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UNIFIED PARADIGM OF INDUSTRY 5.0, CITY 5.0 AND AGRICULTURE 5.0 FOR ENVIRONMENTAL SUSTAINABILITY

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Abstract

This study adopts a holistic perspective to examine the approaches of Industry 5.0, City 5.0, and Agriculture 5.0, which hold potential for contributing to environmental sustainability goals, and aims to propose the AI-supported ICA 5.0 model as an integrated framework for these three domains. In this context, the study seeks to answer the research question: "How can the paradigms of Industry 5.0, Agriculture 5.0, and City 5.0 be structured within a holistic model to support environmental sustainability goals?" Within the proposed ICA 5.0 model, it is demonstrated that all three domains are structured on the basis of transferring data from physical environments to digital platforms via sensors and analyzing these data using AI-driven techniques. At the core of the model, it is proposed that data obtained through this process be analyzed within a centralized public cloud infrastructure alongside strategies developed by policymakers, through an interdisciplinary approach that supports the formulation of environmentally conscious policies. In addition, the use of blockchain technology in the data collection infrastructure is emphasized to ensure data security and transparency. The study employs qualitative research methods, combining document analysis, descriptive content analysis and case study method. The ICA 5.0 model has been exemplified through a case study focused on Türkiye. The sample of the study consists of 49 research articles published between 01.01.2021 and 31.12.2024 in the Scopus database that are relevant to the research topic. Based on the findings, the study discusses how the ICA 5.0 model can be structured and what contributions it may offer in the context of environmental sustainability.

Keywords: Digital transformation, Industry 5.0, Agriculture 5.0, Artificial intelligence, Environmental sustainability.

JEL Codes: M19, O19, Q19

ÇEVRE SÜRDÜRÜLEBİLİRLİĞİ İÇİN ENDÜSTRİ 5.0, ŞEHİR 5.0 VE TARIM 5.0 BİRLEŞİK PARADİGMASI

Öz

Bu çalışma, çevresel sürdürülebilirlik hedeflerine katkı sunma potansiyeli taşıyan Endüstri 5.0, Şehir 5.0 ve Tarım 5.0 yaklaşımlarını bütüncül bir perspektiften ele almakta ve bu üç alanı entegre edebilecek yapay zekâ destekli bir çerçeve olarak ICA 5.0 modelini ortaya koymayı amaçlamaktadır. Bu bağlamda, "Endüstri 5.0, Tarım 5.0 ve Şehir 5.0 paradigmaları çevresel sürdürülebilirlik hedeflerini desteklemek üzere bütüncül bir model kapsamında nasıl yapılandırılabilir?" sorusuna yanıt aranmaktadır. Önerilen ICA 5.0 modeli kapsamında, her üç alanın da fiziksel ortamlardan elde edilen verilerin sensörler aracılığıyla dijital ortama aktarılması ve bu verilerin yapay zekâ temelli analizine dayalı olarak yapılandığı ortaya konulmuştur. Modelin merkezinde, çevre odaklı politika geliştirme süreçlerini desteklemek üzere, disiplinler arası bir yaklaşımla elde edilen verilerin politika yapıcılar tarafından üretilen stratejilerle birlikte merkezi bir kamu bulutu altyapısında analiz edilmesi önerilmektedir. Ayrıca, veri güvenliği ve şeffaflığın sağlanması amacıyla veri toplama altyapısında blockchain teknolojisinin kullanımına vurgu yapılmıştır. Araştırmada nitel yöntemlerden doküman analizi, betimleyici içerik analizi ve örnek olay metodu birlikte kullanılmıştır. Örnek olay kapsamında ICA 5.0 modeli Türkiye örneği sunulmuştur. Çalışmanın örneklemini, 01.01.2021-31.12.2024 tarihleri arasında Scopus veri tabanında yayımlanmış ve araştırma konusuyla ilişkili 49 araştırma makalesi oluşturmaktadır. Elde edilen bulgular doğrultusunda ICA 5.0 modelinin

nasıl yapılandırılabileceği ve bu modelin çevresel sürdürülebilirlik bağlamında sağlayabileceği katkılar tartışılmıştır.
Anahtar Kelimeler: Dijital dönüşüm, Endüstri 5.0, Tarım 5.0, Yapay zekâ, Çevresel sürdürülebilirlik.
JEL Kodları: M19, O19, Q19

1. INTRODUCTION

Digital transformation has recently become not only a major driver of technological advancements but also a leading catalyst for societal, economic, and environmental transformations. As this transformation is grounded in data and knowledge management, it has emerged as the central focus of interdisciplinary communication and has elevated decision-making processes to a more effective and predictable level. Through Internet of Things (IoT) technologies, interaction with physical objects has formed the foundation of digitalization across numerous domains, from manufacturing to public administration, from transportation to healthcare, especially with the advent of the Fourth Industrial Revolution (Industry 4.0). In this context, it has become possible to obtain real-time digital data from objects in the physical environment, initiating a bidirectional interaction between physical and digital domains. However, within the structure of Industry 4.0, concepts such as human-centeredness and environmental sustainability have remained secondary, as technological progress has predominantly been interpreted in terms of efficiency and automation. At this juncture, Industry 5.0 represents a new approach that transcends technological innovation by placing human beings and nature at the center. In this period, where human–machine collaboration is redefined, it is explicitly emphasized that the ultimate aim of technological progress is not solely to enhance productivity but also to improve human quality of life and preserve ecological balance. With the Industry 5.0 approach, similar transformation processes have begun to take shape in other areas such as agriculture and urbanization. Agriculture 5.0 is being shaped not only by the aim to enhance productivity in food production but also by environmental objectives such as the preservation of water resources, the recovery of soil, and the reduction of chemical inputs. City 5.0 aims to make city life smarter, more livable, and more environmentally friendly. Smart infrastructures, sensor networks, renewable energy systems, and low-carbon strategies are increasingly integrated into city planning. The digital transformation processes in the fields of industry, agriculture, and cities are not independent from one another but are in fact complementary components of an integrated structure. These systems, in which human-centered solutions and environment-oriented goals are harmonized in a unified manner, form the foundation of the Society 5.0 vision, which not only aspires to enhance individual quality of life but also prioritizes the protection of environmental values. Within this framework, environmental sustainability has become an indispensable priority in this new paradigm, and technological systems have started to be restructured in accordance with environmental considerations across various areas, including production processes, urbanization, food supply, and energy use. For instance, soil degradation caused by pesticide use in agriculture or carbon emissions resulting from urbanization can now be identified earlier with the assistance of digital technologies, enabling the development of preventive strategies. At this point, technological tools such as IoT, big data analytics, AI, and decision support systems play a fundamental role in the collection and analysis of environmental data and in the formulation of sustainability-oriented policy recommendations.

In this context, the relationship between Industry 5.0, City 5.0, and Agriculture 5.0 and environmental sustainability has been addressed in the literature through various studies, either separately or within the framework of the influence of Industry 5.0 on the other domains. For instance, Breque et al. (2021) highlighted the contribution of Industry 5.0 to environmental goals such as energy efficiency, waste reduction, and the minimization of carbon footprint, emphasizing the critical role of technologies such as IoT and artificial intelligence (AI) in this process. Kasinathan et al. (2022) examined the environmental benefits of Industry 5.0, including the reduction of water and carbon footprints, improvement in waste management, and protection of ecological diversity. The study demonstrates that technological collaboration supports sustainable development goals. Yoşumaz and Uzun (2024) investigated the relationship between the Industry 5.0 process and the ESG (Environmental Social Governance) process within the scope of the companies Arçelik and Vestel. Talla and McIlwaine (2024) analyzed how the integration of digital technologies with the circular economy contributes to waste reduction. Becker et al. (2023) examined how City 5.0 improves energy efficiency, reduces carbon emissions, and enhances waste management through IoT and AI. The study underlines that real-time data analysis increases environmental performance. Ferreira et al. (2023) discussed the impact of smart home technologies on energy efficiency and environmental awareness, supporting the sustainability potential of City 5.0. Li et al. (2022) explored how IoT and big data analytics improve environmental monitoring and resource management in cities. Martos et al. (2021) investigated the environmental benefits of remote sensing technologies in terms of water conservation, reduction of pesticide use, and preservation of soil health. Ragazou et al. (2022) discussed the impact of Agriculture 5.0 on energy efficiency and the reduction of environmental footprint, emphasizing that technological integration strengthens agricultural sustainability. Polymeni et al. (2023) addressed the potential of 6G and IoT technologies to promote water conservation and reduce chemical usage through precision agriculture practices. Tombe and Smuts (2023) examined how digitalization supports agricultural sustainability and emphasized the importance of cross-sectoral integration. Abd Al Ghaffar (2024) analyzed the strategic advantages of public cloud systems in data collection.

