaries between the physical and digital worlds become increasingly permeable. Within this paradigm, new institutions of property, labour, consumption, and production are emerging, and sustainable development is achieved through digital inclusion, algorithmic governance, and intelligent systems.

Accordingly, the Virtual Economy can be regarded as an integrative platform of post-industrial development, enabling the convergence of technological paradigms, industrial revolutions, economic cycles, and the Sustainable Development Goals into a single cognitive-virtual continuum. In this sense, technological development should be viewed not merely as a process of innovative renewal but as the structural basis of sustainability – through the establishment of digital institutions, new forms of employment, data systems, and platform-based ecosystems. At the micro level, this manifests in intelligent devices and digital services; at the meso level, in Industry 4.0 and smart cities; at the macro level, in national digital strategies; and at the mega level, in global network structures, metaverses, and cognitive economies.

The objective of this editorial is to propose a conceptual framework that unites the ideas of technological cyclicity, the theory of industrial revolutions, and the strategy for achieving the Sustainable Development Goals within the paradigm of the Virtual Economy. The structure of the paper is as follows: the first section examines the conceptual and methodological foundations for analysing technological cycles and paradigms; the second presents a literature review encompassing key theoretical approaches and scientific perspectives; the third explores the interrelation between technological paradigms, waves, and the SDGs across multiple levels;

the fourth demonstrates the alignment of the findings with the thematic scope and interdisciplinary orientation of *Virtual Economics*; and the final section formulates the main conclusions and outlines directions for further research.

2. Conceptual and Methodological Foundations

Understanding the phenomenon of technological development in the context of achieving the Sustainable Development Goals (SDGs) requires a systemic–evolutionary and interdisciplinary approach that integrates multiple levels of analysis—technological, economic, social, and institutional. The theoretical and methodological foundations of this study are based on the synthesis of three interrelated frameworks: the theory of long waves and technological paradigms, the concept of industrial revolutions, and the paradigm of sustainable development.

The first methodological foundation derives from N. D. Kondratieff's [1] theory of long waves, further developed in the works of J. Schumpeter [2], C. Freeman and F. Louçã [3], C. Perez [4], S. Glazyev [5], B. Z. Milner and D. S. Lvov [6], among others. According to this approach, economic dynamics are inherently uneven and cyclical: periods of accelerated growth alternate with structural crises, driven by wave-like processes originating in technological innovation. Each long wave, typically lasting 45–60 years, is accompanied by the emergence of a new technological paradigm – a set of core technologies that determine the development of key industries, infrastructure, and social organisation.

Equally important is the understanding of the interconnection between technological paradigms and industrial revolutions. While Kondratieff's long waves [1] describe the internal rhythm of innovation-driven renewal, industrial revolutions signify qualitative leaps in productive forces and social relations. Each revolution marks a new mode of interaction between humans and machines, labour and capital, information and energy. In this sense, technological paradigms and industrial revolutions form a synchronous system of phase transitions, in which technological innovations act as catalysts for profound institutional and socio-cultural transformations.

The second methodological dimension relates to the theory of sustainable development, which encompasses the principle of balance between economic growth, social well-being, and environmental preservation. Conceptually, it traces back to the Brundtland Report [7] and is institutionalised today through the United Nations' 17 Sustainable Development Goals [8]. Within this paradigm, technology is viewed not as an autonomous force, but as a means of achieving sustainable progress through inclusive innovation, energy efficiency, reduction of inequality, and equitable resource distribution.

In the present study, the theory of sustainable development is interpreted dynamically rather than statically – as a process embedded within the cycles of technological and economic renewal. Each technological wave carries the potential to advance sustainability objectives, while simultaneously generating new risks such as resource depletion, digital inequality, and environmental strain. Therefore, it is methodologically justified to conceptualise sustainable development as a function of the technological cycle rather than as an external or independent category.

The third methodological component is the Virtual Economy paradigm, which serves as an integrative framework linking technological, social, and cognitive evolution. The Virtual Economy defines a new research field where economic processes unfold within hybrid – simultaneously physical and digital – spaces. It examines the creation, exchange, and distribution of both material and immaterial assets, including data, knowledge, algorithms, digital representations, and meanings.

As a conceptual framework, the Virtual Economy combines elements from information theory [9, 10], institutional economics [11-13], network theory [14], cognitive science, and systems analysis. Methodologically, it employs a multi-level approach that spans from microeconomic models of digital interactions to megaeconomic scenarios of global digitalisation.

A central methodological tool in this framework is mathematical modelling, which enables the identification of regularities and the prediction of technological cycle dynamics. Classical models of economic dynamics [15-17] are complemented by modern nonlinear approaches that incorporate phase transitions, technological sinusoidal patterns, and feedback mechanisms. The application of mathematical methods allows for quantitative assessment of innovation cycles, identification of acceleration points, and modelling of economic resilience under conditions of technological turbulence.

By integrating these approaches, the study employs a systemic–evolutionary method that interprets development as a multi-level process of self-organisation and adaptation. This approach enables the linkage between macroeconomic phenomena (cycles, waves, crises) and micro-level innovation processes, while also revealing how, at the mega level – within global technological systems – the preconditions for a new technological paradigm and corresponding forms of sustainability are established.

Methodologically, it is also essential to recognise the significance of the meso level, which encompasses network, sectoral, and regional structures. At this level, technological innovations become institutionally embedded through the formation of innovation clusters, technology parks, digital platforms, and ecosystems that act as carriers of the emerging technological paradigm.

Particular attention is given to the concept of the metaverse as a potential institutional and cognitive form of the seventh technological paradigm. Methodologically, the metaverse is conceptualised as an integrative space of interaction between humans, data, and technologies—a domain in which new forms of economic activity, digital ownership, and social organisation emerge. It may thus be regarded as an empirical laboratory for observing the transition from the digital to the cognitive economy and for modelling processes of virtual sustainability.

In summary, the conceptual and methodological foundation of this research represents a synthesis of several interconnected domains: (1) the evolutionary–cyclical theory of technological development; (2) the sustainable development paradigm as a dynamic process; (3) the Virtual Economy as an integrative platform of the post-industrial world; and (4) mathematical modelling as a tool for analysing and forecasting phase transitions.

