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Research in Globalization

Provided in Cooperation with:
Elsevier

Suggested Citation: Hassan, Ali H. et al. (2025) : A cyber physical sustainable smart city framework toward society 5.0: Explainable AI for enhanced SDGs monitoring, Research in Globalization, ISSN 2590-051X, Elsevier, Amsterdam, Vol. 10, pp. 1-15,
https://doi.org/10.1016/j.resglo.2025.100275

Research in Globalization 10 (2025) 100275

Contents lists available at ScienceDirect

Research in Globalization

journal homepage: www.sciencedirect.com/journal/research-in-globalization

A cyber physical sustainable smart city framework toward society 5.0: Explainable AI for enhanced SDGs monitoring☆

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ARTICLE INFO

Keywords:
Smart City Framework
SDGs
Explainable AI
Edge Computing
Blockchain
Off-chain
IoT
Cyber-physical system

ABSTRACT

Industry 4.0 has revolutionized modern urbanization and smart cities. However, the relationship between Industry 4.0 technology advances such as Artificial Intelligence (AI) and their impact on the earth, environment, people, and biological ecosystems needs further consideration, particularly during pandemics like COVID-19. This paper proposes a cyber-physical Industry 5.0 framework that is compliant with the Sustainable Development Goals (SDGs) defined by the United Nations (UN) in general and SDG 11 (Sustainable Cities and Communities) in particular. The framework targets three main pillars of SDGs from a technical perspective: global society, economy, and environment. It breaks down the cyber-physical system (CPS) into smaller components, linking them to each of the 17 SDGs and grouping them into broader categories. These components use four leading technologies: blockchain for secure data handling, B5G network function virtualizations, edge-cloud computing for scalable and flexible data processing and AI to deliver insights into the model's data. This paper addresses the challenge of monitoring the indicators of 17 SDGs by utilizing Industry 5.0 advancements. It offers practical validation of the framework through use cases in energy and water management. Results demonstrate how the framework can enhance SDG monitoring's precision, transparency, and scalability while providing stakeholders with helpful information.

Introduction

The revolution in Industry 4.0 has been driven by several technological advancements, including cyber-physical systems, industrial IoT, machine learning, beyond 5G, cloud computing, explainable AI, blockchain, virtual reality (VR), digital twin technology, robotics, and smartphone technologies. Together, these developments add to the revolutionary shifts observed in Industry 4.0. However, while Industry 4.0 prioritized urbanization and technological advancements, it did not address the needs of global society, the economy, or the environment, which cities, corporations, or governments did not govern. In response to these limitations, the progress toward Industry 5.0 has been driven by concern for fundamental components like human nature, society, and the environment (Nahavandi, 2019). Innovative technologies and Industry 5.0 applications combined with societal ideals, environmental sustainability, and the circular economy create the foundation of Society 5.0 (Shiroishi et al., 2018). Central to Society 5.0′s vision is user-centric explainable AI (XAI), which ensures that the use of AI technologies remains transparent, understandable, and aligned with human needs and values (Khanna et al., 2024; Tóth et al., 2023).

The United Nations' 17 Sustainable Development Goals (SDGs) provide a framework for incorporating human-centric and environmental factors with technological innovations that promote a more balanced and sustainable approach to development (van Zanten & van Tulder, 2021). Each goal has several targets and indicators that need tracking and monitoring. Goals are grouped to form high-level entities

☆ This article is part of a special issue entitled: 'Smart Cities' published in Research in Globalization.
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https://doi.org/10.1016/j.resglo.2025.100275
Received 3 September 2024; Received in revised form 23 January 2025; Accepted 11 February 2025
Available online 18 February 2025

such as SDG 1, SDG 2, and SDG 3, representing Healthy Life together. In other words, to measure the quality of healthy life in a community, city, state, or country, SDG1-3 indicators are being used (Boto-Álvarez & García-Fernández, 2020). However, a significant challenge in achieving the SDGs is effectively monitoring and quantifying progress. According to the 2024 Sustainable Development Goals Report, several crises have impacted progress toward achieving the SDGs, including the COVID-19 pandemic, climate change, and regional disputes (UN DESA, 2024). The research also highlights how these problems worsen already-existing disparities since they disproportionately impact the world's most disadvantaged groups. Several studies have also underlined the necessity of strong monitoring systems to track advancement and pinpoint areas that need urgent attention (Nakhle et al., 2024; Nilashi et al., 2023; Saner et al., 2020). Traditional methods of monitoring SDG indicators are often manual, have data deficiencies and are not as automated as required for accurate, real-time monitoring. Due to a lack of essential data points and data sets or manual management of indicator data, not all KPIs are fully maintained (Koilo, 2020). Data is limited because data collecting for the different SDGs is mostly manual. The absence of comprehensive monitoring and assessment of these indicators is a significant barrier for global and regional authorities in measuring progress toward these objectives. This is where advances in Industry 5.0 can help by enabling specific components to monitor different degrees of Society 5.0 (Vinuesa et al., 2020). Advanced technologies such as artificial intelligence (AI), blockchain, IoT and B5G enable secure data collection, evaluation and decision-making in real time. Explainable AI (XAI), for example, helps to ensure that complicated algorithms for data collection and analysis are clearly understood by a wide range of stakeholders, including individuals, governments, academic institutions and businesses (Bernardo & Seva, 2023; Hassan et al., 2023). Moreover, individual citizens, startup businesses, medical caregivers, communities, academic institutions, industries, municipalities, governments, and small and medium enterprises can use the Industry 5.0 advancements to support different applications such that society, the environment, and the economy all become optimum (Setó-Pamies & Papaoikonomou, 2020). For example, while sharing data with other nations, the critical data of one entity must be kept safe and unaltered. Technological advancements such as Blockchain, 5G, AI, and IoT can work together to uphold collaborative secure file authoring and monitoring, secure IoT devices and data, secure data communication, secure logistics support and asset management, secure HR management working for SDG projects. (Fu & Zhu, 2019).

Despite these promising advancements, the challenge remains to effectively utilize these technologies to monitor, measure, and optimize SDG indicators. By incorporating user-centric XAI, Industry 5.0 frameworks can be designed to optimize the collection and analysis of SDG indicators, empowering stakeholders to make informed decisions based on accurate and transparent data. For example, industry 5.0 can address this by enabling real-time solutions for AI and IoT applications that support SDG monitoring, softwarizing network services, and customizing network infrastructures. Communication between AI and IoT can occur within milliseconds delay through B5G Software Defined Networks (SDN). SDN enables the softwarization of network functions serving Industry 5.0 applications (Ahmad et al., 2019) that require custom network slices. Each indicator can book custom network slices with customized virtualized infrastructure needed for IoT or AI applications. In other words, industry 5.0 will allow key Society 5.0 KPIs to be measured for different aspects such as corporate social responsibilities, creating social values, circular economy, and cyber-physical things. While the task settings, cause-and-effect modeling, policy design and recommendation, 21'and execution can be done by human intelligence, the simulation and classification of multiple scenarios as the national level can be performed using AI and other technological panes.

Acknowledging these challenges, this paper addresses the question of 'How can a user-centric cyber-physical framework driven by Industry 5.0 technologies enhance the measurement and monitoring of Sustainable Development Goals (SDGs) within the context of Society 5.0?' The primary objective of this research is to propose a cyber-physical framework that integrates user-centric explainable AI, machine learning, blockchain, edge-cloud computing, and beyond 5G (B5G) network virtualizations. This framework facilitates real-time monitoring and analysis of SDG indicators, ensuring that data collection processes remain transparent and aligned with the needs of diverse stakeholders. These technologies enable real-time data collection, analysis, and decision-making, offering a more dynamic and automated approach to tracking SDG progress. This paper introduces several key contributions. Firstly, it proposes an Industry 5.0 framework designed to support user-centric SDG monitoring within Society 5.0. Secondly, it presents a cyber-physical system for monitoring the development of Society 5.0. Thirdly, the paper outlines a technological panel aimed at optimizing each Sustainable Development Goal (SDG) component by understanding the interdependence among SDGs. Additionally, the paper defines deep learning-based Key Performance Indicators (KPIs) for each SDG component of the cyber-physical system, which are measurable through the technological panel. Furthermore, it designs a cyber-physical system to measure SDG KPIs using Industry 5.0 and showcases various smart city cyber-physical system applications as realizations of the Society 5.0 SDG model.

The remainder of this study is illustrated in Fig. 1. Section 2 provides background information, section 3 introduces methodology, section 4 describes the proposed framework, Section 5 details the implementation, Section 6 presents the results analysis, and Section 7 concludes the paper.

Preliminaries and literature review

UN sustainable development goals

To deliver a sustainable future by 2030, 193 nations pledged to work on 17 sustainable development goals in 2015. The 17 goals presented in Table 1 are broken down into targets and indicators that aim to address a range of global challenges, including hunger, poverty, inequality and clean water (Fonseca et al., 2020).

To ensure that efforts are aligned with the long-term objectives of the 17 goals, track and monitor if these goals are essential. Industry 5.0 offers a new way of tracking and monitoring the SDGs. Another aspect and challenge of the monitoring process is ensuring that optimizing one SDG does not affect the quality of other SDGs. For example, research by (Sørup et al., 2020) has shown that most of the SDG6 supporting clean water treatment plants cause high levels of emissions, thereby crossing planetary boundaries and seriously endangering the SDG13. Another salient example of SDG6 monitoring is corruption. Most of the UN funding for clean water projects does not have remote sensing of water plant filtering mechanisms. Industry 5.0 will allow water quality monitoring, the amount of water being filtered etc. to uphold the SDG6.