A review of the existing literature reveals that studies on environmental sustainability have predominantly addressed the domains of industry, agriculture, and urban systems in a fragmented and isolated manner. However, achieving comprehensive and long-term environmental sustainability requires an integrative approach that simultaneously considers the interactions and interdependencies among these three domains. This necessity stems from the fact that adverse environmental practices in one domain can directly or indirectly affect the others. For instance, industrial waste discharged into natural ecosystems may contaminate water sources used in agricultural production, thereby compromising the quality and safety of agricultural outputs. Similarly, urban emissions and land use decisions may exert ecological pressures on adjacent agricultural zones or industrial districts. Given the interconnected nature of these environmental challenges, there is a growing need for a unified monitoring and decision-making framework that enables the identification of root causes and facilitates the formulation of coordinated policy responses. Despite this need, no existing study has been found that holistically examines the Industry 5.0, City 5.0, and Agriculture 5.0 paradigms in an integrated manner, synthesizes their environmental sustainability contributions, and proposes a cohesive model across these domains. To address this critical gap, the present study explores how technological advancements in industrial, city, and agricultural domains can be brought together under a unified framework to support environmental sustainability goals. In this context, the following research question is posed:

RQ. How can the paradigms of Industry 5.0, Agriculture 5.0, and City 5.0 be structured within a holistic model to support environmental sustainability goals?

2. METHODOLOGY

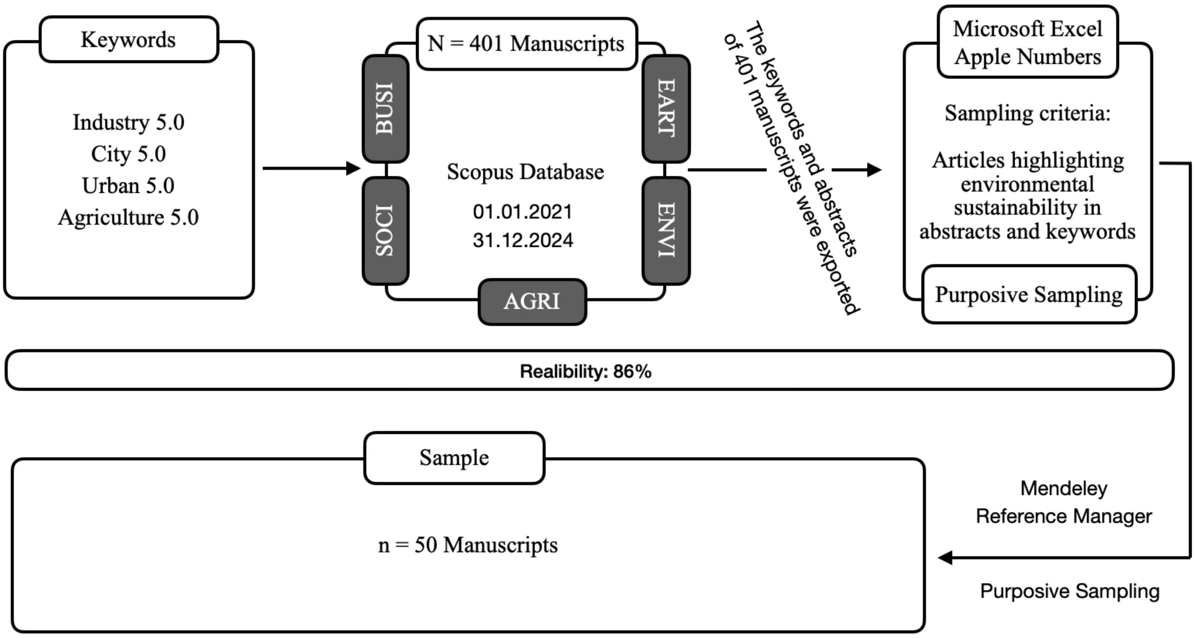
Within the scope of this study, document analysis, descriptive content analysis, and the case study method, which are among qualitative research approaches, were employed. Document analysis can serve as a stand-alone qualitative method or complement other analytical techniques (Nas et al., 2021). The population of the research consists of 401 manuscripts published in the Scopus database between 01.01.2020 and 31.12.2024 that include the keywords Industry 5.0, City 5.0, and Agriculture 5.0 and fall under the categories of Environmental Science (ENVI), Social Sciences (SOCI), Earth and Planetary Sciences (EART), Agricultural and Biological Sciences (AGRI), and Business, Management and Accounting (BUSI). From this population, a total of 50 documents were selected through purposive sampling. The criterion for selecting these documents was the researcher’s judgment that they serve the objective of the study.

(TITLE-ABS-KEY ("industry 5.0") OR TITLE-ABS-KEY ("agriculture 5.0") OR TITLE-ABS-KEY ("city 5.0") OR TITLE-ABS-KEY ("urban 5.0")) AND (LIMIT-TO (SUBJAREA , "SOCI") OR LIMIT-TO (SUBJAREA , "EART") OR LIMIT-TO (SUBJAREA , "AGRI") OR LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (

SUBJAREA , "BUSI")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2023) OR LIMIT-TO (PUBYEAR , 2024))

The research process of the study is structured as presented in Figure 1.

Figure 1. *Research process* (Author elaboration).



The manuscripts examined are presented in Table 1.

Table 1. *Examining manuscripts.*

No	Examining Manuscripts	Year
1	Purchase intention of green products following an environmentally friendly marketing campaign: Results of a survey of Instagram followers of innisfreeindonesia	2020
2	AI - Robotic Applications in Logistics Industry and Savings Calculation	(2021)
3	Industry 5.0: Ethereum blockchain technology based DApp smart contract	(2021)
4	Design Culture in the Era of Industry 5.0: A Review of Skills and Needs	(2021)
5	6G Vision: Toward Future Collaborative Cognitive Communication (3C) Systems	(2021)
6	Care in dairy farming with automatic milking systems, identified using an Activity Theory lens	(2021)
7	Managing industry 4.0 automation for fair ethical business development: A single case study	(2021)
8	Trends in science, technology, and innovation in the agri-food sector	(2022)
9	Towards Industrial Revolution 5.0 and Explainable Artificial Intelligence: Challenges and Opportunities	(2022)
10	Cloud supply chain: Integrating Industry 4.0 and digital platforms in the "Supply Chain-as-a-Service"	(2022)
11	Urban Agriculture 5.0: An Exploratory Approach to the Food System in a Super Smart Society	(2022)
12	City 5.0: Citizen involvement in the design of future cities	(2023)
13	Do industry 5.0 advantages address the sustainable development challenges of the renewable energy supply chain?	(2023)

No	Examining Manuscripts	Year
14	Converging on human-centred industry, resilient processes, and sustainable outcomes in asset management frameworks	(2023)
15	Developing a Skilled Workforce for Future Industry Demand: The Potential of Digital Twin-Based Teaching and Learning Practices in Engineering Education	(2023)
16	Systems-theoretic interdependence analysis in robot-assisted warehouse management	(2023)
17	An Industry 5.0 Perspective on Feeding Production Lines	(2023)
18	An approach towards demand response optimization at the edge in smart energy systems using local clouds	(2023)
19	ESG and Industry 5.0: The role of technologies in enhancing ESG disclosure	(2023)
20	Society 5.0 versus Industry 5.0: An examination of industrialization models in driving sustainable development from a normative stakeholder theory perspective	(2023)
21	Blockchain adoption in sustainable supply chains for Industry 5.0: A multistakeholder perspective	(2023)
22	Does industry 5.0 model optimize sustainable performance of Agri-enterprises? Real-time investigation from the realm of stakeholder theory and domain	(2023)
23	An IoT-based and cloud-assisted AI-driven monitoring platform for smart manufacturing: design architecture and experimental validation	(2023)
24	Adoption Case of IIoT and Machine Learning to Improve Energy Consumption at a Process Manufacturing Firm, under Industry 5.0 Model	(2023)
25	Application of Quality 4.0 (Q4.0) and Industrial Internet of Things (IIoT) in Agricultural Manufacturing Industry	(2023)
26	The Industry 5.0 framework: viability-based integration of the resilience, sustainability, and human-centricity perspectives	(2023)
27	Blockchained smart contract pyramid-driven multi-agent autonomous process control for resilient individualised manufacturing towards Industry 5.0	(2023)
28	Examining Rental House Data With MRL Analysis: An Empirical Approach for Future Perspective of E-Business for Smart Cities and Industry 5.0	(2023)
29	Expediting decarbonization in energy, waste, and water sector through digitalization in sustainable smart cities (SSC): Case-studies in Malaysia and China based on Industry 5.0 paradigm	(2024)
30	The relationship between industry 5.0 Process and ESG process: A qualitative analysis in the context of Türkiye's BIST Sustainability 25 Index white good sector	(2024)
31	From Industry 5.0 to Forestry 5.0: Bridging the gap with Human-Centered Artificial Intelligence	(2024)
32	AI-based autonomous UAV swarm system for weed detection and treatment: Enhancing organic orange orchard efficiency with agriculture 5.0	(2024)
33	Reinvigorating algal cultivation for biomass production with digital twin technology - a smart sustainable infrastructure	(2024)
34	Technology-Organization-External-Sustainability (TOES) Framework for Technology Adoption: Critical Analysis of Models for Industry 4.0 Implementation Projects	(2024)
35	Enabling Industry 5.0-Driven Circular Economy Transformation: A Strategic Roadmap	(2024)
36	Integrating human-centric automation and sustainability through the NAToRM framework: A neuromorphic computing approach for resilient industry 5.0 supply chains	(2024)
37	Human-Centered Systems Thinking in Technology-Enhanced Sustainable and Inclusive Architectural Design	(2024)