This comprehensive approach allows technological development to be understood not as a series of isolated innovations, but as a systemic, wave-like, and manageable process shaping the contours of an emerging cognitive–virtual civilisation.

3. Literature Review

The contemporary academic discourse on the interrelation between technological development and sustainable progress is characterised by a high degree of fragmentation and interdisciplinarity. Over recent decades, several research trajectories have emerged, each offering distinct interpretations of the role of technology in achieving the Sustainable Development Goals (SDGs) – ranging from studies of energy efficiency and digital transformation to analyses of cognitive and virtual economic systems. Within the new technological paradigm – marked by the transition from Industry 4.0 to Industry 5.0 and the formation of the seventh techno-economic paradigm – the study of the cyclicality of technological change, its socio-economic implications, and its potential integration with the concept of sustainability has become particularly significant.

The present literature review seeks to identify existing scholarly approaches to conceptualising technological development within the framework of sustainable progress, to analyse key research trends and gaps, and to determine the directions in which the concept of the Virtual Economy may serve as a unifying framework. It is important to emphasise that digital and cognitive transformation are examined here not only as technological processes, but also as institutional and cultural ones that reshape economic interactions, social structures, and models of governance.

Recent studies confirm that technological innovation exerts an ambivalent influence on sustainability. On the one hand, it enhances resource and energy efficiency, supports the development of "green" technologies, and facilitates data-driven economic management. On the other, it generates new forms of digital inequality, technological dependence, and environmental risks. These contradictions reveal the complex cyclical nature of technological development: each wave of innovation brings both opportunities for sustainable growth and challenges that demand new models of regulation and responsibility.

To provide a systematic analysis of the research landscape, this study employs the method of bibliometric mapping, which enables the visualisation of key topics, authors, and conceptual connections among such categories as technological development, sustainable development, digital economy, virtual economy, and Industry 4.0/5.0. The visualisation, presented in *Figure 1*, was created using the VOSviewer software based on data from the Scopus database, applying the following parameters: document type – articles; language – English; coverage period – 2006–2024; and a total of 276 publications analysed.

The search employed an extended Boolean query incorporating key terms representing three interrelated conceptual domains: (1) technological evolution and cycles (technological development, technological paradigm, industrial revolution, Kondratieff cycle); (2) sustainable development and its derivatives (sustainable development, green transformation, inclusive innovation); and (3) digital, virtual, and cognitive economies (digital economy, virtual economy, metaverse, Industry 4.0/5.0).

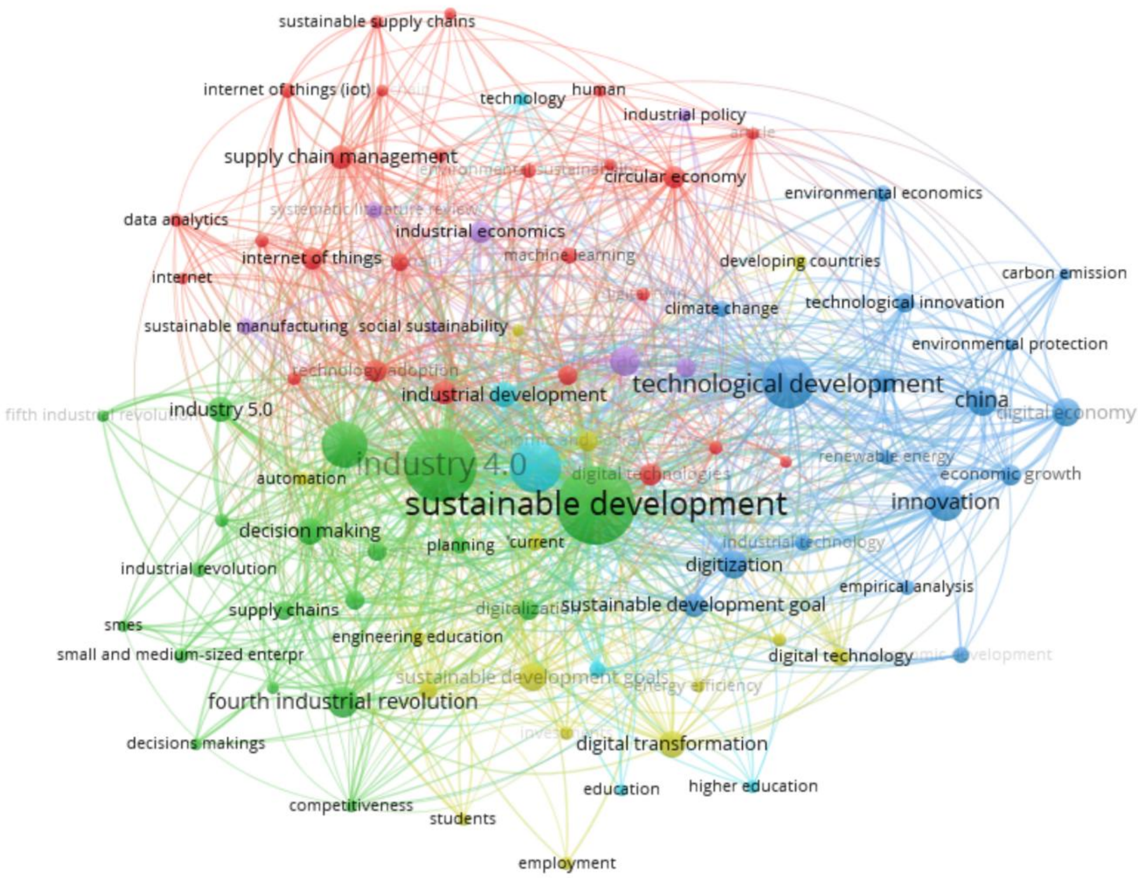

Figure 1. Bibliometric Network Visualization of Co-Occurring Keywords on Technological Development and Sustainable Development within the Digital Economy Framework.
Source: Compiled by the Author Using Data From the Scopus Database [18] and Visualised with Vosviewer [19].