Researchers have proposed different key performance indicators that will allow us to measure and monitor these SDGs (Sørup et al., 2020). This solves one of the challenges faced by some countries or cities, which is associating quantifiable values for each granular indicator, grouping these for each target and then finding the SDG value in a numeric number (Bressan & Marques, 2019). Then, each city or country can compare the intra-SDG and inter-SDG values among the UN nations (Guan et al., 2019). Once the SDG values are known by city, state and country, the SDGs that are poorly scored can be identified, the root cause of the deficiency can be defined, new steps and control measures can be taken and continuous monitoring of those indicators can be performed (Boto-Álvarez & García-Fernández, 2020). For example, by leveraging the advancement of AI technologies, which supports teaming with humans, AI can reduce human and financial costs of SDG indicator monitoring (Nam et al., 2019). AI will allow the SDG monitoring cycle of observing, orienting, deciding, act by keeping human actors in the loop. Moreover, recent advancements in explainable and ethical AI can bring

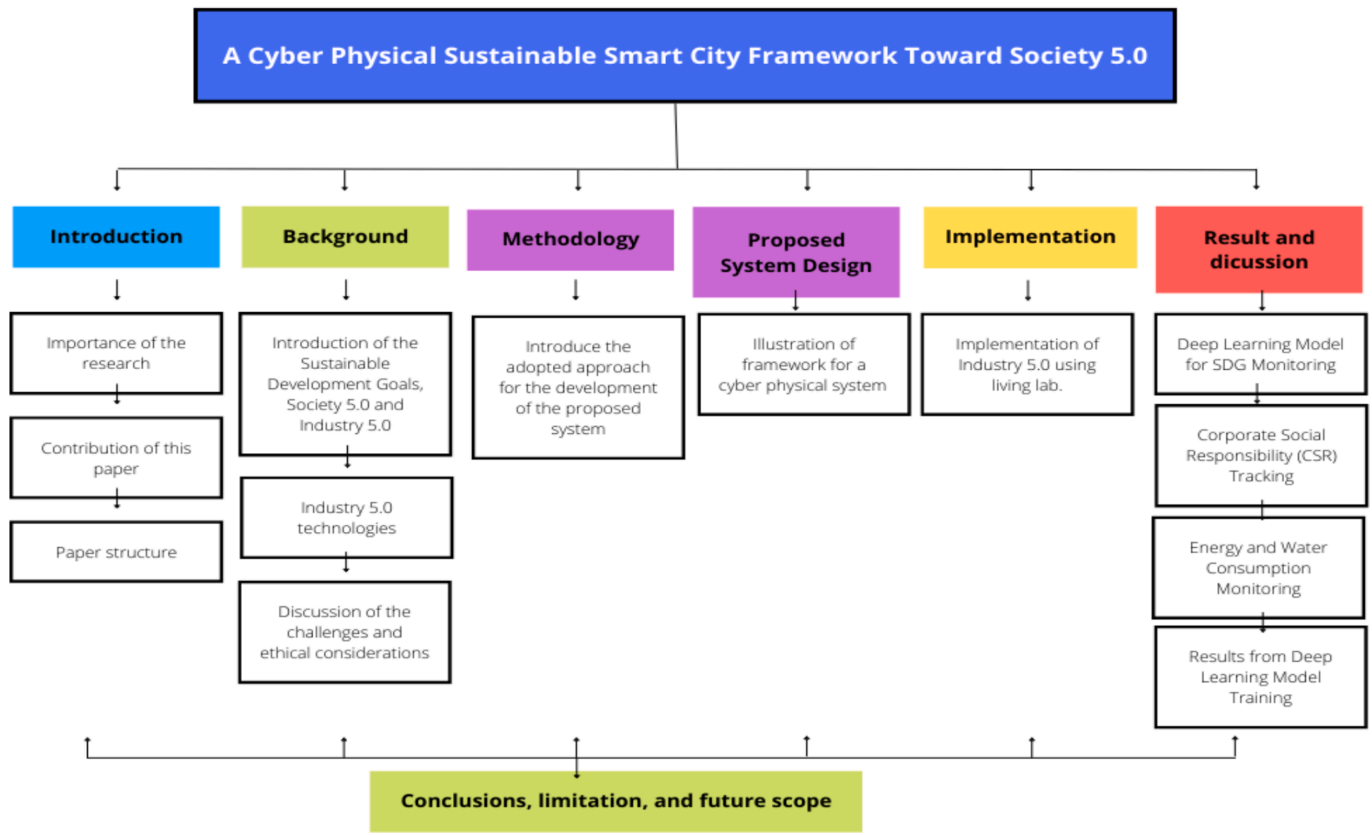

Fig. 1. Roadmap of the paper's structure.

Table 1
Sustainable Development Goals.

Sustainable Development Goals	Targets
Goal 1	No poverty
Goal 2	Zero hunger
Goal 3	Good health and well-being
Goal 4	Quality education
Goal 5	Gender equality
Goal 6	Clean water and sanitation
Goal 7	Affordable and clean energy
Goal 8	Decent work and economic growth
Goal 9	Industry, innovation, and infrastructure
Goal 10	Reduced inequality
Goal 11	Sustainable cities and communities
Goal 12	Responsible consumption and production
Goal 13	Climate action
Goal 14	Life below water
Goal 15	Life on land
Goal 16	Peace and justice strong institutions
Goal 17	Partnerships to achieve the goal

trust in those SDG application areas where demand for automation across society is of utmost necessity. Together, AI-enabled cyber agents and humans can provide SDG applications with real-time or historical data from IoT devices, reasoning on possible causes, and sensible decisions (Singh et al., 2024).

Society 5.0

The vision of a more balanced and comprehensive approach to social development has pushed forward the concept of Society 5.0. The baseline of Society 5.0 focuses on creating a more sustainable and human-centric society that aligns with the economic and technological advancements (Fukuda, 2020; Ghobakhloo et al., 2024; Yuko Harayama, n.d.). Technological innovations, such as artificial intelligence, the Internet of Things, and big data, are leveraged to cater to their citizens for an improved future, which complies with the 17 sustainable development goals (De Felice et al., 2021). Industry 5.0 builds upon the foundations of Society 5.0 to deliver human-centric technological advancements (Ferreira & Serpa, 2018). Industry 5.0 advancements in smart agriculture and smart Food can contribute to the fulfillment of SDGs 1–2, while the data available from SDG3 can be used as an indicator of an early health warning system (Ferroni et al., 2019; Nawaz et al., 2024). For example, when the whole world faced the COVID-19 pandemic, the following vulnerabilities were observed:

- Loss of income has led to poor performance in SDG1, where the vulnerable population of society falls below the poverty line (Elavarasan et al., 2022).
- Almost all countries needed improvement in SDG 2 (Zero Hunger) due to social isolation, industries closed, jobs, no mobility and so on. Food production and distribution have severely disturbed SDG2 development (Filho et al., 2020).
- Countries were inconsistent in achieving SDG 3 (in the areas of poor health support, there is no vaccine, PPE, proper COVID-19 testing facility on a mass level, etc.), SDG 9 (Innovation, Industry, Infrastructure) and SDG 10 (Reducing Inequality) (Filho et al., 2020; Martín-Blanco et al., 2022).
- SDG4 suffered due to schools being closed, remote learning being either ineffective, or a large population not having access to the remote learning environment.
- SDG5 has observed a blow as women's income has suffered or increased levels of domestic violence (Kuhlmann et al., 2023).
- Supply chain and personnel shortages have disrupted SDG6 and SDG7.
- SDG8 has been severely disturbed by interrupted economic operations, decreased income, fewer work hours, and unemployment in

some job categories (Elavarasan et al., 2022; Martín-Blanco et al., 2022).
- Disruptions in SDG4, SDG5, SDG8, and SDG11 altogether have affected SDG10 (Ibn-Mohammed et al., 2021)
- Population and migrants living in slums have high population density and poor sanitation, which results in poor performance of SDG11.
- Collectively, all countries performed poorly in SDGs 12 – 15.
- Finally, SDG13, SDG15, and SDG17 failed heavily due to lack of commitment and collaboration (Filho et al., 2020; Ibn-Mohammed et al., 2021).

Industry 5.0

Industry 5.0 builds on the technological advancements in Industry 4.0, emphasizing a sustainable, human-centric, and resilient approach for the future (Leng et al., 2022; Pereira & dos Santos, 2023). It strongly emphasizes collaboration between humans and robots to improve process efficiency by combining innovative technology with human creativity (Tóth et al., 2023). Industry 5.0 aims to shift from mass customization to mass personalization using artificial intelligence for sustainable growth (Slavic et al., 2024; Tiwari et al., 2022). Revolution in Industry 5.0 technologies is assumed to contribute to Society 5.0 in several ways by interweaving SDGs (Aslam et al., 2020; Humayun, 2021). Fig. 2 illustrates how various Society 5.0 applications are related to specific Industry 5.0 technologies, including the Internet of Things (IoT), machine learning, sensors, 5G/6G, cloud explainable AI, blockchain/off-chain, virtual reality, digital twin, and robotics, to name a few. Industry 5.0 technological advancements have contributed toward different high-level applications in various areas, including healthcare, agriculture, manufacturing, and supply chain (Adel, 2022; Tóth et al., 2023). Integrating the Sustainable Development Goals (SDG) with the revolution in Industry 5.0 technology is thought to have an encouraging influence on Society 5.0 (Aslam et al., 2020). The SDGs were established to end poverty and stop climate change. The 17 SDGs are each related to various Society 5.0 domains and address issues like poverty, climate change, clean water, good health, and industry. For example, SDG3 targets 'Better Health,' which aims to give everyone access to healthcare solutions and control their health and health data (Narvaez Rojas et al., 2021). These applications can then be mapped to a subset of SDGs as contributors or performance indicators. SDGs are then grouped to satisfy higher-level indicators, e.g., SDG13-15 contribute to the Environment eco-friendliness, whereas SDG8, SDG9, SDG10, SDG12 and SDG17 indicate the health of the Economy. The rest of the SDGs are tied to Societal values. Similarly, SDG6-7 helps us to monitor Universal Access to Basic Services, and SDG4 and SDG8 represent our Support for the Next Generation. In order to make urbanization sustainable and smart, SDG9, SDG11, and SDG12 are being measured while lowering gender inequality is being targeted by SDG5 and SDG10. How a community or business upholds the eco-friendliness, SDG13-15 is being monitored. Finally, international collaboration is maintained via SDG16 and SDG17. Although many initiatives have been proposed in the past, the urbanization challenge lies in the global optimization of the 17 SDGs by putting no single SDG over the other.