No	Examining Manuscripts	Year
38	A path to sustainable development of agri-industries: Analysis of agriculture 5.0 versus industry 5.0 using stakeholder theory with moderation of environmental policy	(2024)
39	Digital transition from industry 4.0 to industry 5.0 in smart manufacturing: A framework for sustainable future	(2024)
40	Human-Centered and Sustainable Artificial Intelligence in Industry 5.0: Challenges and Perspectives	(2024)
41	Towards Climate Neutrality – The key role of the Digital Twin in Industry 5.0	(2024)
42	6G-Enabled Ultra-Reliable Low Latency Communication for Industry 5.0: Challenges and Future Directions	(2024)
43	Digital humanism and artificial intelligence: the role of emotions beyond the human–machine interaction in Society 5.0	(2024)
44	Bridging Industry 5.0 and Agriculture 5.0: Historical Perspectives, Opportunities, and Future Perspectives	(2024)
45	Sustainability analysis of FarmFox IoT device towards Agriculture 5.0	(2024)
46	Smart cities and environmental sustainability: Industry 5.0 applications	(2024)
47	Digital Technologies for Sustainable Development of Agri-Food: Implementation Guidelines Toward Industry 5.0	(2024)
48	Remote Sensing for Agriculture in the Era of 5.0-A Survey	(2024)
49	Agricultural and business digitalisation degree in achieving sustainable development goals	(2024)
50	Artificial Intelligence and Biodiversity	(2024)

All data were manually compiled using Microsoft Excel and Apple Numbers applications. For the illustration of the figures, Apple Pages and Draw.io were used, and all figures were drawn by the researcher in accordance with the thematic integrity of the study.

In order to ensure the reliability of the study, the research method, process, and analytical techniques were evaluated by three field experts. During this evaluation process, each expert was asked five questions covering the scope of the study, its methodology, the criteria for document selection, the approach adopted in the analysis, and an overall assessment, resulting in a total of fifteen evaluations. Consensus was achieved among the experts in thirteen of these evaluations, while two evaluations revealed disagreement. Both experts expressed differing views regarding the inclusion of the Web of Science (WoS) database in addition to Scopus. However, considering that the inclusion of WoS would significantly expand the scope of the study and complicate the research process, these suggestions were not taken into account. Accordingly, the reliability of the study was calculated using the formula proposed by Miles and Huberman (1994, p. 64), as follows: Reliability = Agreements / (Agreements + Disagreements) = 13 / (13 + 2) = 0.86 (86%).

3. FINDINGS AND DISCUSSIONS

This study is structured in two phases in order to comprehensively address the research question. In the first phase, technological developments related to the monitoring of the physical environment in the processes of Industry 5.0, City 5.0, and Agriculture 5.0, the transfer of this data to the cyber domain, and the structuring of decision-making processes based on the obtained data are examined. In the second phase, the ICA 5.0 model is proposed, aiming to integrate these technological developments into a single platform through public collaboration, and the configuration of the required software infrastructure for the implementation of this model is explained.

In the study conducted by Yoşumaz and Uzun (2024), the Industry 5.0 process is expressed through the following equation: “Industry 4.0 + Environmental Sustainability + Resilience + Society.” This formulation clearly demonstrates that the Industry 5.0 approach is built upon the technological infrastructure developed under Industry 4.0 and incorporates components such as environmental sustainability, organizational resilience against various threats, and societal well-being. The reflection of this approach in the agricultural sector is referred to as Agriculture 5.0, while its counterpart in the field of urbanization and urban governance is defined as City 5.0. Within this framework, it can be stated that each of these domains is structured to incorporate the environmental sustainability dimension of Industry 5.0. Accordingly, the configuration of an uninterrupted data communication infrastructure among industrial, agricultural, and city systems is described below.

3.1. Establishing a Continuous Data Monitoring Infrastructure Through the Implementation of Digital Transformation Solutions in Industry, Agriculture, and City Areas

At the core of the infrastructures of Industry 5.0, City 5.0, and Agriculture 5.0 lies the transmission of data obtained from machines, equipment, human resources, and environmental conditions in physical environments into digital format through sensors supported by the IoT infrastructure (Caiazzo et al., 2023; Das et al., 2024). This data transmission enables comprehensive and real-time monitoring of ecosystems; the collected data are stored in cloud computing infrastructures (Caiazzo et al., 2023; Ivanov et al., 2022; Javed et al., 2023) and subjected to AI-supported analytical processes (Taj & Jhanjhi, 2022). These analyses produce critical knowledge for decision support mechanisms and play a decisive role in the management of operational and strategic processes across all relevant sectors. The data-driven system architecture, which is commonly adopted in the applications of Industry 5.0, City 5.0, and Agriculture 5.0, facilitates continuous monitoring of ecosystems and enables the development of real-time interventions, particularly in areas related to environmental sustainability. Consequently, a digitalization approach emerges, wherein knowledge derived from the physical environment is analyzed in the digital domain to enhance the efficiency of decision-making processes. This integrated digitalization approach not only enhances operational efficiency but also lays the groundwork for the development of environmental monitoring systems that contribute to sustainable development goals (Bairagi et al., 2023; Hazrat et al., 2023; Osello et al., 2024; Rastogi, 2023).

The Industry 5.0 process provides significant contributions to environmental sustainability by reduction of water and carbon footprints in industrial production, enhancement of waste management, preservation of ecological diversity, prevention of marine pollution (Breque et al., 2021; Kasinathan et al., 2022), improvement of energy efficiency, increase in labor productivity, and extension of the operational lifespan of machinery and equipment through predictive maintenance practices (Goh et al., 2024). The realization of these environmental contributions is directly dependent on the structuring of data- and knowledge-based digital transformation processes by industries. In this context, digital transformation for an industry requires the establishment of an infrastructure in which all objects within the production environment (machines, equipment, workers, etc.) can operate in an integrated and collaborative manner through a software system (Ivanov, 2023). Today, such software infrastructures can be developed specifically for the industry in question or can be configured by adapting off-the-shelf software such as SAP to industrial business processes. In industrial settings, it is possible to manage all processes with a single software system or to operate each process through separate software systems. Communication between these different software systems is enabled by interfaces known as Application Programming Interfaces (APIs). APIs function similarly to translators who mediate between speakers of different languages, allowing software systems with different protocols and functions to operate together in a coordinated manner (Yoşumaz & Uzun, 2024).

The City 5.0 process provides significant contributions to environmental sustainability by enhancing energy efficiency in city areas, improving waste management, reducing carbon emissions, preserving green spaces, and minimizing environmental impacts through smart transportation systems. Achieving these contributions is contingent upon the integration of AI-assisted city management applications, sensor technologies, and data-driven decision support systems into city infrastructures. Within this framework, prominent solutions include sensors monitoring air quality and traffic density, smart grids balancing energy consumption, electric transportation vehicles, waste collection systems optimized for recycling, and digital twin technologies aimed at mitigating city heat island effects (Becker et al., 2023; Goh et al., 2024; Lata et al., 2024). As in Industry 5.0, City 5.0 also necessitates equipping devices and systems within city infrastructures with sensors and IoT technologies, enabling continuous monitoring of environmental and city data and converting this data through AI algorithms into policy and action recommendations (Yoşumaz & Uzun, 2024). For example, dynamic updating of public transportation schedules based on traffic data, automatic dimming of lighting in high energy-demand areas, or restricting vehicle access based on air quality data are decisions grounded in these analytical processes (Becker et al., 2023; Lata et al., 2024). Effective execution of this process depends on the development and deployment of City 5.0-focused software infrastructures. To ensure these systems operate in harmony with city management systems and to process knowledge from various data sources on a unified platform, API technologies are utilized (Yoşumaz & Uzun, 2024). These API-based systems enable continuous and meaningful data exchange between different municipal departments, environmental monitoring systems, and citizen engagement platforms, thereby contributing to the development of sustainable, livable, and resilient city systems.

The Agriculture 5.0 process provides significant contributions to environmental sustainability by reducing pesticide use in agricultural activities, optimizing irrigation, fertilization, and energy consumption, managing biological waste efficiently, and preserving biodiversity. The realization of these contributions requires the integration of advanced digital and technological infrastructures into agricultural practices. In this context, solutions such as smart irrigation systems equipped with sensors capable of monitoring weather conditions and soil moisture in real time, electric tractors, autonomous spraying and seeding drones, and green energy systems that convert biological waste into energy have come to the fore (Catala-Roman et al., 2024; Das et al., 2024; Zhang, 2024). Similar to Industry 5.0, Agriculture 5.0 also relies on equipping machines and equipment with sensors and IoT infrastructures to collect environmental data, which are then analyzed and transformed into inputs for decision-making processes (Yoşumaz & Uzun, 2024). For example, decisions such as postponing irrigation based on weather conditions and soil moisture levels, applying minimal irrigation, or optimizing fertilizer quantity based on the mineral content of the soil are made possible through such analyses. The effective management of this process necessitates the use of software infrastructures specific to Agriculture 5.0. To ensure the interoperability of these software systems with different platforms, API technologies are employed. APIs facilitate data exchange among diverse software systems, enabling the agricultural digital transformation to function in an integrated manner.