Such a synthetic search formulation provides a comprehensive view of the interdisciplinary field where studies of economic dynamics, innovation, sustainability, and digital transformation intersect.

The visualisation (see *Figure 1*) reveals a structured distribution of research areas across thematic clusters and allows for the identification of the degree of integration between technological and sustainable development. The analysis demonstrates that, while there is a high concentration of research on “Industry 4.0,” “digital transformation,” “sustainability,” and “circular economy,” topics such as “virtual economy,” “metaverse,” and “cognitive technologies” remain underrepresented. This finding confirms the existence of a methodological and conceptual gap between classical theories of technological waves and contemporary models of sustainable digital development.

In this regard, the literature review does not merely summarise existing findings but aims to uncover research lacunae related to the insufficient integration of cyclical development theories with the sustainability paradigm, as well as to the limited conceptualisation of the Virtual Economy and the Metaverse as emerging stages in the evolution of technological paradigms.

The bibliometric analysis reveals that the research field situated at the intersection of technological development, sustainability, and digital transformation exhibits a high degree of interdisciplinarity and thematic clustering. The bibliometric map identifies several stable thematic clusters, each reflecting a specific aspect of the interaction between technology and sustainable development.

The first (green) cluster is centred around the concepts of "Industry 4.0," "Industry 5.0," "digital transformation," and "decision making," representing the techno-industrial dimension of the research landscape. This cluster links technological paradigms and industrial revolutions with issues of production digitalisation, automation, and engineering education. It constitutes the core of contemporary studies focusing on the transition from the Fourth to the Fifth Industrial Revolution, where cognitive and human-centred technologies begin to assume a pivotal role.

The second (red) cluster encompasses terms such as "supply chain management," "sustainable manufacturing," "circular economy," "industrial policy," and "environmental economics." It points to a consistent scholarly interest in integrating sustainability principles into production and logistics systems. This cluster reflects a meso-level approach, examining sustainability through the management of supply chains, industrial policy frameworks, and social innovation mechanisms.

The third (blue) cluster is associated with terms including "technological development," "innovation," "digital economy," "renewable energy," "economic growth," and "environmental protection." It represents a macro-economic and institutional perspective, wherein the digital economy is conceptualised as a central driver of "green" growth and the energy transition. The presence of the term "China" indicates a regional concentration of empirical research, underscoring the dominance of Asian scholarship within this thematic area.

The fourth (yellow) cluster connects the terms "higher education," "students," "engineering education," and "sustainable development goals." It captures the social-cognitive dimension of technological development, focusing on issues such as digital learning, future-oriented competences, and human capital formation for sustainable digital economies. This cluster is closely aligned with research on inclusive innovation and social equality in access to technology.

An interesting feature of the bibliometric map is the emergence of the terms virtual economy, metaverse, and cognitive technologies, which occupy a peripheral yet strategically significant position. This indicates their growing, though still insufficiently integrated, role in current scholarship and points to the formation of a new research trajectory – the transition from a digital to a cognitive–virtual paradigm of sustainable development, corresponding to the seventh techno-economic paradigm.

Overall, the results of the bibliometric analysis confirm that, despite the maturity of research on sustainable development and digital transformation, the integration of concepts such as technological cycles, virtual economy, and metaverse remains limited. This evidences an existing scholarly gap between the classical theories of technological waves (Kondratieff, Schumpeter, Freeman, Perez) and contemporary models of sustainability and digitalisation. Consequently, future research should aim at synthesising these theoretical approaches and constructing a unified conceptual framework of the Virtual Economy as an integrative platform for technological and sustainable evolution.

Contemporary studies reaffirm that technological development and digital transformation constitute not a linear, but a cyclical process in the evolution of socio-technical systems, wherein each new technological wave generates an impulse for the creation of novel models of sustainable production, management, and human–technology interaction.

Masoomi et al. [20] demonstrate that the transition from Industry 4.0 to Industry 5.0 is accompanied by a shift from automation to human-centric technologies, enabling enhanced sustainability of supply chains in the renewable energy sector. The authors argue that the principles of Industry 5.0 emphasise the integration of cognitive technologies, artificial intelligence, and human–machine symbiosis, thereby laying the foundations for more adaptive and environmentally resilient production systems. Their findings thus confirm the emergence of a new technological cycle in which social and ethical dimensions become central drivers of technological progress.

In his conceptual study "Virtual Reality and Real Virtuality," Kwilinski [21] explores the epistemological foundations of the virtual economy and the metaverse as a new sphere of perception and economic interaction. He introduces the notion of a perceptual economy, where virtual environments function not merely as spaces for digital exchange but as cognitive domains in which value and sustainability are co-constructed. This concept is complemented by the work of Miskiewicz [22], who examines the diffusion of interdisciplinarity in understanding the relationship between the virtual and the real in economics. He argues that modern science is entering a stage of integration among cognitive, cultural, and technological models, thereby shaping a new ontology of economic reality in which the boundaries between material and immaterial production are becoming increasingly blurred.

Pathak et al. [23] further develop this idea by conceptualising the metaverse as an institutional platform for sustainable innovation. The authors posit that metaverse technologies can serve as catalysts for societal transformation through the creation of a sustainable value portfolio — a system of ethical and environmentally conscious digital participation. In this context, the metaverse is viewed not as an entertainment space but as a new technological paradigm capable of integrating economic, cultural, and ecological dimensions of development.

Piedra-Muñoz et al. [24] provide a systematisation of digital technologies within the framework of the circular economy and sustainable manufacturing. Their research proposes a classification of technologies according to their contribution to closed production cycles and waste minimisation, emphasising that digitalisation and industrial greening are mutually reinforcing processes. This confirms the intrinsic link between technological paradigms and sustainable development models, where technological innovation functions as a structural foundation of sustainability.

Kardas et al. [25] explore the practical dimension of technological evolution through the concept of digital twins as a tool for quality management and predictive control within the framework of Industry 4.0. The authors demonstrate that digital twins establish a cyber-physical foundation for self-regulating and sustainable production systems, thereby creating the preconditions for cognitive management of technological cycles.