While remote and automated systems provide an advantage over working with massive volumes of IoT data from different SDG applications, human judgment remains essential for SDG applications. For example, underwater life monitoring marine vessels face the threat of mines. The Mine Countermeasures (MCM) are done via UAV and UUVs, which can be equipped to recognize, locate and neutralize sea mines along with underwater life monitoring for SDG applications by leveraging AI-powered synthetic aperture sonar (SAS) classification via centimetre-resolution acoustic imagery of the seafloor. AI-powered Automatic Identification System (AIS) can be used to analyze voluminous amounts of SDG-related information from fixed radar stations, UAVs, USVs, drone swarms, and UUVs. Another dimension of AI is that AI in the wrong hands will lead to the autonomous stockpiling of software vulnerabilities (e.g., zero-day attacks). These systems will automatically decide on the most effective adversarial attack on SDG applications and defense vectors using machine learning approaches. In the future, 'SDG data warfare' will include a virtual battle between artificial intelligence seeking to disable one another and infect SDG command and control systems with disinformation or malicious code.

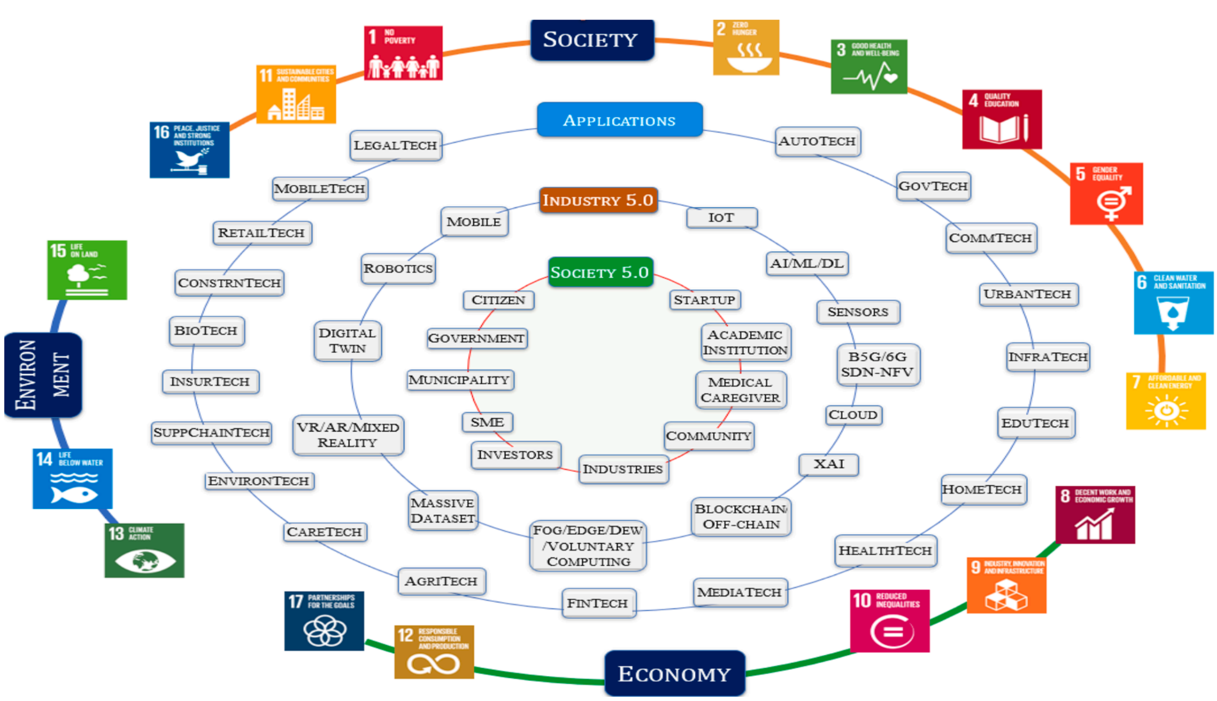

Fig. 2. Relationship between Society 5.0 applications and specific Industry 5.0 technologies.

Smart city

A smart city is an urban city that aims to improve the quality of life for its citizens. This is archived using technology and data to enhance infrastructure services and address critical problems in modern cities (Hassan et al., 2023). The individual stakeholders in a smart city include public administrators, technology designers, entrepreneurs and, business owners and the general citizen (Jayasena et al., 2019). Smart cities may improve citizens' living standards while promoting sustainability and efficiency. Authors in (Parappallil Mathew & Bangwal, 2024) assert that Big Data and IoT-enabled sustainable infrastructure can help overcome many modern cities' shortcomings in crucial aspects of a high-quality lifestyle. These technologies can assist governments and communities deal with the challenges of growing urbanization. A smart city initiative is to create efficient, liveable environments by combining innovative technology and critical services in six key areas: People, Economy, Mobility, Living, Governance, and Environment. These cities' prosperity is intimately related to the quality of life experienced by their citizens (Parappallil Mathew & Bangwal, 2024). Smart cities align with SDG goals by enhancing living standards through efficient resource management (Sharifi et al., 2024). Moreover, smart cities can contribute to the SDGs by providing real-time monitoring and data analysis through Industry 5.0 technologies to ensure sustainable urban development (Costa et al., 2024; Yin et al., 2023).

Key enabling technologies towards the transformation

AI and explainable AI

Existing AI systems have three main components: computing capability, advanced machine learning algorithms, and Access to sufficient quantities and quality of field data – both the data to train the AI system and the data to be exploited (Adadi & Berrada, 2018). Society 5.0 Applications and Autonomous Systems need an enormous volume of automatic data processing to deduce inferences. These three things together make an intelligent connection between perception to action. Given the available information, an AI system is intelligent to the extent that it does the right thing, i.e., the action expected to achieve a certain SDG or a Society 5.0 outcome or maximize the expected utility. The sensing, acting, and decision-making cycles are performed autonomously and in the order of milliseconds for some applications.

Existing machine learning (ML) and deep learning (DL) models work like a black box, which suffers from Explainability (Adadi & Berrada, 2018). This explainability hinders the smooth relationship between human and machine teaming. Human actors do not always understand how a machine learning algorithm comes to a final decision due to the Black-box nature (Hassan, Sulaiman, et al., 2021). Hence, critical machine learning applications such as healthcare, defense, Industrial IoT, and IoT-based automated insurance claim processes etc. suffer from ethical obligation and semantics. Thanks to the recent advancements in explainable AI (XAI), which adds explainability and semantics in different aspects of ML and DL models, human subject matter experts can have inner sights, visualize the datasets and various parameters used, observe the progress of different layers and approve or give feedback to the final decisions(Adadi & Berrada, 2018; Hassan, Abdulhak, et al., 2021; Schoenborn & Althoff, 2019). This helps stakeholders of AI i.e., human–machine teaming for higher-level operations. Through XAI, human strategic guidance combined with the tactical acuity of AI would allow SDG planners to concentrate on strategic planning instead of spending so much time on manual calculations (Vinuesa et al., 2020).

IoT

The Internet of Things (IoT) has penetrated almost every part of human life and the industrial arena. While Industry 4.0 primarily focused on IoT hardware and software design for automated industrial-economic processes, the side effects of such growth were not measured through the lens of SDGs. As a result, the primary motivation to push toward Industry 5.0 is to allow smooth human-IoT interaction, society-IoT integration, and SDG-IoT support. IoT devices in the physical world will be able to provide the much-needed data of different SDG and Industry 5.0 indicators. For example, Medical IoT devices will be able to supply much-needed monitoring data (Hassan et al., 2023) of various Industry 5.0 indicators to their global counterpart, as seen in Fig. 3. XAI entity for big data analytics and the design of individualized services and products. The Internet of Things (IoT) is becoming more popular in healthcare, with applications such as data collecting, report verification, patient tracking, remote treatment, monitoring, and surveillance. In the event of medical therapy, real-time monitoring is used to follow infected patients and check their conditions such as blood pressure and heart rate, ECG, EEG, SpO2, breathing rate, and skin temperature (Hossain, 2017)and (Muhammad et al., 2021).