All processes of Industry 5.0, City 5.0, and Agriculture 5.0 can be continuously monitored through IoT infrastructures, sensors, and computer software, and the interoperability of these systems can be ensured through API-based features. This makes it possible to develop shared policies for environmental sustainability. However, the establishment of such an infrastructure is not feasible through the efforts of the private sector alone. Due to both the high costs involved and the collection of personal data during data acquisition, it is essential for the public sector to play a central role in this process. In this regard, the recommended model is the ICA 5.0 model, which is explained below.

3.2. ICA 5.0 Model

In line with the information presented in Section 3.1, the effective structuring of Industry 5.0, City 5.0, and Agriculture 5.0 processes necessitates the presence of one or more software infrastructures capable of holistically monitoring and managing these processes. These software systems can operate in an integrated manner through API features that enable compatible data sharing. In this context, a state-supported public cloud infrastructure is proposed to consolidate and evaluate data generated across the relevant sectors. The ICA 5.0 model, developed accordingly, offers an AI-supported system architecture that enables the integrated monitoring and management of the components of Industry 5.0, Agriculture 5.0, and City 5.0 from an environmental sustainability perspective. When supported by public policies, this infrastructure may contribute to the interdisciplinary analysis of environmental impacts, the optimization of resource use, and the reinforcement of data-driven public decision-making mechanisms. The primary objective of the model is to support data-based decision-making processes through public cooperation, to ensure that environmental impacts are monitored through an integrated approach, and to render sustainability policies manageable via digital systems. To achieve this objective, a specialized AI model aligned with public policy priorities must be embedded into the system architecture. The general framework of this process and operational structure is presented in detail in Figure 2.

As illustrated in Figure 2, all data generated from the processes of Industry 5.0, Agriculture 5.0, and City 5.0 are evaluated by AI infrastructures alongside government-developed policies. Based on this evaluation, decisions produced by AI systems are subject to human oversight (human acknowledgement) before being implemented in industrial, city, and agricultural applications related to environmental sustainability. These implementations may be structured either autonomously or manually. In this regard, examples of both autonomous and manual applications are provided:

a. Autonomous application example: Based on the evaluation of weather conditions and soil moisture data derived from Agriculture 5.0 processes, irrigation services may be automatically suspended for farmers engaging in excessive water use, or the fees for the water provided may be increased automatically.

b. Manual application example: When data from City 5.0 processes indicate that the waste in garbage containers in a specific city area consists predominantly of chemical materials, the corresponding municipality may be tasked with investigating the situation.

As illustrated in Figure 2, the design of a three-layered data collection and monitoring structure related to the domains of Industry, City, and Agriculture through a blockchain-based infrastructure (Rupa et al., 2021; Wang et al., 2023) emerges as a mechanism to ensure the accuracy and integrity of the collected data. This structure not only provides data security but also establishes a foundation for the development of digital twins in the domains of Industry 5.0, City 5.0, and Agriculture 5.0. A digital twin refers to the real-time digital reconstruction of a physical object by continuously generating data through sensors and transmitting this data to a cyber environment. In this context, the proposed model also offers the potential to enhance decision-making processes aimed at environmental sustainability by enabling the real-time monitoring of physical objects and the timely implementation of necessary actions (Osello et al., 2024; Sheik et al., 2024).

3.2.1. The Requirements for the Establishment of the ICA 5.0 Infrastructure

The requirements for the establishment of the ICA 5.0 infrastructure are outlined below;

a. Establishment of infrastructures capable of data acquisition in the domains of industry, city, and agriculture. These infrastructures consist of sensors within the scope of IoT and communication infrastructures through which the data collected by these sensors can be transmitted to the ICA 5.0 infrastructure (Hazra et al., 2024). In this context, the costs associated with the infrastructures to be deployed in industry, city, and agriculture may vary. In particular, landowners or cultivators in agricultural areas may face financial difficulties in covering these costs. Therefore, it is crucial for the public sector to offer payment facilities and to provide interest-free, long-term credit arrangements for those affected.

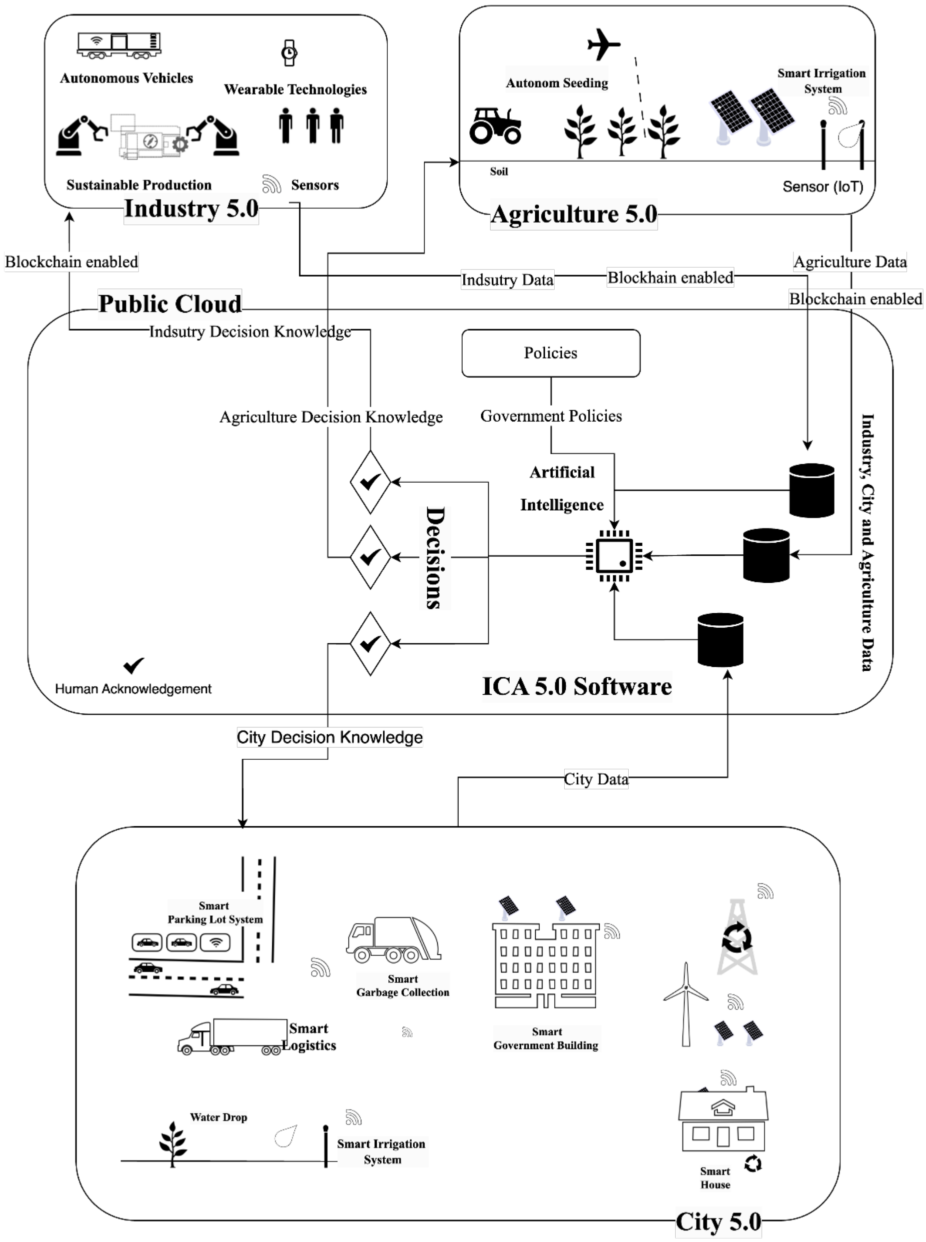
b. Implementation of necessary legal regulations. The integration of modern technologies such as intelligent systems and AI must encourage and support sustainable energy and production policies (Lu et al., 2020; Lv, 2023). Public policies should incorporate demarketing strategies to restrict the use of natural resources, establish recycling networks, and design waste management systems tailored to technological requirements (Lu et al., 2020; Lv, 2023).

c. Development of a public cloud infrastructure capable of storing data generated from industry, city, and agriculture processes (Abd Al Ghaffar, 2024).

d. Establishment of an AI infrastructure for the analysis of data stored in the public cloud and for ensuring the alignment of data-driven outcomes with public policy priorities (Abd Al Ghaffar, 2024; Martini et al., 2024).

e. Development of management software to oversee the entire process. When all processes are integrated through a blockchain-based infrastructure, both enhanced data security and verifiability of data accuracy can be achieved (Lv, 2023).