Stacho et al. [26] complement this context with an organisational and economic perspective, showing that the degree of digitalisation in human resource management directly correlates with firms' financial performance. The authors highlight the importance of integrating digital tools into strategic management to enhance organisational resilience. This represents the micro-level of technological development, where sustainability emerges through the digitalisation of corporate practices.

Kwilinski et al. [27] introduce the notion of a "culture of sustainable governance," conceptualising it as the foundation of green economic development. In their interpretation, sustainability is not merely a product of technological innovation but is shaped through institutional, ethical, and cultural mechanisms of adaptation to the digital economy. Thus, the authors link governance culture to the technological cycle, arguing that the transition to sustainability requires both cognitive and cultural transformation of society.

Continuing the systematisation of recent research, it becomes evident that contemporary scholarship increasingly connects digital transformation and technological innovation with the objectives of sustainable development — from spatial and institutional analyses to the formulation of new digital–ecological paradigms.

Gómez-Valenzuela and Holl [28] address the problem of rural depopulation in the context of Industry 4.0 technologies. They show that digitalisation, automation, and intelligent technologies can not only offset human resource shortages in rural areas but also stimulate new forms of innovative activity and sustainable entrepreneurship. Hence, 4.0 technologies are conceptualised as instruments of spatial sustainability and regional revitalisation.

Abdelmagid et al. [29] expand this perspective by proposing the integration of metaverse environments and generative artificial intelligence to advance the green digital economy and promote digital entrepreneurship within higher education systems. Their study demonstrates that interactive metaverse environments can serve as cognitive learning ecosystems, modelling sustainable economic practices that support digital inclusion and entrepreneurial engagement. In this context, the metaverse functions not only as a technological but also as an educational tool for achieving the Sustainable Development Goals (SDGs), particularly SDG 4 (quality education), SDG 8 (decent work and economic growth), and SDG 9 (industry, innovation, and infrastructure).

The economic dimension of technological leadership is examined by Kwilinski [30], who analyses the interrelations among GDP per capita, foreign direct investment, and national technological potential. The author argues that technological leadership results from the interaction of macroeconomic and institutional factors, where the digital economy serves as a mediator between growth and sustainability. This approach reinforces the understanding of technological development as a cyclical process, in which investment and innovation waves correspond to phases of long-term economic expansion.

Comparable conclusions are drawn by Dong and Xu [31], who investigate how the digital economy contributes to inclusive, green, and equitable economic growth. Using cross-country data, the authors find that digitalisation enhances resource allocation efficiency, stimulates innovation, and reduces environmental pressure—provided that adequate institutional frameworks are in place.

Lyulyov et al. [32] further argue that digital inclusion acts as a key driver of green economic growth, as it ensures a more equitable distribution of opportunities within the digital economy and facilitates the implementation of SDGs 7 (affordable and clean energy), 9 (industry, innovation, and infrastructure), and 13 (climate action). The authors emphasise that technological transformation should be viewed as an instrument for creating fair and environmentally responsible economic systems.

Chen et al. [33] make a significant empirical contribution to the understanding of these processes by demonstrating how digitalisation, renewable energy, and natural resources shape environmental performance. Using a quantile-on-quantile analytical framework, the authors show that a high level of digital maturity accelerates the transition toward environmental excellence but simultaneously necessitates optimisation in the use of natural resources—indicating the dual nature of technological modernisation.

In their systematic review, Narkhede et al. [34] provide a comprehensive overview of Industry 5.0 and sustainable manufacturing. The authors identify three interrelated pillars of the new industrial paradigm – human centricity, collaboration, and ecological responsibility. Their work confirms that the Fifth Industrial Revolution represents a cognitive and ethical superstructure over Industry 4.0, designed to achieve equilibrium between technological progress and sustainable development.

Xue et al. [35] illustrate the impact of digital innovation and big data on energy efficiency and sustainability, drawing on an analysis of China's Big Data Comprehensive Experimental Zones. Their findings reveal that the establishment of Big Data infrastructure facilitates energy optimisation and technological breakthroughs in resource management, making digital innovation a foundational element of the sustainable transition.

The transformation of consumer and cultural behaviour within the metaverse context is examined by Tran [36]. The author argues that the metaverse could become a driver of sustainable tourism by 2050, as it enables the modelling and promotion of environmentally responsible practices while reducing physical pressure on natural resources. This broadens the scope of sustainable development to include virtual forms of human–environment interaction as part of the sustainable economy.

The systematic review by Hammad et al. [37] demonstrates that environmental, social, and governance (ESG) strategies in the era of Industry 4.0 require the integration of digital technologies – including artificial intelligence, the Internet of Things, and blockchain – to enhance transparency and the efficiency of sustainable management. This reflects a broader trend toward the institutionalisation of digital sustainability at both corporate and governmental levels.

Kwilinski [38] links e-commerce with the advancement of Sustainable Development Goals (SDGs 2, 12, and 13) within the context of the European Union. The author demonstrates that e-commerce promotes sustainable patterns of consumption and production, thus contributing to the formation of an integrated digital–sustainable economy.

One of the most salient trends in contemporary research concerns how digital and network technologies underpin the infrastructure of sustainable governance. Yoon et al. [39] show that the adoption of blockchain technology facilitates the establishment of collaborative mechanisms for sustainable development by enhancing transparency among economic agents and reducing transaction costs. Blockchain is conceptualised not only as a tool for security but also as an architecture of trust in managing sustainable projects, with direct implications for achieving SDGs 9 (industry, innovation, and infrastructure) and 12 (responsible consumption and production).

Shet and Pereira [40] extend this discussion by focusing on managerial competencies in the context of Industry 4.0. They identify social sustainability in decision-makingmanifested through flexible competencies, digital leadership, and readiness for transdisciplinary collaboration – as a key factor in the successful implementation of new technologies. Their findings highlight the necessity of incorporating cognitive and ethical dimensions into the governance of technological progress.