Blockchain and off-chain

Blockchain allows decentralized transactions without borders, while off-chain enables big data to be stored decentralized (Alam, 2023). Blockchain ensures data security and integrity. Blockchain secures data and allows sharing it with the right SDG entities. Blockchain supports secure, private networks via permission mode. One country can maintain its own private Blockchain and secure the private data while making only the needed data available to other partners. Blockchain allows keeping the information in a specific SDG network while allowing only needed information shared with the SDG collaborators. For example, Blockchain allows one country operating with allies within SDG17 to decide the KPI data to be shared with the allies, and the information that needs to be private. Blockchain shows promising prospects in areas such as supply chain management, health data storage and sharing, fintech, agricultural transformation, multi-party classified data sharing with data privacy, provide transparency and trust, sharing economy, and so on. Hence, blockchain can be used for upholding different SDG values. For example, Blockchain supported SDG1 by empowering crypto-currencies and other blockchain-based tokens for trade and transactions. Blockchain can be used to support SDG3 by allowing patient EHR and EMR records to be shared securely. Disease outbreak statistics and transactions can be saved onto the blockchain, in addition to the supply chain and relief management. Goals 12, 14 & 15 i.e., responsible production and consumption, life below water and life on land can be supported by Blockchain. Blockchain can support good provenance throughout supply chains and circular economy. Blockchain framework provides a digital wallet, smart contract, distributed app support for personalized, privacy-oriented, and immutable transactions suitable for SDG applications. It also supports different SDG modes such as public, private, and federated. Recent Blockchain smart contract advancement allows secure IoT data automation, and secure multi-party transactions. SDG Blockchain can help nations safeguard their data including critical infrastructure data and other sensitive urbanization roadmap information.

B5G/6G

B5G/6G technologies mandate enhanced mobile broadband, mission-critical services, and massive IoT. As a result, enabling technologies such as virtual reality, telemedicine, tactile internet, augmented reality, and autonomous driving, to name a few, are becoming a reality. Tactile Internet can deliver remote physical experiences globally e.g., remote surgery. Massive IoT applications such as smart building and smart agriculture are becoming commonplace. Critical IoT applications such as remote healthcare, remote manufacturing, and surgery are becoming affordable. Digitization and automation of all production processes such as automotive halls and logistic warehouses can be performed with increasing efficiency, cost reduction, and remote operator-controlled collaboration (Attaran, 2023). With the introduction of fog and mobile edge computing with B5G, the remote latency concerning the analytics chain tends to be in milliseconds. A constantly growing number of sensing and

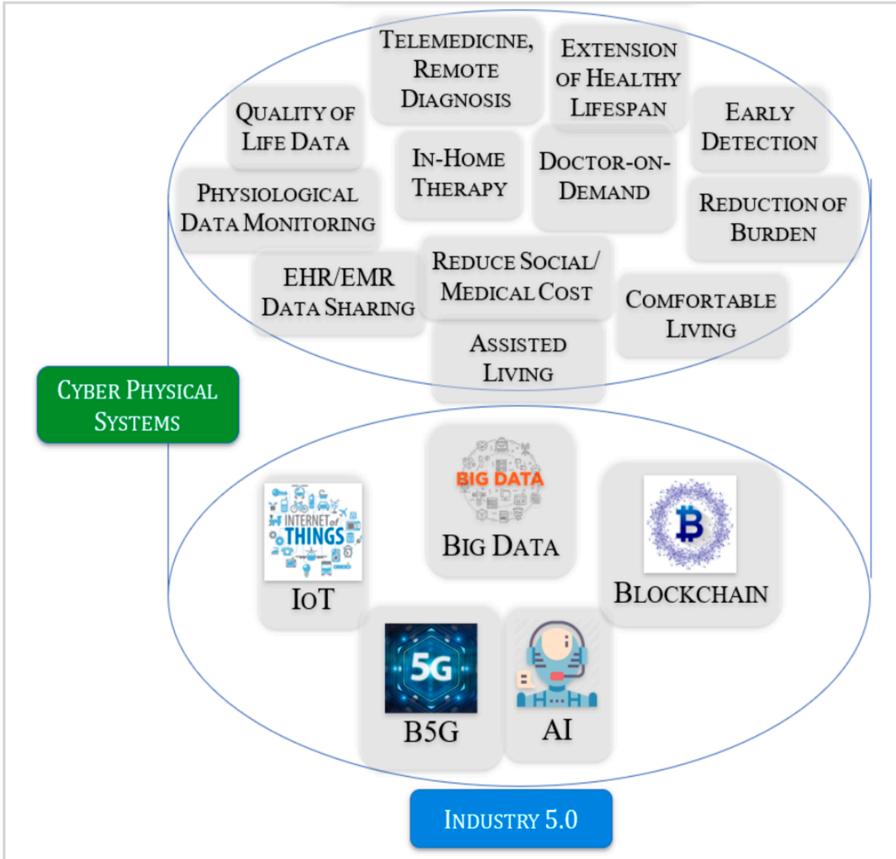

Fig. 3. Medical IoT devices supply monitoring data through Industry 5.0 technologies.

communication-capable devices are deployed in our homes, offices, and transportation means. Due to the support of 5G mmWave technologies, the Internet of wearable things with excellent user experience is becoming a reality. Remote monitoring of phenomena and processes with the help of autonomous vehicle fleets, real-time communication between remote workers and command centers is gaining traction. Anytime, anyplace connectivity for X2X allows humans to make decisions based on real-time analysis generated by integrating Sensory data from unmanned sensors from a remote location. B5G can support real-time monitoring of smart facility energy and security management systems, inventory, and supply chain management system through customized 5G RAN, network slicing, advanced MIMO, device-to-device communication, Network function virtualization and software-defined networking capability. The SDG visions align with the B5G/6G visions such as connected health, connected things, smart wearables, smart mobility, smart cars, smart grid, and other smart utility management.

Challenges and ethical considerations of integrating industry 5.0 technology for SDG monitoring

The integration of Industry 5.0 technologies into Society 5.0 to improve the measurement and monitoring of the Sustainable Development Goals (SDGs) poses some challenges and ethical considerations that need to be taken into account. Technologies such as AI, B5G, IoT and blockchain can optimize resource use and improve operational efficiency, which supports sustainability goals (E. Costa, 2024). However, challenges include the complexity of deploying advanced technologies in different regions, especially in areas with limited digital infrastructure (Hassan et al., 2023). Addressing these challenges requires collaboration across governments and international borders. Other areas that need to be addressed are implementation costs, the lack of global sustainability standards and workforce adaptation (E. Costa, 2024; Paschek et al., 2022). In addition, the trade-off between environmental sustainability and energy consumption of advanced technologies remains a major concern, as AI and blockchain systems are energy-intensive, raising questions about their sustainability. According to studies, blockchain mining and AI training processes waste significant resources, potentially contradicting SDGs 7 (Affordable and Clean Energy) and 13 (Sharif et al., 2024).

The ethical considerations and privacy issues associated with the introduction of new technologies require compliance with regulatory standards (Dhirani et al., 2023). Ethical considerations may arise from the human-centered approach of Industry 5.0, and the human-centric aspect in manufacturing processes (Adel, 2022; E. Costa, 2024). For instance, minority groups might be unable to develop the digital skill sets needed to engage with new systems, hindering their capacity to benefit from this progress. Likewise, ethical issues are also associated with privacy, security and the inappropriate use of private data from individuals, particularly for the purposes of AI-based decision-making (Hassan et al., 2023; Zhou et al., 2020). Though blockchain offers a secure for data sharing, it still has some weaknesses in ensuring the complete anonymization of shared data over global network (Liu et al., 2020).

To address these challenges effectively, several measures are needed to ensure effective and socially responsible integration of Industry 5.0 technologies into SDG monitoring systems. Data protection techniques such as differential privacy and federated learning minimize data exposure while enabling robust analytics (Choudhury et al., 2019). Promoting inclusive governance requires global standards that balance regional inequalities and ensure equal access to technology (Izzo et al., 2020). Futher, sustainable development could be supported by adopting energy-efficient algorithms and green data processing practices to reduce environmental impact (Shi et al., 2020). Finally, capacity building through digital literacy training and investment in infrastructure in underserved regions is critical (Hassan et al., 2023).

AI integration and frameworks for advancing SDG monitoring

The use of AI techniques to measure progress towards achieving the Sustainable Development Goals (SDGs) has been the subject of several research initiatives. However, the current literature falls often short due to technological, methodological and infrastructural limitations. As conventional SDG monitoring methods are mostly based on human processes and data sets, they can lead to errors and inefficiencies. According to research by Nilashi et al., (2023), inadequate datasets lead to poor data quality, which in turn leads to inaccurate assessment of SDG performance. This consequently has a negative impact on the decision-making of governing bodies and limits their ability to develop tactics that work. Guenat et al. (2022), highlight the potential of robotics and autonomous systems to provide real-time insights for sustainable development monitoring. These tools are used to analyze large data sets related to poverty, disease and environmental issues (Guenat et al., 2022). Yet, a number of challenges still remain, especially in terms of scaling these systems and ensuring infrastructure readiness in places with limited technological capacity (UN DESA, 2023). Many existing frameworks lack the integration of advanced technologies such as Artificial Intelligence (AI), Internet of Things (IoT), and blockchain. While studies such as (Vinuesa et al., 2020) and (Lampropoulos et al., 2024) showcase the potential of these technologies to advance SDGs, their real-world applications often fail to meet ethical standards. The study by (Vinuesa et al., 2020), for example, examines how AI tools can influence the achievement of the 17 SDGs and their 169 targets. The authors conclude that AI is likely to advance 128 of these goals. However, despite clear improvements in areas such as efficiency and production, the study raises questions about ethical issues and the possibility for further inequities. The authors emphasize that, while AI has the potential to considerably advance the accomplishment of the SDGs, its full impact is dependent on the implementation of proper legislation and policies. Yin et al., (2023) employ natural language processing (NLP) methods such as cosine similarity to demonstrate how AI may be used to link research articles to SDG-relevant subjects. Their approach assesses how effectively research is aligned with specific SDG objectives, targets, and indicators. They also suggest a text embedding model to help academics better understand how various studies contribute to the 17 SDGs.