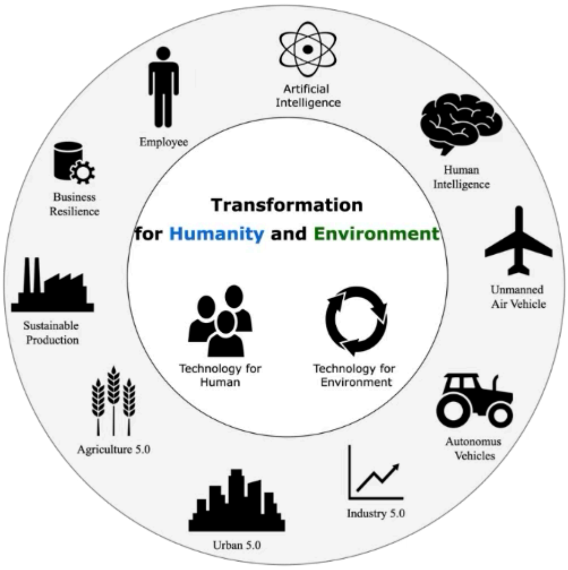
Figure 2. *ICA 5.0 three-tier monitoring and decision infrastructure* (Author Elaboration).



f. Design of a human acknowledgement mechanism to enable human verification and approval of decisions derived from the AI infrastructure. This structure will also enable the emergence of hybrid intelligence by ensuring collaboration between human and AI (Jarrahi et al., 2022; Liu & Zeng, 2021).

g. Preparation of public service announcements to explain the process in more detail to the general public. In this context, the use of effective visuals that present the process in a comprehensible manner is essential. A brief visual of the ICA 5.0 model suitable for this purpose is illustrated in Figure 3.

Figure 3. *ICA 5.0 Digital transformation concept* (Author elaboration).



3.2.2. Contributions of the Model

The contributions of the ICA 5.0 model can be explained as follows;

3.2.2.1. In the Industry 5.0 Domain

With the collection of resource usage data in a public cloud infrastructure, energy and water consumption will become traceable across the sector, enabling savings in resource use during production processes based on these data (Bairagi et al., 2023).

As waste gas emissions and production-based carbon emissions of industrial facilities can be monitored through sensors, regulatory measures and sectoral targets for reducing the carbon footprint will become more tangible and auditable (Goh et al., 2024).

By requiring all industrial facilities to transmit data to the public through a unified software infrastructure, enterprises that fail to meet sustainable production criteria can be identified, allowing the development of public policies that promote environmentally responsible production. For instance, penalties such as higher taxes or exclusion from public incentives may be applied to enterprises that fail to meet environmental sustainability standards, while rewards such as tax reductions or access to incentives may be granted to those that comply.

3.2.2.2. In the City 5.0 Domain

The collection of environmental data, such as energy consumption, waste generation, and carbon emissions, in city areas through public infrastructure will support the development of environmentally conscious city policies (Goh et al., 2024).

When city transportation, parking usage, and energy consumption in buildings are monitored through sensors, emissions from traffic can be reduced, and city carbon management can be supported structurally (Lata et al., 2024).

The availability of publicly accessible data on the type and volume of city waste will facilitate more effective planning of waste management and recycling policies, helping to prevent environmental pollution (Goh et al., 2024).

Central government budget allocations may be increased for municipalities that actively support environmental sustainability initiatives, while reductions in such allocations may be applied to those that fail to demonstrate adequate commitment to these efforts.

3.2.2.3. In the Agriculture 5.0 Domain

Real-time monitoring of soil moisture, temperature, and chemical residue levels through public infrastructure will ensure that irrigation and fertilization practices are applied only when necessary, thereby minimizing water consumption and chemical use (Victor et al., 2024).

When pesticide and fertilizer residues are continuously monitored in public systems, regionally and seasonally targeted intervention strategies can be developed to protect soil health (Varol & Tokatlı, 2022).

Data collected from agricultural production processes can be holistically analyzed to direct public support toward farmers engaged in environmentally sensitive production. To promote the effective management of natural resources, providing landowners and agricultural workers who comply with environmental sustainability policies with access to water and energy at reduced costs can serve as an incentive mechanism. This practice will not only facilitate the achievement of environmental targets but also enhance the practical applicability and sustainability of the proposed model at the field level.

Moreover, the model's hybrid intelligence structure, combining AI-generated recommendations with human oversight, ensures that decision outputs are not only data-driven but also ethically and contextually grounded. These integrated outputs support public agencies in transitioning from reactive to anticipatory environmental governance.

All these contributions are detailed in Table 2 below, presenting the benefits, functionalities, and expected outputs within the contexts of industry, urban, and agricultural sectors.

Table 2. *Contributions of the ICA 5.0 Model.*

Benefit / Functionality	Expected Outputs
Industry 5.0	
Energy and water consumption, along with waste gas and carbon emissions, can be monitored through sensor-based systems integrated into a public cloud infrastructure, enabling comprehensive tracking of industrial environmental performance (Bairagi et al., 2023; Goh et al., 2024).	Sector-wide data on resource use and real-time emission monitoring support the enforcement of carbon reduction targets and environmental regulations, while also enabling the identification of non-compliant enterprises and the implementation of incentive or penalty mechanisms based on environmental performance (Bairagi et al., 2023; Goh et al., 2024).
City 5.0	
City environmental data, including energy, waste, and carbon, are collected alongside sensor-based monitoring of traffic, parking, and energy consumption in buildings (Goh et al., 2024; Lata et al., 2024).	Data that supports the formulation of environmentally oriented urban strategies and infrastructure planning provides operational insights for optimizing mobility systems, improving energy balance, and managing urban carbon emissions (Goh et al., 2024; Lata et al., 2024).
Agriculture 5.0	
Real-time monitoring of soil moisture, temperature, and chemical residues, along with continuous tracking of pesticide and fertilizer residue (Victor et al., 2024; Varol & Tokatlı, 2022).	Real-time monitoring of soil moisture, temperature, and chemical residues, along with continuous tracking of pesticide and fertilizer residues, provides environmental metrics for optimizing irrigation and fertilization to support reduced water and chemical use policies, as well as seasonal and regional data on chemical accumulation that guide interventions to protect soil and crop quality (Victor et al., 2024; Varol & Tokatlı, 2022).

Benefit / Functionality	Expected Outputs
Integrated Holistic Monitoring System	
ICA 5.0 model enabling mandatory data transmission and holistic monitoring across industry, city, and agriculture sectors.	The ICA 5.0 model establishes an integrated and cross-sectoral framework that enables mandatory data transmission and holistic monitoring within the domains of industry, urban governance, and agriculture. Through this framework, non-compliant enterprises, municipalities, and environmentally sensitive agricultural actors can be systematically identified based on measurable environmental performance. The model facilitates the implementation of differentiated incentive and sanction mechanisms aimed at promoting sustainable practices while discouraging environmentally detrimental behaviors. It incorporates real-time monitoring of key urban environmental indicators, such as energy consumption, waste separation, and pollution levels, alongside agricultural metrics including soil moisture levels and residual agrochemical concentrations. This comprehensive monitoring architecture enhances resource optimization and ecological protection. By synthesizing operational data from all three sectors, the model supports evidence-based policy development and the provision of targeted interventions, thereby advancing environmental sustainability, regulatory compliance, and efficient resource use. Moreover, its hybrid intelligence infrastructure, integrating AI-based analytics with human oversight, ensures that decisions are both data-informed and contextually grounded. This approach enables public institutions to transition from reactive environmental management toward a more anticipatory and strategic mode of governance (Goh et al., 2024; Lata et al., 2024; Victor et al., 2024; Yoşumaz & Uzun, 2024).

3.3. Implementation of ICA 5.0

ICA 5.0 has been designed independently of any specific country context. However, due to varying political, cultural, and social structures, its implementation will inevitably differ from country to country. Within the scope of this study, an example implementation framework that could be adopted across Türkiye is presented.

3.3.1. The Case of Türkiye

The implementation of the ICA 5.0 model in Türkiye should be supported by a centralized yet multi-stakeholder and multi-level governance structure. In this context, applications to be developed in the fields of industry, city management, and agriculture should be coordinated centrally and executed within sector-specific institutional structures. In order to ensure a holistic and synchronized implementation, it is recommended to establish specialized units focused on these three key sectors under the Presidency’s Digital Transformation Office. These units would coordinate with relevant public institutions, local authorities, private sector actors, and professional organizations to guide and supervise the implementation process. The required components of this process are outlined below.

3.3.1.1.Public Cloud Architecture

One of the core components of the model is the establishment of a public cloud infrastructure. Rather than establishing a wholly new infrastructure, it is proposed that underutilized IT capacities within existing public institutions be leveraged to support scalability and redundancy. In particular, virtualization infrastructures and data centers at universities may be used for city-scale data storage and analysis. A regionally clustered cloud architecture, where neighboring cities back up each other's infrastructure, can be developed.

This structure would not only provide a practical short-term solution but also lay a strategic foundation for the long-term development of a national and sovereign cloud architecture in Türkiye.

This infrastructure should be established in the short term, while its capacity is gradually scaled over the long term.

3.3.1.2. Development of ICA 5.0 Management Software

The digital governance of the model requires a dedicated software infrastructure. The development process should be supported through public-private collaboration, especially via TÜBİTAK-funded projects. The software must be capable of managing the entire ICA 5.0 cycle, including data collection, analysis, and decision support mechanisms. A mobile application should also be developed to ensure active engagement from factory managers, municipal officers, farmers, and citizens.

Furthermore, integration with the national e-Government portal (e-Devlet) would facilitate transparent feedback mechanisms, thereby enhancing the model's transparency and accountability.

This software, together with the public cloud infrastructure, should be prioritized and developed in the short term.

3.3.1.3. Sectoral Implementation Strategies

In the industrial domain, implementation can be coordinated by the Ministry of Industry and Technology. Sub-implementing agencies may include Organized Industrial Zones, exporters' unions, chambers of industry, and sectoral associations. These organizations will play a key role in establishing systems for collecting environmental data (e.g., carbon emissions, waste generation, and energy consumption), implementing traceability systems, and promoting environmentally responsible production strategies.