Similarly, Bai et al. [41] evaluate Industry 4.0 technologies from a sustainability perspective, identifying their multidimensional effects on production, environmental, and social parameters. The authors emphasise that the adoption of IoT, cyber-physical systems, and big data must balance technological advancement with the sustainability of supply chains. This aligns with the broader understanding of technological paradigms as phases of innovation integration into the socio-economic system.

A closely related idea is developed in the study by Manavalan and Jayakrishna [43], which demonstrates that the integration of the Internet of Things (IoT) into Industry 4.0 supply chains enables the implementation of sustainable models of resource and logistics management. IoT infrastructures function as elements of self-regulating systems – digital analogues of technological cycles – that minimise losses and ensure the circularity of production processes.

This line of inquiry is reinforced by Esmaeilian et al. [44], who show that blockchain technologies provide the foundation for sustainable supply chains through mechanisms of transparency, traceability, and decentralisation. These findings are crucial for understanding how technological innovation transforms classical management models toward distributed and cooperative sustainability.

Litvinenko [45] offers a macroeconomic perspective on the digital economy as a factor of technological advancement in resource-based industries. He argues that digitalisation acts as a catalyst for structural shifts, creating the conditions for a new technological paradigm within the extractive sector, where data, energy efficiency, and process greening become key parameters. This study is significant in illustrating how digital technologies penetrate traditional sectors, reshaping their institutional and production models.

A substantial contribution to the theoretical and empirical understanding of the relationship between technology and ecology is made by Kwilinski [46], who demonstrates the nonlinear effect of digital technology development on CO_2 reduction. Using advanced modelling techniques, the author shows that digitalisation can simultaneously reduce the carbon footprint and enhance economic growth, with the effect unfolding in phases—thus confirming the cyclical nature of technological waves.

Similar dynamics are identified by Chen et al. [47], who examine the impact of technological innovation on energy efficiency in the Industry 4.0 era, taking into account the influence of the shadow economy. The authors conclude that while a high level of technological development promotes sustainable energy use, the effectiveness of this process depends on institutional transparency. This underscores the need for an integrated approach that combines digital innovation with institutional regulation.

The institutional and legal dimensions of digital transformation are explored by Alves, Lunardi, and Correia [48], who analyse virtual forms of justice and mediation in the digital age. Their systematic review reveals that the digitalisation of legal institutions can enhance access to justice, transparency, and efficiency but also necessitates new regulatory frameworks to safeguard digital rights and AI ethics – directly linked to SDG 16 (Peace, Justice, and Strong Institutions).

Pérez-Rico et al. [49] complement this picture by analysing how digital transformation contributes to the achievement of SDG 4 (Quality Education) and SDG 5 (Gender Equality) in European companies. Their longitudinal analysis demonstrates that the digitalisation of corporate practices fosters gender balance and inclusion, thereby establishing new social standards for sustainable management.

A particularly notable contribution is made by Kwilinski [42], whose bibliometric analysis explores the relationship between sustainable development and digital transformation. The author identifies the emergence of a new research domain – digital sustainability studies – in which technological innovation is conceptualised as an integral component of global sustainability strategies.

Taken together, studies [39–49] indicate that contemporary academic thought is evolving toward the institutionalisation of sustainable technological development, where digital, cognitive, and managerial innovations function as inseparable components of a unified process. Three interconnected trends emerge within these works: (1) Technological institutionalisation of sustainability, expressed through the formation of digital governance ecosystems based on blockchain, IoT, and big data; (2) Ethical and social reorientation of management, marked by a shift from an emphasis on efficiency to the development of sustainable competencies and digital leadership; and (3) Cognitive–legal evolution, involving the emergence of new forms of interaction – such as virtual courts, metaverses, and digital inclusion – as elements of “virtual sustainability.”

Thus, the contemporary literature reveals a systemic shift from a fragmented examination of technology and sustainability to a synthetic approach that integrates economic, managerial, cognitive, and institutional dimensions. This evolution underscores the necessity of advancing the concept of the Virtual Economy as an integrative framework for the sustainable technological cycle.

Studies [50–62] further elaborate the social, institutional, and educational dimensions of digital transformation as a key driver of sustainable development, framing the digital society as a new phase of the technological paradigm in which human capital and cognitive technologies form the core of economic evolution.

Rahmanov et al. [50] demonstrate that educational digitalisation serves as a crucial instrument for achieving SDG 4 (Quality Education), enhancing both the quality and inclusivity of educational systems, particularly in developing countries. This trend is extended by Shenkoya and Cho [51], who link the Fifth Industrial Revolution to the formation of sustainable higher education, where digital inclusion operates not merely as a technological principle but also as an ethical one.

Muneer et al. [52] demonstrate that digital transformation and energy consumption constitute an interdependent system that determines the sustainability of macroeconomic growth. Similarly, Vărzaru and Bocean [53] provide empirical evidence of the systemic interactions between digital transformation, sustainable orientation, and economic outcomes across EU countries. Rubio-Andrés et al. [54] refine this analytical framework at the organisational level, proving that a digital transformation strategy serves as a determinant of innovativeness and organisational efficiency, thereby defining the managerial dimension of technological sustainability.

The contribution of Kwilinski et al. [55] lies in the conceptualisation of digital culture as a mediator between technology and the achievement of the SDGs, where the culture of digital interaction becomes a new form of global sustainability. Bokenchin et al. [56] extend the analysis into the financial sphere, demonstrating how digital financial technologies support the sustainable development of regional markets through inclusive investment models and green finance.

In the social and educational domain, Katona and Gyonyoru [57] show that AI-based adaptive learning helps to overcome digital inequality by developing competencies essential for participation in the knowledge economy. Tsakalerou et al. [58] introduce an institutional dimension by proposing a customised DESI framework for assessing digital transformation, taking into account the socio-economic context of individual countries. This approach strengthens the linkage between digital indices and sustainable growth policies.