One of the major challenges with AI is the lack of transparency in how decisions are made, which often erodes trust among stakeholders. Black-box algorithms, in particular, make it difficult for researchers, policymakers, and communities to fully rely on AI systems. To close this gap, explainable AI (XAI) has become essential, as it helps make AI's decision-making processes more transparent and easier to understand (Ehsan et al., 2023; Hassan, Sulaiman, et al., 2021; Schoenborn & Althoff, 2019). Despite progress in XAI, more comprehensive frameworks are required to address moral dilemmas and link AI outputs are closely aligned with SDG goals.

Methodology

Several methods and processes were involved in the development of the proposed framework to enable effective data acquisition, processing, and feedback mechanisms. The framework combines IoT, AI, blockchain and B5G/6G technologies to allow real-time, interpretable monitoring of Sustainable Development Goals (SDGs through a cyber-physical system. This integration was chosen because IoT and B5G/6G technologies provides for seamless and ultra-low latency communication, which is essential for real-time monitoring (Hassan et al., 2023; Sharma et al., 2024). Blockchain ensure data security and integrity and allows sharing between entities through secure, private networks (Goel et al., 2019; Liu et al., 2020). Moreover, the use of Explainable AI (XAI) promotes trust and transparency, both of which are crucial aspects of using AI to achieve the SDGs, as highlighted by (Singh et al., 2024; Vinuesa et al., 2020).

Framework development

The framework follows a multi-layered approach to bridge the physical and digital domains effectively as illustrated in Fig. 4.

1. Data Collection and Transmission: Data was gathered from open-source data sets available on platforms such as Zindi, with specific attention given to features relevant to energy and water consumption metrics. This included variables indicating energy efficiency by building type, street-level consumption, and broader city-level trends. Data preprocessing involved several techniques including data cleaning, Missing values were handled through imputation techniques, and data normalization was performed to standardize the input features. Key elements were chosen and modified to better capture the relationships required for tracking SDG KPIs. Among these were engineering composite indicators that depicted water and energy consumption trends. IoT devices are deployed to gather data from the physical environment, digitizing and converting it for meaningful insights before transmission to the cyber domain. B5G/6G allows for real-time data transfer with ultra-low latency and high-bandwidth connectivity, ensuring timely analysis and feedback loops.
2. Data Processing and Analysis: AI and cloud architectures process and analyze the data to extract insights, detect anomalies, and predict future trends. Insights are offered through SHapley Additive exPlanations (SHAP) plots to provide interpretable visualizations of AI outputs, ensuring transparency in predictions.
3. Data Security and Sharing: The implementation employed Hyperledger Fabric and Ethereum blockchain in permissioned and federated modes for secure stakeholder collaboration and data-sharing. Compared to a traditional centralized systems that is difficult to supervise, decentralized blockchain technology, helps to minimize risks of single points of failure and enhances accountability (Zhu et al., 2023). Blockchain's tamper-proof storage and smart contracts automate data validation, significantly lowering the risks associated with unauthorized modifications or breaches (Rai et al., 2024). Alternatives, such as advanced encryption, which safeguard data in transit and at rest but do not guarantee traceability or immutability, lack blockchain's collaborative and transparent aspects. Therefore, blockchain is the most suitable solution to address the data security requirements for private information.
4. Visualization and Feedback: Visualizes collected sensory data through customizable dashboards, charts, and widgets, facilitating real-time monitoring and informed decision-making to enhance the impact of the Industry 5.0 system on societal and environmental goals.

Deep learning architecture

The AI architecture includes PyTorch and TensorFlow to implement the models, leveraging both libraries' flexibility and efficiency for building complex neural network architectures. Input layers helped to process the raw data from the IoT sensors. A combination of convolutional neural networks (CNNs) and recurrent neural networks (RNNs) was employed to extract spatial features, such as variations in energy usage across locations and to capture temporal dependencies in the sequential data, such as daily water usage patterns. To provide insights into the model's data, SHAP visualizations helped to highlight the most influential factors in model predictions, ensuring outputs are transparent and actionable. Although, traditional statistical models provide some transparency, they lack the scalability and capability to handle

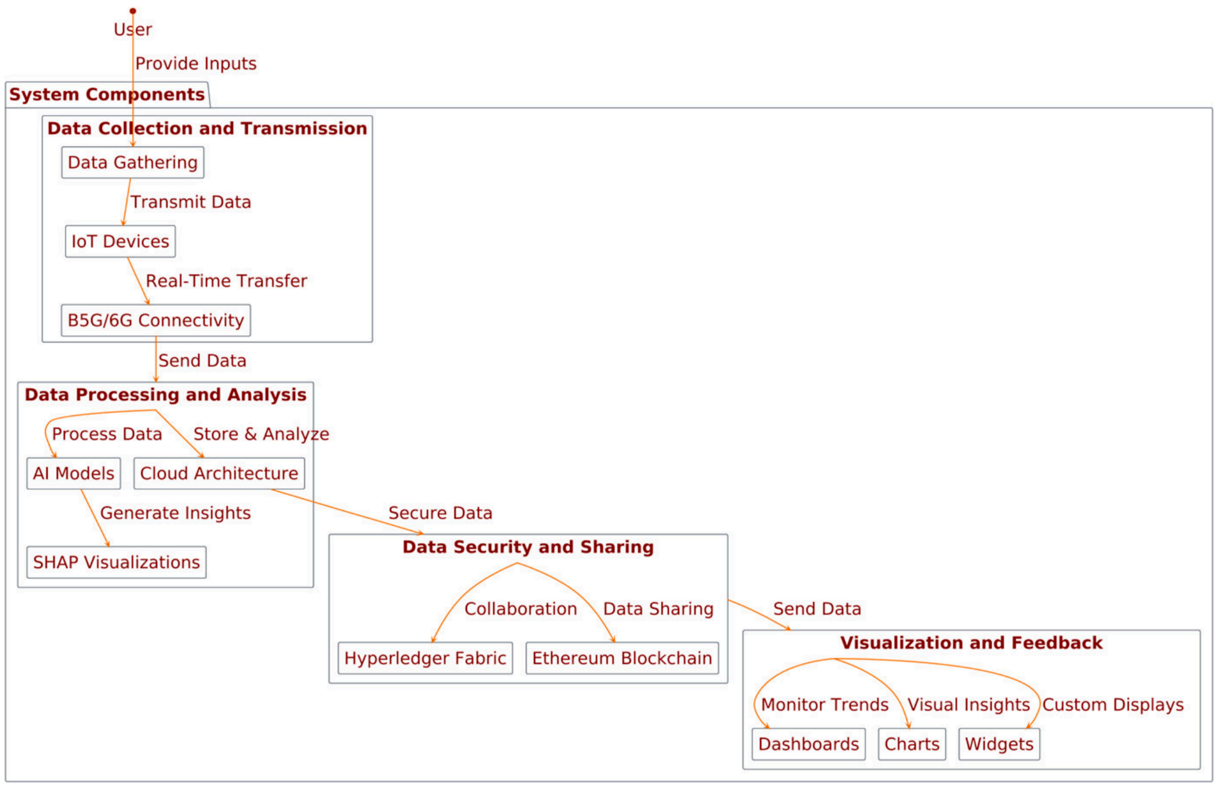

Fig. 4. Overview of the multi-layered approach to bridge the physical and digital domains.

complicated, high-dimensional data such as SDG indicators. XAI overcomes this gap by adhering to the ethical and accountability criteria of SDG activities.

The decision to integrate these technologies — IoT, B5G/6G, blockchain, AI and XAI — was based on their ability to solve the unique problems of SDG monitoring. While standalone solutions can meet individual requirements, they do not have the comprehensive capabilities required for a system that balances real-time responsiveness, security, transparency and interpretation.

Evaluation framework

The system's performance was evaluated using several metrics including:

Accuracy Metrics:

- Prediction Accuracy: Assesses the correctness of AI predictions for energy and water monitoring.
- Root Mean Squared Error (RMSE): Evaluates the model's ability to minimize errors in continuous predictions.

Efficiency Metrics:

- Latency: Measures system responsiveness, with a target of < 10 ms for real-time data processing.
- Scalability: Assesses the framework's ability to maintain performance with increased data loads.

Statistical Validation:

- Cross-validation: Ensures the generalizability of AI models across datasets.
- Comparative Benchmarks: The framework was compared with an existing SDG monitoring system.

Implementation strategy

Demonstration: Validates the system through a living lab setup, demonstrating deep learning and blockchain applications for measuring and prioritizing KPIs.

Data Flow Testing: Conduct end-to-end sensory data flow tests using residential (energy meter) and industrial-grade sensors (water flow meter).

Technology Stack: The backend uses Java, Node.js, and MQTT; the front end utilizes AngularJS for dynamic UI.

The framework was implemented in living lab setup using two use cases:

1. **Energy Monitoring**:
   a. A smart energy meter captured 33 sensory data points in real-time.
   b. The system predicted energy consumption patterns, with anomaly detection and SHAP-based explanations.
2. **Water Flow Monitoring**:
   a. Industrial-grade flow meters tracked real-time water usage.
   b. AI models optimized irrigation schedules, reducing resource wastage by 15 %.

Proposed system design

Due to the massive number of entities involved in the Industry 5.0 monitoring process, smooth coordination between cyberspace and physical space will be needed. Data originated from the physical space through IoT, and people need to be sensed, and digitized, conversion of meaningful data extraction needs to be done before sharing the data to the cyber world. With the help of B5G/6G tactile internet, the data from the physical world will reach cyberspace with ultra-low latency and enhanced bandwidth. The cyber system will leverage AI, cloud processing and other technologies to process, analyze and deduce important KPIs from the received data, which is shared with the utilization services such as healthcare, smart factory, automatic operations etc. The analytics generated in the cyber world are then passed on to the physical world as a feedback mechanism to address societal gaps and value creation purposes such as labor shortage, environmental pollution, and biodegradation, increased medical costs, and other sustainable goals. The mitigation techniques and target-achieving policy are then passed to the machines, IoTs and other entities in the physical world for execution. In other words, the data available from sensing systems of different SDG applications are passed to the industry 5.0 technological panes in the cyber world for necessary big data processing and Society 5.0 indicator achievements.