While the data collection infrastructure may differ between industries and institutions, the primary objective is to standardize collected data and enable integration through APIs to the public cloud system. A comparable example exists in hospital information systems, where different public and private hospitals use distinct systems, yet all transmit uniform data to the Ministry of Health.

In the city domain, implementation should be planned under the coordination of the Ministry of Environment, Urbanization and Climate Change, along with the Ministry of Transport and Infrastructure. Municipalities, metropolitan transportation departments, and infrastructure service providers should serve as implementing actors. The goal should be to deploy digital systems for real-time monitoring of parameters such as building energy use, waste generation, traffic congestion, and air quality. Data on parking occupancy, mobility flows, and emissions can be integrated into digital public infrastructure to support data-driven spatial decision-making processes.

In the agricultural domain, the Ministry of Agriculture and Forestry should serve as the primary coordinator. Key implementing institutions may include the State Hydraulic Works (DSİ), chambers of agriculture, agricultural cooperatives, and local producer organizations. The collection of data on soil health, moisture levels, and pesticide residues via sensors will enhance traceability in environmentally sustainable production.

To ensure participation from small-scale farmers, it is critical that the necessary equipment be provided free of charge or at minimal cost. In this regard, regional support programs should be developed and managed through agricultural cooperatives.

3.3.1.4. Implementation Phases and Planning

The first step in operationalizing the model should be the preparation of a comprehensive national implementation plan. This plan must clearly outline short-, medium-, and long-term objectives, actionable steps, and responsible stakeholders. The plan should also provide distinct listings of the required equipment and software for the industrial, city, and agricultural domains. In particular, mechanisms to support small producers and farmers should be proactively designed.

Institutions such as KOSGEB and TÜBİTAK should not only serve as financiers but also as partners in technology development throughout the implementation process.

4. CONCLUSION

Industry 5.0, City 5.0, and Agriculture 5.0 approaches represent a new paradigm in which the digital transformation process is integrated with a focus on human and environmental sustainability. Within this paradigm, technologies such as AI, IoT, and cloud computing are increasingly discussed in the literature in terms of their contributions to human and environmental sustainability. The ICA 5.0 model proposed in this study is recommended as a model that enables the integrated monitoring and management of these three approaches from the perspective of environmental sustainability. This model aims to establish a data collection infrastructure based on blockchain across the domains of industry, city, and agriculture, and to develop integrated solutions by subjecting the collected data to an analysis process supported by public policies.

In this context, in the industrial domain, the collection and analysis of environmental indicators such as carbon emissions, waste generation, and energy consumption originating from production processes in publicly accessible digital infrastructures allow for the development of data-driven policies that can accelerate the transition of industrial enterprises toward environmentally friendly production processes. This approach not only enhances the visibility of environmental impacts across the sector but also offers a strategic advantage to public institutions in monitoring and guiding sectoral sustainability targets. At the city domain, the real-time monitoring of variables such as building energy consumption, traffic density, waste generation, and air quality enables more efficient and timely decision-making in spatial planning to reduce the carbon footprint of cities. Practices such as monitoring parking occupancy rates and optimizing intra-city transportation not only contribute to the reduction of emissions but also support the development of environmentally conscious smart city applications. In the agricultural domain, the transfer of indicators related to soil health, such as moisture levels, mineral balance, and pesticide residues, to public infrastructures through sensors ensures that production processes are conducted not only with a focus on productivity but also in alignment with ecological goals (Catala-Roman et al., 2024; San Emeterio de la Parte et al., 2024; Varol & Tokatlı, 2022). In this framework, for instance, providing resources such as water and energy at reduced costs to farmers and workers who comply with environmental sustainability policies fosters an incentive structure for environmentally friendly agricultural practices and enhances the applicability of the model at the field level. In this respect, the ICA 5.0 model proposes a multi-layered, public-supported digital sustainability architecture in which ecological impacts can be identified in advance, and it enables data-driven, preventive, and inclusive policymaking in the domains of industry, city, and agriculture. The study contributes to the literature by presenting the conceptual ICA 5.0 model, which enables the integrated and holistic monitoring of Industry 5.0, Agriculture 5.0, and City 5.0 processes from the perspective of environmental sustainability. The tripartite structure proposed by the model seeks to address a significant gap in the literature by approaching environmental monitoring processes within a systematic and interdisciplinary framework.

In order to illustrate its feasibility, the ICA 5.0 model has been exemplified through a Türkiye-specific case in this study. In this example, it is proposed that the implementation be managed through a centralized but multi-actor governance structure coordinated under the Digital Transformation Office of the Presidency. Sector-specific sub-units for industry, city, and agriculture would be established to coordinate implementation across relevant public institutions, municipalities, organized industrial zones, and cooperatives. A national public cloud architecture, the development of a dedicated ICA 5.0 management software system, and the phased planning of short-term, medium-term, and long-term goals are all considered key implementation steps. This case offers a concrete pathway to operationalize the ICA 5.0 model in practice and demonstrates how a coordinated digital governance structure can enhance environmental sustainability across key domains.

In light of the findings presented in this study, the ICA 5.0 model is conceptually compatible with the core themes emphasized in the literature on Industry 5.0, City 5.0, and Agriculture 5.0. This compatibility is particularly evident in the areas of real-time environmental monitoring, integrated digital infrastructures, and the use of AI for sustainability-oriented decision-making. However, the existing body of research offers fragmented solutions, proposing independent models tailored to specific domains. For instance, Bairagi et al. (2023) introduced the Smart Factory 5.0 model in the industrial context, focusing on integrating cyber-physical systems in production environments. In city studies, Lata et al. (2024) emphasized the use of AI-powered digital twins for real-time city management and environmental planning. Similarly, Catala-Roman et al. (2024) and Victor et al. (2024) developed smart agriculture frameworks that use sensor-based technologies to optimize irrigation, fertilization, and pest control. While these approaches contribute significantly to their respective fields, they often lack a comprehensive architecture that addresses the interconnections among industrial, city, and agricultural sustainability processes. The ICA 5.0 model fills this gap by proposing a unified architecture through which industrial, city, and agricultural systems can be monitored, managed, and guided under a single, integrated framework. The integration of blockchain and public cloud infrastructures, as proposed in this study, aligns with the technological priorities emphasized by Goh et al. (2024) and Osello et al. (2024). These researchers underscore the necessity of secure, transparent, and interoperable platforms for environmental governance. ICA 5.0 design emphasizes not only technical integration but also institutional coordination through centralized public oversight, an aspect not sufficiently addressed in prior models. Additionally, the model's emphasis on hybrid intelligence, where human oversight complements algorithmic processing, reflects the recommendations of Jarrahi et al. (2022) and Liu & Zeng (2021), who argue that effective sustainability governance necessitates human-AI collaboration to balance efficiency, ethical reasoning, and contextual judgment. Unlike earlier models that generally target sector-specific optimization, ICA 5.0 offers a holistic, cross-sectoral approach, enhancing system-level interoperability while supporting data-driven public policy implementation.

The main limitation of this study lies in the fact that the proposed ICA 5.0 model focuses solely on the environmental sustainability dimension of digital transformation processes. While digitalization practices are increasingly widespread within the frameworks of Industry 4.0 and Industry 5.0 and possess a multidimensional structure, components such as employees, society, and resilience remain outside the scope of this study. Furthermore, due to constraints in time and resources, the technical components of the software infrastructure that could form the basis for the practical applications of the model have not been examined in detail. Future studies focusing on the development of concrete prototypes, system architectures, and technical requirements of software that can be integrated into the proposed public cloud model will contribute to strengthening the theoretical foundation and enhancing the practical applicability of the model.

Disclosure Statements

1. The author of this article confirm that their work complies with the principles of research and publication ethics.

2. No potential conflict of interest was reported by the author.

3. This article was screened for potential plagiarism using a plagiarism screening program.

REFERENCES

Abd Al Ghaffar, H. t. A. N. (2024). Government Cloud Computing and National Security. *Review of Economics and Political Science*, 9(2). https://doi.org/10.1108/REPS-09-2019-0125

Adriaensen, A., Pintelon, L., Costantino, F., Di Gravio, G., & Patriarca, R. (2023). Systems-theoretic interdependence analysis in robot-assisted warehouse management. *Safety Science*, 168. https://doi.org/10.1016/J.SSCI.2023.106294

Asif, M., Searcy, C., & Castka, P. (2023). ESG and Industry 5.0: The role of technologies in enhancing ESG disclosure. *Technological Forecasting and Social Change*, 195. https://doi.org/10.1016/J.TECHFORE.2023.122806

Asmara Dewi, W. W., Avicenna, F., & Meideline, M. M. (2020). Purchase intention of green products following an environmentally friendly marketing campaign: Results of a survey of Instagram followers of InnisfreeIndonesia. *Asian Journal for Public Opinion Research*, 8(2), 160–177. https://doi.org/10.15206/ajpor.2020.8.2.160

Avsec, S., Jagiłło-Kowalczyk, M., Żabicka, A., Gil-Mastalerczyk, J., & Gawlak, A. (2024). Human-centered systems thinking in technology-enhanced sustainable and inclusive architectural design. *Sustainability*, 16(22), 1–45. https://doi.org/10.3390/SU16229802/S1