Muzulon et al. [59] clarify the notion of engineering competencies, emphasising the need to develop meta-skills required to operate within digital ecosystems, while Pu et al. [60] examine the interaction between government policy and regional digital transformation through the lens of the innovation ecosystem approach, where sustainability is understood as the co-evolutionary coordination of technological and institutional actors.

In the agricultural and territorial context, Wang and Xu [61] identify the synergistic evolution of digital transformation along the e-commerce supply chain, illustrating how digitalisation enhances the sustainability of rural economies. This body of work is complemented by Crisan et al. [62], whose bibliometric analysis captures the transition from a traditional understanding of digitalisation to its conceptualisation as a systemic mechanism for building a sustainable economy.

Taken together, these studies indicate a shift in the research focus from purely technological innovation toward human-centred, educational, and institutional aspects of sustainability. This evolution reflects the emergence of a new cognitive–virtual paradigm, in which sustainability becomes a function of digital maturity within society. The findings collectively affirm the need to integrate the theories of technological cycles, sustainable development, and the Virtual Economy into a unified evolutionary framework that describes the transition toward a post-industrial, cognitively sustainable civilisation.

4. Technological Waves and Industrial Revolutions as the Foundation of Socioeconomic Progress

The economic and technological evolution of human civilisation unfolds in waves and cycles, reflecting the intrinsic rhythm of self-organisation characteristic of complex socio-technical systems. Cyclicality represents a fundamental property of global dynamics, manifested in the regular alternation of phases of growth, stability, and crisis, each followed by structural renewal. This regularity was first conceptualised in the theory of long economic waves by Nikolai Kondratieff (1925) and later refined by Joseph Schumpeter, Christopher Freeman, and Carlota Perez, becoming one of the principal paradigms for explaining the long-term logic of technological change.

According to this framework, innovation does not progress linearly but arises in clusters of "creative destruction", whereby successive technological paradigms disrupt and transform the existing economic order. These waves form a multi-layered structure of cyclical motion, with each level corresponding to a particular depth of systemic transformation:

– Kitchin cycles (3–4 years) – short-term business fluctuations caused by changes in inventories and immediate demand.
– Juglar cycles (7–11 years) – investment and credit cycles reflecting the rhythm of capital renewal and industrial modernisation.
– Kuznets cycles (15–25 years) – demographic and construction waves associated with urbanisation, migration, and infrastructural development.
– Kondratieff waves (45–60 years) – structural technological waves determining the dominant production systems and institutional frameworks of each epoch.

Each long Kondratieff wave corresponds to the rise and maturity of a technological or techno-economic paradigm – a coherent complex of interrelated technologies, energy sources, communication infrastructures, and organisational models. Thus, industrial revolutions should not be seen as random bursts of innovative activity but rather as macro-phases of systemic reconfiguration within the global economy, marking transitions between successive techno-economic paradigms.

From the First Industrial Revolution, grounded in steam power and mechanisation, to the Second, driven by electricity and mass production; the Third, characterised by automation and electronics; and the Fourth, centred on digitalisation and cyber-physical systems – each wave expanded the horizons of productivity, communication, and social organisation. Today, the global economy is entering a transitional phase between the sixth and seventh techno-economic paradigms, where digital, cognitive, and existential technologies – such as artificial intelligence, bioinformatics, the metaverse, and neuro-communication systems – outline the contours of a new civilisational formation.

This transition heralds the advent of Industry 5.0, a human-centric stage of technological development that seeks to synthesise automation with empathy, intelligence with ethics, and digitalisation with sustainability. Unlike previous revolutions, in which technology served merely as an instrument, the current phase positions the human being as an organic component of the cyber-physical ecosystem – not merely an operator but a co-evolving agent within intelligent systems.

Accordingly, the seventh techno-economic paradigm may be interpreted as a cognitive-virtual revolution, in which knowledge, perception, and virtual presence become the primary factors of production. Its essence lies not only in technological refinement but also in the redefinition of the human–technology relationship, paving the way for a new model of sustainable progress – one that unites innovation, inclusivity, and ecological balance within the virtual continuum of the global digital economy.

The analysis of technological waves and industrial revolutions reveals a structural regularity in the evolution of the global economic system: each successive wave of innovation not only transforms production and technological processes but also reshapes the socio-economic, institutional, and cultural architecture of society. In this sense, technological development should be understood as a complex systemic process in which technical inventions, organisational innovations, and transformations in social values evolve synchronously, forming an interdependent dynamic of technological and social regimes.

Historically, every industrial revolution has been accompanied by a transformation in the model of sustainability – from material-industrial resilience during the age of mechanisation and coal, to energy-ecological sustainability in the twentieth century, and finally to digital-cognitive sustainability in the twenty-first. This transition illustrates the growing complexity of the interaction between technology and sustainable development. Whereas earlier techno-economic paradigms were primarily focused on productivity gains and economic expansion, contemporary ones are increasingly centred on balancing innovation, resource constraints, and social equity.

The current paradigm of technological progress is characterised by the integration of three interrelated dimensions, which together define the emerging model of sustainable technological evolution:

1. Technological dimension – the development of cyber-physical, cognitive, and virtual systems that create new forms of production, decision-making, and socio-technical organisation.
2. Institutional dimension – the formation of digital ecosystems that regulate the interactions between the state, business, and civil society, embedding technology within governance and policy frameworks.

3. Value-based (socio-humanitarian) dimension – the gradual shift from technocratic efficiency towards sustainability, responsibility, and human-centric innovation.

Together, these dimensions enable the transition from a techno-centric model of growth to a cognitive-sustainable model of development, in which innovation is perceived not as an end in itself but as a mechanism for achieving systemic harmony among economic, ecological, and cultural systems.

From the perspective of the long-wave theory, the contemporary stage represents the ascending phase of the seventh techno-economic paradigm, in which digital, cognitive, and virtual technologies constitute the core of a new global development cycle. The distinctive feature of this phase is not only large-scale automation but also the virtualisation of social and economic spaces — the expansion of virtual economies, metaverse environments, and artificial intelligence systems as dominant arenas of interaction, creativity, and value generation. Within this emerging configuration, technological innovation begins to align with the direction and logic of sustainable development, forming the foundation of a new type of synthesis — technologically enabled sustainability.