Once the low-level SDG metrics are defined, monitored, and measured, another monitoring process can benefit from it. Fig. 5 illustrates how circular economy, powered by Industry 5.0 technologies can benefit from the framework. Backed by Industry 5.0 technologies, a circular economy differs from liner economy in the fact that the circular economy ensures little to no resource or waste disposal, less natural resource extraction, green production, reduced usage, reuse, recycling and remanufacture and finally responsible policies such as corporate social responsibility, all the part of the SDG mandates. Thus, the circular economy can be measured, enforced, and incentivized while maintaining economic growth, and contributing to society and a sustainable environment.

For example, using IoT, 5G, AI, and Blockchain, waste monitoring, collection, and processing at the remanufacturing plant is converted, heated, processed, and separated for diversified targets such as feeding renewable energy sources, reusable raw materials, etc. All the individual sub-processes within the loop such as CO_2 emission reduction, raw material conservation, innovative technology innovation, durable and efficient products, and new job creation can be monitored, managed, controlled, and automated with the industry 5.0 technologies while human intelligence is in the middle.

Implementation

Fig. 6 shows a living lab example of the implementation of our proposed system. The living lab consists of deep learning and blockchain applications enhanced with explainability features that have been developed as proof of concept to support setting up goals and indicators, measuring and securely sharing those metrics, and finally prioritizing

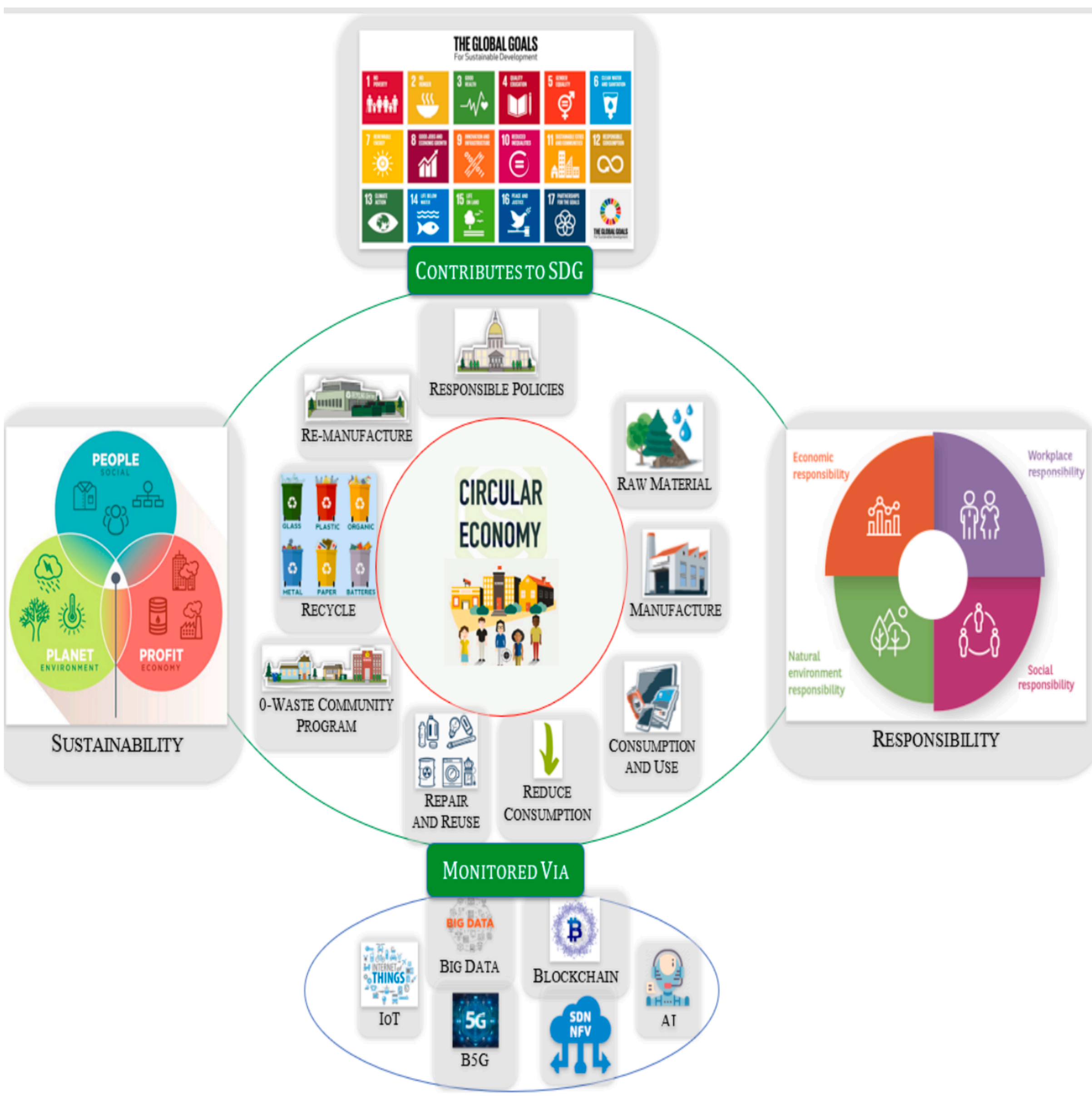

Fig. 5. The high-level scenario of circular economy mapping with SDGs, sustainability, corporate social responsibility, and Industry 5.0 technologies.

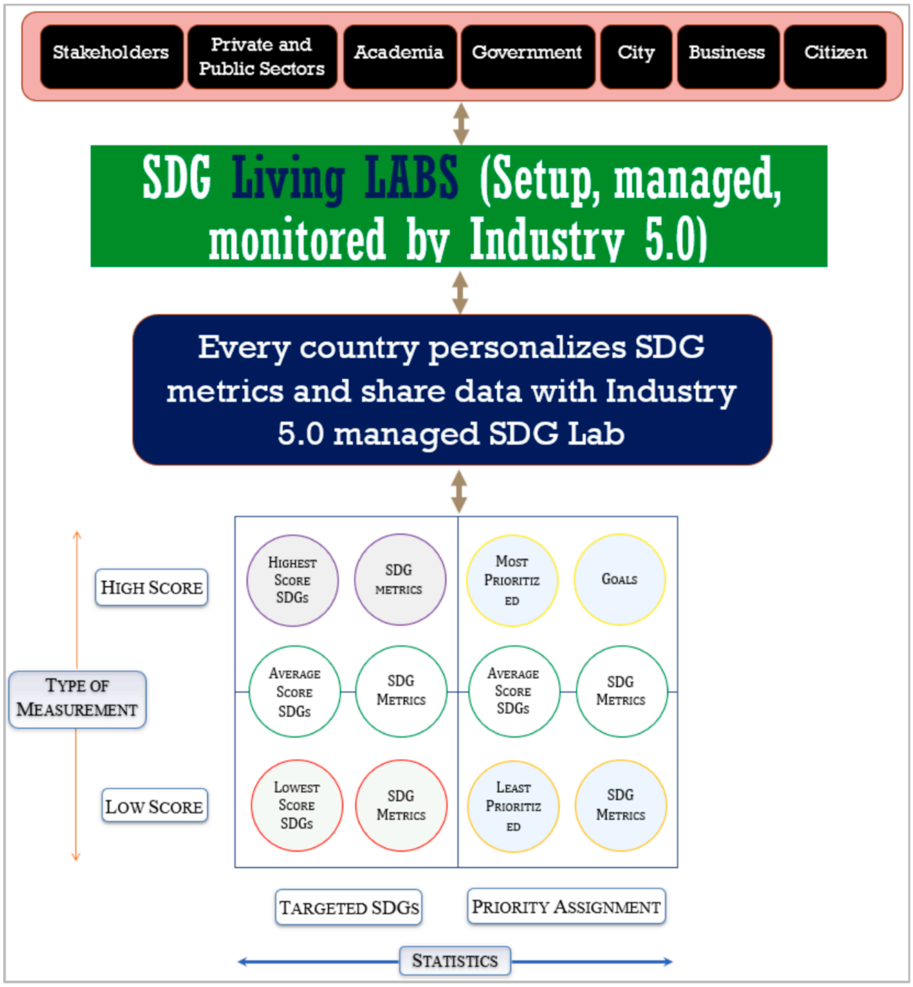

Fig. 6. Implementation of Industry 5.0 using a living lab.

the key performance indicators. Fig. 7 shows the goals and targets that can be measured via different technologies such as IoT, AI, 5G and blockchain. Individual targets and indicators in each category of goal are attached with a dashboard showing the appropriate industry 5.0 technologies that will allow the monitoring process. Individual goals are then grouped together and higher-level phenomena such as society, people, environment, planet, or even higher-level phenomena such as society 5.0. Two primary use cases were tested: energy monitoring and water flow.

Use case 1: Energy monitoring

An end-to-end sensory data flow test with an Energy meter within a home setup was developed by connecting the energy meter to 3 3-phase lines. Energy meter sends 33 sensory data points to the awe's server. These sensory data are aggregated and visualized in real-time via a web-based Dashboard. Explainable AI techniques ensured that users could understand how energy usage patterns aligned with SDG goals, such as energy efficiency and reduced consumption. For instance, deep learning models analyzed energy use intensity, and SHAP values were employed to explain the contribution of specific variables, such as time of day or appliance type.