Bairagi, K., Golam Rabiul Alam, M., Ndikumana, A., Shirajum Munir, M., Redchuk, A., Walas Mateo, F., Pascal, G., & Eloy Tornillo, J. (2023). Adoption case of IIoT and machine learning to improve energy consumption at a process manufacturing firm, under Industry 5.0 model. *Big Data and Cognitive Computing*, 7(1). https://doi.org/10.3390/BDCC7010042

Becker, J., Chasin, F., Rosemann, M., Beverungen, D., Priefer, J., Brocke, J. vom, Matzner, M., del Rio Ortega, A., Resinas, M., Santoro, F., Song, M., Park, K., & Di Ciccio, C. (2023). City 5.0: Citizen involvement in the design of future cities. *Electronic Markets*, 33(1), 1–21. https://doi.org/10.1007/S12525-023-00621-Y/TABLES/6

Breque, M., De Nul, L., & Petridis, A. (2021). *Industry 5.0: Towards a sustainable, human-centric and resilient European industry*. https://doi.org/10.2777/308407

Caiazzo, B., Murino, T., Petrillo, A., Piccirillo, G., & Santini, S. (2023). An IoT-based and cloud-assisted AI-driven monitoring platform for smart manufacturing: design architecture and experimental validation. *Journal of Manufacturing Technology Management*, 34(4), 507–534. https://doi.org/10.1108/JMTM-02-2022-0092

Carolina Dall, A., Ferreira, A., Lenyra Meirelles Campos Titotto, S., & Cristina Santos Akkari, A. (2022). City Agriculture 5.0: An exploratory approach to the food system in a super smart society. *International Journal of Mathematical, Engineering and Management Sciences*, 7(4), 455–475. https://doi.org/10.33889/IJMEMS.2022.7.4.030

Catala-Roman, P., Segura-Garcia, J., Dura, E., Navarro-Camba, E. A., Alcaraz-Calero, J. M., & Garcia-Pineda, M. (2024). AI-based autonomous UAV swarm system for weed detection and treatment: Enhancing organic orange orchard efficiency with agriculture 5.0. *Internet of Things*, 28, 101418. https://doi.org/10.1016/J.IOT.2024.101418

Chabane, B., Komljenovic, D., & Abdul-Nour, G. (2023). Converging on human-centred industry, resilient processes, and sustainable outcomes in asset management frameworks. *Environment Systems and Decisions*, 43(4), 663–679. https://doi.org/10.1007/S10669-023-09943-W/FIGURES/5

Chivilò, M., & Meneghetti, A. (2023). An Industry 5.0 perspective on feeding production lines. *Sustainability*, 15(22). https://doi.org/10.3390/SU152216088

Corallo, A., Latino, M. E., Menegoli, M., & Signore, F. (2024). Digital technologies for sustainable development of agri-food: Implementation guidelines toward Industry 5.0. *IEEE Transactions on Engineering Management*, 71, 10699–10715. https://doi.org/10.1109/TEM.2024.3403251

Das, A., Debnath, B., Sengupta, A., Das, A., & De, D. (2024). Sustainability analysis of FarmFox IoT device towards Agriculture 5.0. *Environment, Development and Sustainability*, 1–29. https://doi.org/10.1007/S10668-024-05356-0/FIGURES/7

De Nunzio, G., & Rizzo, R. (2024). Artificial intelligence and biodiversity. *SCIentific RESearch and Information Technology*, 14, 53–70. https://doi.org/10.2423/I22394303V14SP53

Ferreira, L., Oliveira, T., & Neves, C. (2023). Consumer's intention to use and recommend smart home technologies: The role of environmental awareness. *Energy*, 263. https://doi.org/10.1016/j.energy.2022.125814

Goh, K. C., Kurniawan, T. A., Zainordin, N., Arifah, I. D. C., Abas, M. A., Masrom, M. A. N., Mohamed, S., Omar, R., Khoo, S. L., Gui, H. C., Toh, T. C., & Onn, C. W. (2024). Expediting decarbonization in energy, waste, and water sector through digitalization in sustainable smart cities (SSC): Case-studies in Malaysia and China based on Industry 5.0 paradigm. *Sustainable Cities and Society*, 117, 105969. https://doi.org/10.1016/J.SCS.2024.105969

Guo, L., Sun, D., Warraich, M. A., & Waheed, A. (2023). Does industry 5.0 model optimize sustainable performance of Agri-enterprises? Real-time investigation from the realm of stakeholder theory and domain. *Sustainable Development*, 31(4), 2507–2516. https://doi.org/10.1002/SD.2527

Haloui, D., Oufaska, K., Oudani, M., & El Yassini, K. (2024). Bridging Industry 5.0 and Agriculture 5.0: Historical perspectives, opportunities, and future perspectives. *Sustainability*, 16(9). https://doi.org/10.3390/SU16093507

Hazra, A., Munusamy, A., Adhikari, M., Awasthi, L. K., & Venu, P. (2024). 6G-enabled ultra-reliable low latency communication for Industry 5.0: Challenges and future directions. *IEEE Communications Standards Magazine*, 8(2), 36–42. https://doi.org/10.1109/MCOMSTD.0004.2300029

Hazrat, M. A., Hassan, N. M. S., Chowdhury, A. A., Rasul, M. G., & Taylor, B. A. (2023). Developing a skilled workforce for future industry demand: The potential of digital twin-based teaching and learning practices in engineering education. *Sustainability*, 15(23). https://doi.org/10.3390/SU152316433

Holzinger, A., Schweier, J., Gollob, C., Nothdurft, A., Hasenauer, H., Kirisits, T., Häggström, C., Visser, R., Cavalli, R., Spinelli, R., & Stampfer, K. (2024). From Industry 5.0 to Forestry 5.0: Bridging the gap with human-centered artificial intelligence. *Current Forestry Reports*, 10(6), 442–455. https://doi.org/10.1007/S40725-024-00231-7

Hsu, C.-H., Li, Z.-H., Zhuo, H.-J., & Zhang, T.-Y. (2024). Enabling Industry 5.0-driven circular economy transformation: A strategic roadmap. *Sustainability*, 16(22), 1–25. https://doi.org/10.3390/SU16229954

Ivanov, D. (2023). The Industry 5.0 framework: Viability-based integration of the resilience, sustainability, and human-centricity perspectives. *International Journal of Production Research*, 61(5), 1683–1695. https://doi.org/10.1080/00207543.2022.2118892

Ivanov, D., Dolgui, A., & Sokolov, B. (2022). Cloud supply chain: Integrating Industry 4.0 and digital platforms in the "Supply Chain-as-a-Service." *Transportation Research Part E: Logistics and Transportation Review*, 160. https://doi.org/10.1016/J.TRE.2022.102676

Jarrahi, M. H., Lutz, C., & Newlands, G. (2022). Artificial intelligence, human intelligence and hybrid intelligence based on mutual augmentation. *Big Data and Society*, 9(2). https://doi.org/10.1177/20539517221142824

Javed, S., Tripathy, A., Deventer, J. van, Mokayed, H., Paniagua, C., & Delsing, J. (2023). An approach towards demand response optimization at the edge in smart energy systems using local clouds. *Smart Energy*, 12. https://doi.org/10.1016/J.SEGY.2023.100123

Kasinathan, P., Pugazhendhi, R., Elavarasan, R. M., Ramachandaramurthy, V. K., Ramanathan, V., Subramanian, S., Kumar, S., Nandhagopal, K., Raghavan, R. R. V., Rangasamy, S., Devendiran, R., & Alsharif, M. H. (2022). Realization of sustainable development goals with disruptive technologies by integrating Industry 5.0, Society 5.0, smart cities and villages. *Sustainability*, 14(22). https://doi.org/10.3390/su142215258

Lata, M., Gupta, A., & Kumar, V. (2024). Smart cities and environmental sustainability: Industry 5.0 applications. *International Journal of Global Environmental Issues*, 23(4), 393–407. https://doi.org/10.1504/IJGENVI.2024.144451

Leng, J., Sha, W., Lin, Z., Jing, J., Liu, Q., & Chen, X. (2023). Blockchained smart contract pyramid-driven multi-agent autonomous process control for resilient individualised manufacturing towards Industry 5.0. *International Journal of Production Research*, 61(13), 4302–4321. https://doi.org/10.1080/00207543.2022.2089929

Li, X., Liu, H., Wang, W., Zheng, Y., Lv, H., & Lv, Z. (2022). Big data analysis of the Internet of Things in the digital twins of smart city based on deep learning. *Future Generation Computer Systems*, 128. https://doi.org/10.1016/j.future.2021.10.006

Liu, Z., & Zeng, X. (2021). Hybrid intelligence in big data environment: Concepts, architectures, and applications of intelligent service. *Data and Information Management*, 5(2). https://doi.org/10.2478/dim-2020-0051

Lu, Y., Khan, Z. A., Alvarez-Alvarado, M. S., Zhang, Y., Huang, Z., & Imran, M. (2020). A critical review of sustainable energy policies for the promotion of renewable energy sources. *Sustainability*, 12(12). https://doi.org/10.3390/su12125078