In this context, the Sustainable Development Goals (SDGs) cannot be regarded as an external or purely normative framework. Rather, they represent a new mode of coordination for global innovation cycles, ensuring that each technological wave contributes to the advancement of ecological balance, social inclusion, and long-term resilience. This implies that sustainability is no longer a corrective mechanism for technological excess but an immanent feature of the new techno-economic order.

Consequently, the transition from the sixth to the seventh paradigm marks not merely another stage of technological modernisation, but a qualitative transformation in the logic of progress – a shift from expansionary industrialisation to sustainable digital and cognitive growth. Against this backdrop, technology ceases to function solely as an instrument of economic advancement and becomes a structural foundation for achieving all seventeen SDGs, facilitating their implementation across multiple levels of social organisation: from the individual (micro) to the institutional (meso), national (macro), and global (mega).

This multidimensional correlation will be explored in the following section, which examines the systemic interconnection between technological cycles and the Sustainable Development Goals, conceptualising technological progress as a multi-level architecture of sustainability encompassing micro-, meso-, macro-, and mega-dynamics of global evolution.

5. Technological Development and the Sustainable Development Goals (SDGs)

Contemporary technological development is intrinsically linked to the implementation of the Sustainable Development Goals (SDGs), serving as both their material and institutional foundation. Technology constitutes the infrastructure through which the principles of sustainability – environmental, social, economic, and institutional – are translated into practical reality. There exists a reciprocal relationship between technological cycles and the SDGs: each wave of innovation generates new opportunities for achieving sustainability, while simultaneously introducing new risks that necessitate the adjustment of governance frameworks and ethical priorities.

Technological development manifests across multiple levels – micro, meso, macro, and mega – which should not be viewed as rigidly separated domains. Rather, they form a continuous system of interaction, in which the effects of technological change propagate both vertically and horizontally, and the SDGs themselves emerge as intersecting and overlapping layers within a unified global process.

At the micro level, technologies enhance the quality of life and the development of human capital. The application of artificial intelligence in healthcare (SDG 3), personalised learning and digital education platforms (SDG 4), as well as the advancement of digital literacy and inclusive internet access (SDG 10), create conditions for the realisation of fundamental human rights and social justice. These individual-level improvements are closely linked to other goals – such as sustainable cities and communities (SDG 11) – since the digitalisation of everyday practices transforms the model of urban life and social interaction.

At the meso level, technological innovation becomes an instrument of sustainable industrialisation (SDG 9) and responsible consumption and production (SDG 12). Smart cities and industrial clusters exemplify this relationship: digital management systems, renewable energy, and Internet of Things (IoT) technologies optimise resource use, reduce emissions, and improve energy efficiency (SDGs 7 and 13). At the same time, these processes enhance access to education (SDG 4) and generate new forms of employment (SDG 8), illustrating that the boundaries between social and environmental objectives are often fluid. For instance, the design of urban digital infrastructure simultaneously affects economic growth, climate resilience, and social inclusivity.

At the macro level, technology is embedded within national strategies that target economic growth (SDG 8), innovation and infrastructure (SDG 9), strong institutions (SDG 16), and sustainable management of natural resources (SDG 15). The implementation of digital governance systems, big data analytics, and AI-driven decision-making enhances transparency, accountability, and institutional efficiency, thereby strengthening the legal and political foundations of sustainability. These strategies inherently intersect with social and environmental objectives, as the digitalisation of economies reshapes employment structures, energy consumption, and environmental quality.

At the mega level, technological development transcends national boundaries, creating global ecosystems of sustainability. The metaverse, artificial intelligence, and blockchain form infrastructures that underpin global partnerships (SDG 17), climate action (SDG 13), and the promotion of equality and inclusion (SDGs 5 and 10). For example, the use of AI and satellite monitoring to track greenhouse gas emissions directly links climate goals with responsible production, innovation, and institutional transparency. In this way, technology becomes a universal integrative mechanism connecting diverse dimensions of global sustainability.

A distinctive feature of the current stage of development is that the SDGs are being realised synergistically rather than sequentially. A single technological innovation often contributes to several goals simultaneously. For instance, the development of electromobility supports emissions reduction (SDG 13), innovation and infrastructure (SDG 9), energy efficiency (SDG 7), and sustainable urban environments (SDG 11). Likewise, digital education addresses not only the quality of learning (SDG 4) but also gender equality (SDG 5), digital inclusion (SDG 10), and economic growth (SDG 8). This interdependence demonstrates the indivisibility and mutual reinforcement of the Sustainable Development Goals, fully consistent with their systemic nature, as established in the United Nations 2015 Declaration.

Thus, technological development constitutes a unified framework for the implementation of all seventeen SDGs, embedding them within the economic, social, and institutional dynamics of the modern world. Within the seventh techno-economic paradigm, technology ceases to function merely as an external tool and instead becomes an internal mechanism of sustainability – a platform on which digital, cognitive, and social innovations converge in durable synergy. Contemporary technologies not only enable progress; they embody the principles of sustainable development within the very logic of societal, economic, and cultural functioning, serving as a universal language for harmonising the interests of humanity, nature, and the future.

6. Harmonisation with the Thematic Framework of *Virtual Economics*

The theoretical foundations and empirical results presented in this study are fully aligned with the mission and subject scope of Virtual Economics, a journal that defines itself as an interdisciplinary platform integrating research in the social sciences, economics, management, computer science, cultural studies, health, and applied mathematics. The thematic coverage of the journal includes the following subject areas: Social Sciences (Cultural Studies; Health (social science); Social Sciences (miscellaneous)), Economics, Econometrics and Finance, Business, Management and Accounting (Business and International Management; Management of Technology and Innovation; Management Information Systems), Computer Science (Artificial Intelligence, Data Science and Computational Modelling), and Mathematics (miscellaneous).

It is important to emphasise that these areas do not constrain the interdisciplinary character of the research; rather, they provide a methodological framework within which the synthesis of humanitarian, economic, and technological knowledge is carried out. This structure makes Virtual Economics a unique venue for shaping a new type of academic discourse – a virtually sustainable paradigm of development, in which technology is conceived as an intrinsic element of social and cultural evolution.