Use case 2: Water flow monitoring

A lab-based end-to-end sensory data flow test was developed using an industrial-grade water flow meter. The flow meter sends four sensory data points to the awe's server. These sensory data are aggregated and visualized in real-time via a web-based Dashboard. A water flow meter was installed in a hydroponic water supply demo system. A pump supplies the water at a 6-hour interval while our developed system monitors the instant water flow rate and total accumulated water.

The backend components are based on Java, Node JS, and MQTT Broker while the front-end components are based on AngularJS which provides Dynamic UI support as a Single Page Application (SPA). IoT data is collected from encrypted streams by transport handler services and made available in real-time in telemetry visualization tables equipped with XAI functionalities. From this table, the sensory data can be mapped to any dashboard, charts, or widgets.

Results and discussion

As proof of concept, a deep learning model was developed for some goals such as SDG1, SDG3, SDG6, SDG7, SDG14, and SDG15. Open datasets available from Zindi and others (Boto-Álvarez & García-Fernández, 2020; Guijarro & Poyatos, 2018) was utilized to test our hypothesis. A cluster of four machines were used, each having 128 GB RAM with NVIDIA RTX 2080 Ti with 11 GB VRAM and a workstation having 128 GB RAM with NVIDIA Quadro RTX 6000 24 GB VRAM. As for the protocol stack, Hyperledger fabric and Ethereum was applied as Blockchain in both permission and federated mode, IPFS as off-chain storage, Firebase for real-time database, and PyTorch and TensorFlow as deep learning library. Since the KPIs captured some of the very sensitive and national security data related to land, underwater, industry,

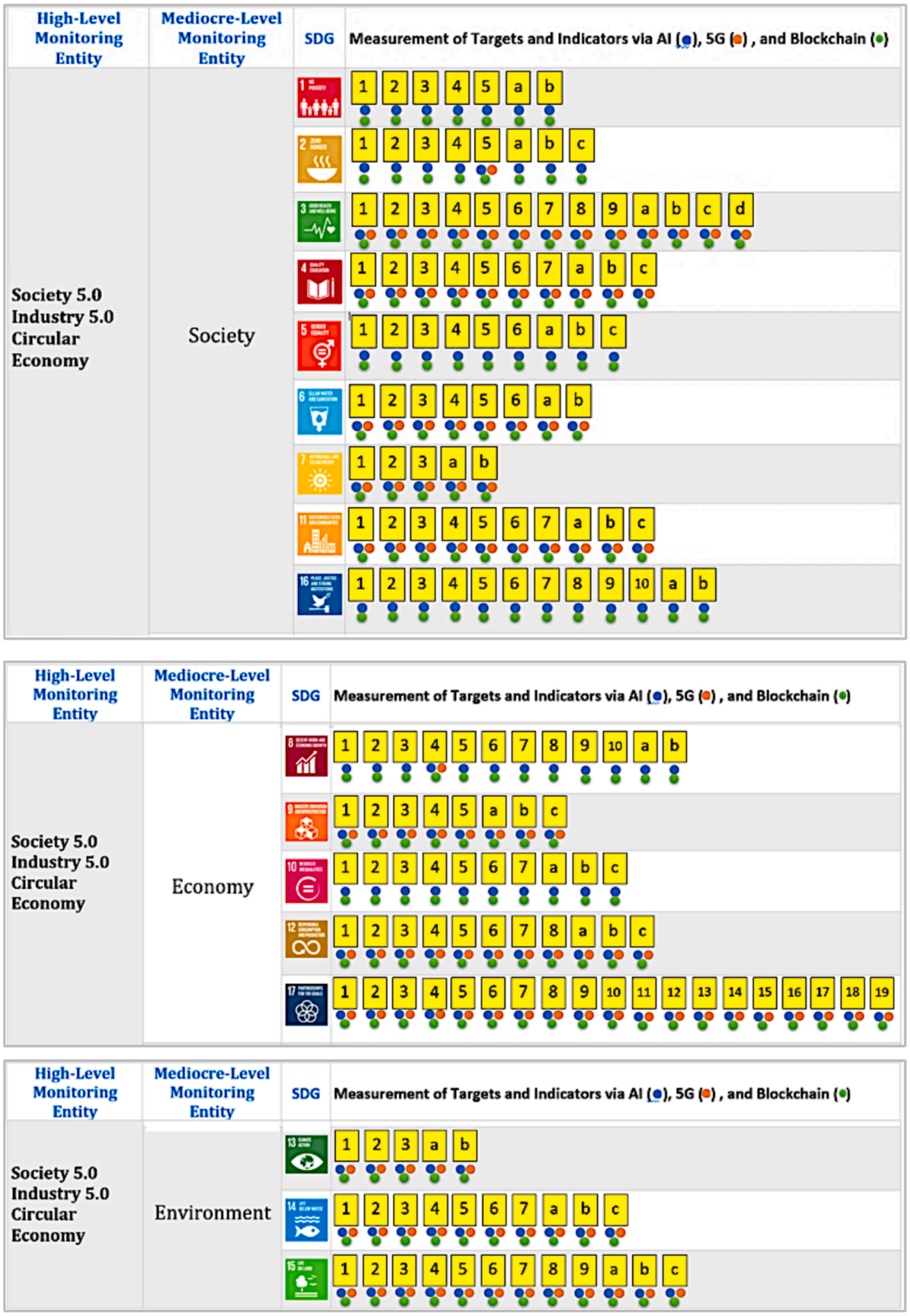

Fig. 7. Measurement of SDG goals using Industry 5.0 technologies (Vinuesa et al., 2020).

urbanization, and political collaboration, blockchain has been used for secure collaboration and data-sharing platforms.

Using machine learning approaches, other types of phenomena such as corporate social responsibility can be monitored via initiatives of different governments (e.g., https://www.csr.gov.in/) (Izzo et al., 2020). Also, individual corporations, businesses or industries can use the Industry 5.0 panes to track, monitor and attain CSR rankings. Various levels of goals and indicators can be set and impact analysis can be made using IoT, AI and other technologies. For example, using AI and IoT, a business can measure its compliance with biodiversity, smart grid support, promote clean and affordable energy, lower poverty, measure urban pollution, carbon economy, reduce energy consumption, and autonomous vehicles.

KPI measurement: Energy and water consumption

Two measurable indicators were chosen to measure the SDG KPIs: energy and water consumption via IoT, 5G, AI, and blockchain. Fig. 8 illustrates the results of our analyses.

1. Energy Consumption Analysis
   - Fig. 8 (a) shows the weighted possibility in terms of the percentage of measuring each of the 17 SDGs via IoT. As can be seen, projects worldwide use IoT data to measure goals such as 9, 11, 7, 3, 12, and 2.
   - Fig. 8 (b-f) shows deep learning-based analytics showing the percentage of IoT data-based energy efficiency of buildings for a particular city-data including:

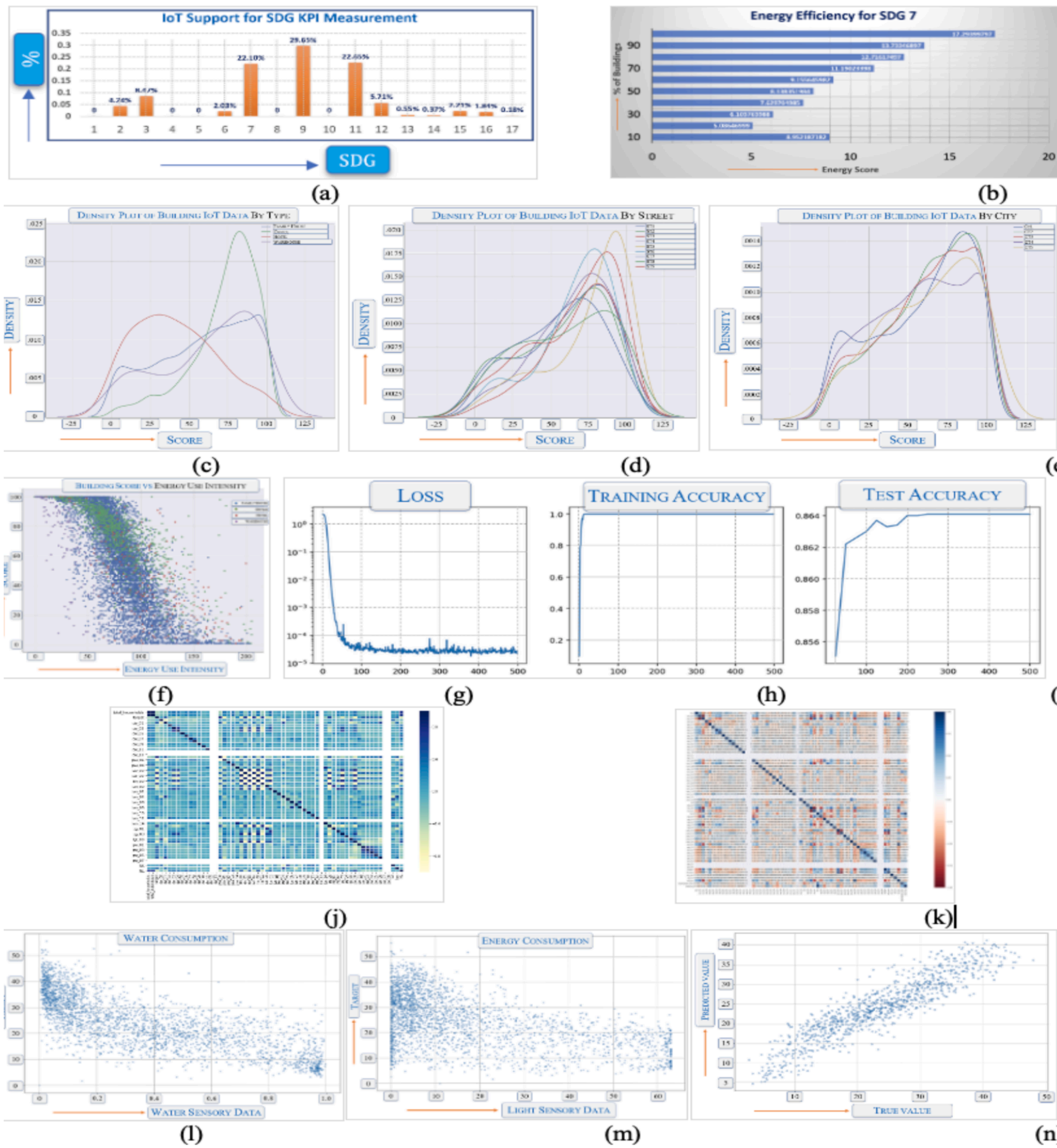

Fig. 8. Deep Learning-based indicator measurement of 2 goals (a-f) energy monitoring using IoT, (g-i) the training and test loss and accuracy for the tested deep learning applications, and (j-n) monitoring of water and energy availability dataset.