Lundström, C., & Lindblom, J. (2021). Care in dairy farming with automatic milking systems, identified using an Activity Theory lens. *Journal of Rural Studies*, 87, 386–403. https://doi.org/10.1016/J.JRURSTUD.2021.09.006

Lv, Y. (2023). Transitioning to sustainable energy: Opportunities, challenges, and the potential of blockchain technology. *Frontiers in Energy Research*, 11. https://doi.org/10.3389/fenrg.2023.1258044

Magni, D., Del Gaudio, G., Papa, A., & Della Corte, V. (2024). Digital humanism and artificial intelligence: The role of emotions beyond the human–machine interaction in Society 5.0. *Journal of Management History*, 30(2), 195–218. https://doi.org/10.1108/JMH-12-2022-0084

Margherita, E. G., & Braccini, A. M. (2021). Managing industry 4.0 automation for fair ethical business development: A single case study. *Technological Forecasting and Social Change*, 172. https://doi.org/10.1016/J.TECHFORE.2021.121048

Martini, B., Bellisario, D., & Coletti, P. (2024). Human-centered and sustainable artificial intelligence in Industry 5.0: Challenges and perspectives. *Sustainability*, 16(13), 5448. https://doi.org/10.3390/SU16135448

Martos, V., Ahmad, A., Cartujo, P., & Ordoñez, J. (2021). Ensuring agricultural sustainability through remote sensing in the era of agriculture 5.0. *Applied Sciences*, 11(13). https://doi.org/10.3390/app11135911

Masoomi, B., Sahebi, I. G., Ghobakhloo, M., & Mosayebi, A. (2023). Do industry 5.0 advantages address the sustainable development challenges of the renewable energy supply chain? *Sustainable Production and Consumption*, 43, 94–112. https://doi.org/10.1016/J.SPC.2023.10.018

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis* (2nd ed., Vol. 1). Sage.

ORAN, I. B., & CEZAYIRLIOGLU, H. R. (2021). AI-robotic applications in logistics industry and savings calculation. *Journal of Organizational Behavior Research*, 6, 148–165. https://doi.org/10.51847/JUXQMVCVQF

Osello, A., Del Giudice, M., Donato, A. J., & Fratto, A. (2024). Towards climate neutrality – The key role of the Digital Twin in Industry 5.0. *AGATHÓN | International Journal of Architecture, Art and Design*, 15, 276–285. https://doi.org/10.19229/2464-9309/15222024

Polymeni, S., Plastras, S., Skoutas, D. N., Kormentzas, G., & Skianis, C. (2023). The impact of 6G-IoT technologies on the development of Agriculture 5.0: A review. *Electronics*, 12(12). https://doi.org/10.3390/electronics12122651

Ragazou, K., Garefalakis, A., Zafeiriou, E., & Passas, I. (2022). Agriculture 5.0: A new strategic management mode for a cut cost and an energy efficient agriculture sector. *Energies*, 15(9). https://doi.org/10.3390/en15093113

Rastogi, R. (2023). Examining rental house data with MRL analysis: An empirical approach for future perspective of e-business for smart cities and Industry 5.0. *International Journal of Cyber Behavior, Psychology and Learning*, 13(1). https://doi.org/10.4018/IJCBPL.333474

Rupa, Ch., Midhunchakkaravarthy, D., Hasan, M. K., Alhumyani, H., & Saeed, R. A. (2021). Industry 5.0: Ethereum blockchain technology based DApp smart contract. *Mathematical Biosciences and Engineering*, 18(5), 7010–7027. https://doi.org/10.3934/MBE.2021349

San Emeterio de la Parte, M., Martínez-Ortega, J. F., Castillejo, P., & Lucas-Martínez, N. (2024). Spatio-temporal semantic data management systems for IoT in agriculture 5.0: Challenges and future directions. *Internet of Things*, 25. https://doi.org/10.1016/j.iot.2023.101030

Sarkar, B. D., Shardeo, V., Dwivedi, A., & Pamucar, D. (2024). Digital transition from industry 4.0 to industry 5.0 in smart manufacturing: A framework for sustainable future. *Technology in Society*, 78. https://doi.org/10.1016/J.TECHSOC.2024.102649

Satyro, W. C., Contador, J. C., Gomes, J. A., Monken, S. F. de P., Barbosa, A. P., Bizarrias, F. S., Contador, J. L., Silva, L. S., & Prado, R. G. (2024). Technology-organization-external-sustainability (TOES) framework for technology adoption: Critical analysis of models for Industry 4.0 implementation projects. *Sustainability*, 16(24), 1–25. https://doi.org/10.3390/SU162411064

Shahzadi, S., Iqbal, M., & Chaudhry, N. R. (2021). 6G vision: Toward future collaborative cognitive communication (3C) systems. *IEEE Communications Standards Magazine*, 5(2), 60–67. https://doi.org/10.1109/MCOMSTD.001.2000044

Sheik, A. G., Kumar, A., Ansari, F. A., Raj, V., Peleato, N. M., Patan, A. K., Kumari, S., & Bux, F. (2024). Reinvigorating algal cultivation for biomass production with digital twin technology – a smart sustainable infrastructure. *Algal Research*, 84, 1–17. https://doi.org/10.1016/J.ALGAL.2024.103779

Singh, J., Ahuja, I. S., Singh, H., & Singh, A. (2023). Application of Quality 4.0 (Q4.0) and Industrial Internet of Things (IIoT) in agricultural manufacturing industry. *AgriEngineering*, 5(1), 537–565. https://doi.org/10.3390/AGRIENGINEERING5010035

Taj, I., & Jhanjhi, N. Z. (2022). Towards Industrial Revolution 5.0 and explainable artificial intelligence: Challenges and opportunities. *International Journal of Computing and Digital Systems*, 12(1), 285–310. https://doi.org/10.12785/ijcds/120124

Talla, A., & McIlwaine, S. (2024). Industry 4.0 and the circular economy: Using design-stage digital technology to reduce construction waste. *Smart and Sustainable Built Environment*, 13(1). https://doi.org/10.1108/SASBE-03-2022-0050

Taverner, C., Trojan, L., Simion, O., & Szkudlarek, E. (2021). Design culture in the era of Industry 5.0: A review of skills and needs. *Cultural Management: Science and Education*, 5(1). https://doi.org/10.30819/cmse.5-1.03

Tombe, R., & Smuts, H. (2023). Society 5.0-inspired digitalization framework for resilient and sustainable agriculture. *EPiC Series in Computing*, 93. https://doi.org/10.29007/xc5q

Várallyai, L., Botos, S., Bálint, L. P., Kovács, T., & Szilágyi, R. (2024). Agricultural and business digitalisation degree in achieving sustainable development goals. *International Journal of Sustainable Agricultural Management and Informatics*, 10(3), 327–345. https://doi.org/10.1504/IJSAMI.2024.139725

Vargas-Canales, J. M., Brambila-Paz, J. de J., Pérez-Cerecedo, V., Rojas-Rojas, M. M., López-Reyna, M. del C., & Omaña-Silvestre, J. M. (2022). Trends in science, technology, and innovation in the agri-food sector. *Tapuya: Latin American Science, Technology and Society*, 5(1). https://doi.org/10.1080/25729861.2022.2115829

Varol, M., & Tokatlı, C. (2022). Seasonal variations of toxic metal(loid)s in groundwater collected from an intensive agricultural area in northwestern Turkey and associated health risk assessment. *Environmental Research*, 204. https://doi.org/10.1016/j.envres.2021.111922

Victor, N., Maddikunta, P. K. R., Mary, D. R. K., Murugan, R., Chengoden, R., Gadekallu, T. R., Rakesh, N., Zhu, Y., & Paek, J. (2024). Remote sensing for agriculture in the era of Industry 5.0 – A survey. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 17, 5920–5945. https://doi.org/10.1109/JSTARS.2024.3370508

Wang, Z. J., Chen, Z. S., Xiao, L., Su, Q., Govindan, K., & Skibniewski, M. J. (2023). Blockchain adoption in sustainable supply chains for Industry 5.0: A multistakeholder perspective. *Journal of Innovation & Knowledge*, 8(4). https://doi.org/10.1016/J.JIK.2023.100425

Williamson, S. M., & Prybutok, V. (2024). Integrating human-centric automation and sustainability through the NAToRM framework: A neuromorphic computing approach for resilient industry 5.0 supply chains. *International Journal of Information Management Data Insights*, 4(2), 100278. https://doi.org/10.1016/J.JJIMEI.2024.100278

Yoşumaz, İ., & Uzun, H. (2024). The relationship between industry 5.0 process and ESG process: A qualitative analysis in the context of Türkiye's BIST Sustainability 25 Index white good sector. *Environmental Research and Technology*, 7(4), 512–529. https://doi.org/10.35208/ERT.1431800

Zhang, Y. (2024). A path to sustainable development of agri-industries: Analysis of agriculture 5.0 versus industry 5.0 using stakeholder theory with moderation of environmental policy. *Sustainable Development*, 32(5), 4829–4843. https://doi.org/10.1002/SD.2923

Zhang, Y., & Li, Y. (2023). Society 5.0 versus Industry 5.0: An examination of industrialization models in driving sustainable development from a normative stakeholder theory perspective. *Sustainable Development*, 31(5), 3786–3795. https://doi.org/10.1002/SD.2625