The first axis – socio-cultural – conceptualises technological development as a driver of cultural, educational, and behavioural transformation. This dimension encompasses studies that approach digitalisation as a cultural and social phenomenon, focusing on the transformation of behavioural models, communication patterns, education, and health under the influence of cognitive technologies. Here, technological development acts not merely as an instrument of progress but as a medium for shaping a new cultural environment based on digital inclusion, AI ethics, and sustainable forms of social interaction. Particular attention is paid to digital education, e-health, and meta-learning, all of which are directly related to SDGs 3, 4, 5, and 10.

The second axis – economic-institutional – interprets the digital economy and sustainable development as interdependent systems. This axis forms the conceptual core of the Virtual

Economics thematic field, where the digital economy is viewed as a strategic foundation of sustainable growth. It covers research on market digitalisation, platform-based economies, global innovation chains, and international digital cooperation. Within this context, sustainability is understood as a new institutional rationality, combining innovation, transparency, and social responsibility. This approach elucidates how digital ecosystems serve as infrastructures for the realisation of the SDGs, particularly Goals 8, 9, 12, and 17.

The third axis – technological-managerial – focuses on innovation, knowledge management, and cyber-physical integration. It brings together research on the digital transformation of organisations, the application of artificial intelligence, machine learning, big data, digital twins, blockchain, and the metaverse. Within the framework of Industry 5.0, these technologies form cognitive ecosystems where management becomes adaptive, intelligent, and human-centric. This perspective positions technological innovation not merely as a means of improving efficiency but as a mechanism for sustainable governance of resources, human capital, and knowledge, thereby facilitating the formation of a cognitive-sustainable economy.

The fourth axis – computational-cognitive – centres on artificial intelligence, data analysis, and sustainability modelling. Derived from the subject area Computer Science (Artificial Intelligence, Data Science and Computational Modelling), this axis performs a linking function between the technological-managerial and mathematical-analytical domains. Within the framework of Virtual Economics, it encompasses research aimed at applying cognitive and computational technologies to sustainable management, strategic forecasting, digital transformation, and sustainability measurement. Artificial intelligence, data analysis, and modelling are not regarded as autonomous engineering tools but as cognitive and managerial mechanisms that integrate economic, social, and technological processes into a coherent and sustainable system.

The fifth axis – mathematical-analytical – concerns modelling, forecasting, and quantitative assessment of sustainability. This axis reflects the methodological foundation of Virtual Economics: the use of quantitative and computational methods to analyse the interdependencies between technological development and sustainability. Here, system modelling, machine learning, and predictive analytics are applied to forecast innovation cycles, energy efficiency, digital inclusion, and sustainable growth. Mathematical modelling serves a key integrative function, linking data and methodologies from diverse disciplines and facilitating the formation of a unified cognitive space for the science of sustainable technological development.

In summary, the research concept of this article is fully consistent with the interdisciplinary profile of Virtual Economics. It integrates social, economic, managerial, technological, computational, and analytical approaches within a single theoretical model – that of the Virtual Economy as an integrative framework of the sustainable technological cycle. In this respect, the journal serves not only as an academic platform but also as a conceptual centre for the formation of a new school of economic thought, in which digitalisation, cognitive innovation, and sustainable development are viewed as parts of a single evolutionary process.

7. Conclusions

The conducted research has enabled the formation of a comprehensive understanding of technological development as a self-organising and cyclical process, in which innovation functions not merely as a source of economic growth but as a mechanism for the structural and value-based evolution of society. This approach extends the classical interpretation of technological waves, demonstrating that each new phase of progress transcends the production sphere to encompass the institutional, cultural, and cognitive foundations of sustainability. Accordingly, the current stage of global development can be characterised as a transition from a material-industrial to a cognitive-sustainable model, in which technology acts not solely as an instrument but as a systemic principle of harmonisation between humanity, the economy, and the environment.

The bibliometric mapping revealed that the contemporary research landscape at the intersection of technological development, sustainability, and digital transformation exhibits a pronounced interdisciplinary and clustered structure. The dominant thematic directions integrate the issues of Industry 4.0 and 5.0, sustainable production, circular economy, digital inclusion, and the metaverse. At the same time, the concepts of virtual economy and metaverse occupy a strategically significant yet insufficiently integrated position, indicating the emergence of a new cognitive-virtual paradigm of sustainable development.

The literature review demonstrated that digital transformation has become a systemic driver in the implementation of the Sustainable Development Goals (SDGs). At the micro level, it enhances quality of life and educational inclusiveness; at the meso level, it promotes energy efficiency and sustainable production; at the macro level, it drives economic digitalisation and employment; and at the mega level, it facilitates the formation of global digital ecosystems that support partnerships and climate objectives. In this way, technological progress has evolved into an integral component of the architecture of sustainability, encompassing all seventeen SDGs.

From the perspective of long-wave theory, the current phase may be interpreted as the ascending stage of the seventh techno-economic paradigm, the core of which comprises digital, cognitive, and existential technologies. These technologies enable the convergence of innovation dynamics with the sustainable development agenda, forming the foundation for technologically enabled sustainability – a new mode of interaction between humanity, the economy, and the virtual environment.

Within this conceptual framework, "Virtual Economics" performs a pivotal role as an interdisciplinary platform uniting economic, technological, and humanitarian approaches to the study of digital and cognitive transformation. The journal serves as a conceptual nucleus of a new school of economic thought, in which the virtual economy is regarded as an integrative framework for the sustainable technological cycle.

Future research may be directed towards the development of quantitative models describing the interaction between technological cycles and the SDGs, the assessment of cognitive sustainability within digital ecosystems, and the analysis of institutional mechanisms for regulating the virtual economy. A particularly promising avenue lies in the advancement of a theory of technologically enabled sustainability, elucidating the roles of artificial intelligence, the metaverse, and neurotechnologies as the primary drivers of a new phase in global development.

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