- Energy consumption by building type and location (Fig. 8 c-d).
- City-level energy analytics to inform urban planning and sustainability policies (Fig. 8 e).
- Energy use intensity plotted against observed energy data scores, aiding in identifying inefficiencies (Fig. 8 f).

4. Water Consumption Analysis:

- Fig. 8 (j-n): Analysis of a dataset comprising 62 features, including water usage patterns and related services. Deep learning models uncovered correlations essential for monitoring water-related SDG indicators (e.g., SDG6 and SDG14). Key outcomes include identifying inefficiencies in domestic water usage and optimizing resource allocation.

Fig. 8 (g-i) shows the result of training the deep learning models. The training and test losses and accuracies were observed to be acceptable since the result was shared with the human actors for their acceptance.

Evaluation and performance metrics

The system's performance was evaluated using the metrics seen in Table 2. These provided a detailed view of how well the model accurately predicted energy and water consumption. Cross-validation was performed on the AI models, yielding an average F1-score of 0.91.

Comparative analysis of SDG monitoring systems

Traditional SDG monitoring systems rely primarily on manual data collection. While these systems are beneficial, they have some limitations, including inefficiency and mistakes. Manual techniques can result in insufficient datasets and inaccuracies, limiting the predictive capability of the monitoring process. Furthermore, most systems are not capable of providing real-time monitoring, which slows response time. Finally, with limited implementation of emerging technologies such as IoT, AI, and blockchain, they are unprepared for board scalability and dynamic adjustments. Numerous studies have proposed methods for monitoring SDG indicators to address these challenges. However, these systems frequently have scalability, real-time feedback, and sophisticated technological integration limitations. To demonstrate the efficiency of the proposed framework, a comparison was made with the following two studies:

Study 1: IoT-based systems for SDG monitoring

Forhad et al., (2024) offers an IoT-based real-time water quality monitoring system. The system monitors parameters such as pH, turbidity and dissolved oxygen in water treatment plants. Real-time data was collected through IoT sensors and centralized data processing for decision making.

Study 2: Satellite data and regional indicators for SDG target mapping

The work of Nakhle et al., (2024) applies the SDG framework for environmental monitoring in European regions by utilizing satellite data and regional indicators to assess progress towards SDG targets such as clean water, sustainable cities and climate action.

Like Forhad et al (2024) the proposed cyber-physical Industry 5.0 framework combines IoT for water monitoring. However, it goes beyond WTPs by integrating XAI for transparency, blockchain for data security, and B5G/6G for ultra-low latency communication. This makes it possible to monitor water-related SDG indicators, such as waste management and water resource optimization, in a more thorough manner. The suggested system offers granular data analysis through AI and real-time monitoring capabilities with IoT and B5G/6G, whereas Nakhle et al., (2024) delivers a thorough overview of regional SDG progress. Data security is further improved by blockchain, which makes it more appropriate for worldwide applications, particularly in settings with limited resources.

Security and privacy and adaptability

Data security and privacy issues may arise due to the framework's reliance on private information for IoT devices, blockchain for storage, and AI-driven analytics. By using permissioned and federated blockchain architectures (like Hyperledger Fabric and Ethereum), which restrict data access to only authorized users, this can be avoided. According to Goel et al., (2019) blockchain has shown promise in reducing the risk of unauthorized modifications or breaches. Cyberattacks may target IoT devices used for data collection. Therefore, when transmitting data, encryption and robust authentication methods should be applied (Tawalbeh et al., 2020). Large datasets analyzed using deep learning models may include sensitive information. Sharing this information among different stakeholders can lead to privacy concerns.

Future versions of the system could incorporate advanced privacy protection approaches such as differential privacy or federated learning to better safeguard personal data (Choudhury et al., 2019). In regions with poor infrastructure, there are major barriers. Maintaining secure data centers and networks requires cooperation with regional authorities and groups. Financial difficulties, poor levels of digital literacy, and limited access to cutting-edge technology are common issues in under-resourced areas. The system could be enhanced by utilizing community-based data collecting, lightweight AI models, and affordable IoT devices to reduce expenses without compromising functionality. For example, current 5G networks can be replaced by low-power wide-area network (LPWAN) technologies like LoRaWAN, which guarantee connections at reduced costs and energy consumption (Chen et al., 2022). Using federated learning to lessen the requirement for data transfer could be a solution in areas with limited bandwidth while keeping privacy intact (Mohammadi et al., 2024). Using Industry 5.0 technologies in social structures can also impact jobs and governance. While these technologies make processes more efficient and focus on human improvement, they raise concerns about job loss due to more automation (Attaran, 2023). Solutions needs to be in place to strike a balance between technological progress and the well-being of society to limit negative social and economic effects. This includes creating policies for providing training to worker, ensuring that employees can move into new roles created by technological advances (Gamberini & Pluchino, 2024). Strong governance frameworks are also necessary to oversee the ethical use of new technologies, prevent misuse, and ensure fair benefits for everyone. Collaboration between governments, companies, and educational institutions is key for forming policies that support fair growth and address the socio-economic challenges posed by Industry 5.0.

Finally, our results demonstrate that combining AI, blockchain, and IoT with a focus on explainability can achieve reliable SDG monitoring. Deep learning models were tested to analyze the dataset and find key correlations. The findings confirm the effectiveness of the proposed framework for tracking SDG indicators. Blockchain integration guarantees safe data transfer, while Explainable AI makes the system's outputs more transparent. The framework can be implemented in companies using automated analytics to make operational adjustments and guarantee that sustainability metrics are satisfied. Similar datasets can be automated, and understandable insights into IoT data can be provided using our proposed deep-learning model.

Table 2
The model performance is in predicting energy and water consumption.

Metric	Energy Monitoring	Water Flow Monitoring
Prediction Accuracy	96.8 %	93.4 %
RMSE	0.045 kWh	0.02 L/min
Anomaly Detection Rate	85 %	80 %
Processing Latency	8 ms	9 ms

Conclusions, limitation, and future scope

This paper discussed the ability of technologies related to Industry 5.0 such as AI, IoT, B5G and edge cloud computing to measure and monitor various SDGs within Society 5.0. The study demonstrated that SDG indicators can be linked to technological frameworks that enable real-time monitoring and measurement of metrics such as global society, economy, and environment. The results show how Industry 5.0 uses modern data analytics and automation to solve global issues, therefore offering a more efficient and adaptable method of monitoring sustainability. Through the application of these advanced tools, we may maintain real-time monitoring, enhanced data transparency, and improved decision-making process to address important concerns like resource consumption and environmental sustainability.

Some might argue that widespread implementation of new advanced technologies may widen present digital gaps and pose ethical concerns. Yet, this research shows that good government, inclusive policies, and energy-efficient choices help to reduce these challenges. This study offers a dynamic, automated, and real-time method for monitoring development toward the SDGs, therefore guiding our approach to sustainable development. The research has limits, however. For example, only a limited number of SDG indicators were studied, leaving others unaddressed, limiting the scope of the research. Moreover, depending on the adoption of modern technology like B5G, artificial intelligence, and blockchain which are still in their early phases of adoption, creates difficulties regarding scalability and practical application. Data availability, especially in poor areas, and concerns about privacy and ethics in data collection are also significant barriers. The framework may provide implementation challenges in sectors with inadequate technology infrastructure, and its complexity necessitates considerable resources, which may be unfeasible for smaller organizations. This research primarily aimed to propose the framework rather than conduct rigorous validation; hence, further real-world testing is required.

Looking ahead, this research will expand to cover a broader range of SDG indicators, including economic growth (SDG8), sustainable communities (SDG11) and responsible consumption and production (SDG12), aiming to further refine the integration of Industry 5.0 technologies into sustainable development efforts. To further guide the following stages of research real-world validation, could involve pilot deployments in diverse settings (urban, rural, and industrial areas) to validate the framework's performance. By developing more sophisticated tools, we will enable the measurement of increasingly diversified indicators, offering more profound insights into how these technologies can drive societal, environmental, and economic progress. This work will pave the way for future research on optimizing the interaction between advanced technologies and SDG goals, ensuring more effective monitoring and implementation.

CRediT authorship contribution statement

Ali H. Hassan: Writing – original draft. **Elsadig Musa Ahmed:** Writing – review & editing. **Jamal M. Hussien:** Writing – original draft. **Riza bin Sulaiman:** Supervision. **Mansoor Abdulhak:** Supervision. **Hasan Kahtan:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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