

Review Article

Environmental Sustainability in the Digital Age: The Role of Smart Technologies in Agriculture, Urban Development, and Energy Management

ABSTRACT

Environmental sustainability is a pressing global challenge that demands innovative solutions to balance ecological preservation with human development. In the digital age, smart technologies have emerged as transformative tools for addressing these challenges by optimizing resource management, reducing environmental impact, and promoting sustainable practices. This review explores the role of smart technologies across three critical domains: agriculture, urban development, and energy management. In agriculture, precision farming, IoT-enabled monitoring, and sustainable water management are enhancing productivity while minimizing resource use. Urban development benefits from smart city initiatives, intelligent transportation systems, and innovative waste management solutions that improve efficiency, reduce emissions, and enhance urban living standards. In energy management, technologies such as smart grids, renewable energy integration, and energy-efficient building systems are revolutionizing energy distribution and consumption. This paper also examines the benefits of these technologies in advancing sustainability goals and highlights the Government of India's initiatives to promote smart technologies in agriculture. By integrating digital tools with sustainability objectives, smart technologies offer a pathway to a resilient, sustainable future, underscoring their vital role in mitigating environmental challenges.

Keywords: Agriculture, Energy Management, Environmental Sustainability, Renewable Energy, Smart Technologies, Urban Development.

1. Introduction

In recent years, the urgency to address pressing environmental challenges such as climate change, pollution, and resource depletion has become increasingly evident (Ang *et al.*, 2017). As humanity confronts the consequences of unsustainable practices, technology emerges as a powerful ally, providing innovative solutions to reduce environmental degradation and foster long-term resilience (Alzayani *et al.*, 2024). At its essence, sustainable development focuses on fulfilling present needs without compromising the capacity of future generations to meet

theirs. Within this framework, smart technologies serve as both a catalyst for transformation and a driver of progress (Anagnostopoulos *et al.*, 2018). Smart technologies encompass advanced systems and devices that harness data, automation, and connectivity to enhance efficiency and effectiveness. These technologies have diverse applications, ranging from renewable energy systems and smart grids to IoT-enabled water management and precision agriculture (Asaee *et al.*, 2019). By utilizing real-time data and advanced analytics, they facilitate informed decision-making and optimized resource use, reducing environmental impact and advancing sustainability goals. One of the most transformative applications of smart technologies is in energy management [46,47]. Smart grids improve the efficiency and reliability of electricity distribution by integrating renewable energy sources and managing demand and supply through real-time data (Balaji *et al.*, 2019). Energy storage solutions like batteries and pumped hydro systems are vital for balancing the intermittent nature of renewable sources such as solar and wind power. These advancements contribute to reduced greenhouse gas emissions, improved energy security, and greater system resilience (Cai *et al.*, 2019).

Water management represents another critical area where smart technologies excel (Zhang and He, 2020). IoT-enabled water systems optimize usage across agriculture, industry, and households. Smart irrigation systems employ sensors to deliver water precisely when and where it is needed, minimizing waste and boosting crop yields. Additionally, water quality monitoring technologies help ensure access to clean and safe water, addressing a fundamental global challenge. In waste management, smart technologies are transforming traditional processes. Automated sorting systems separate recyclables efficiently, while smart bins signal collection needs. Waste-to-energy technologies convert refuse into usable energy, reducing reliance on landfills and generating renewable power. These advancements help mitigate environmental pollution while creating economic opportunities (Deb *et al.*, 2018). The transportation sector is also experiencing a shift through smart technologies. Electric and autonomous vehicles lower greenhouse gas emissions and enhance fuel efficiency. Smart public transportation systems leverage real-time data to optimize routes and schedules, easing congestion and reducing pollution (Gharaibeh *et al.*, 2017). These innovations promote sustainable urban mobility and improve the quality of life for city residents. Smart buildings contribute significantly to sustainability through energy-efficient designs and environmentally friendly practices (Popova *et al.*, 2023). These structures integrate intelligent HVAC systems and automation to minimize energy consumption. By using sensors and

analytics to adjust heating, cooling, and lighting according to occupancy and weather, smart buildings achieve energy savings while enhancing indoor environmental quality (Harkouss *et al.*, 2018).

In agriculture, precision farming leverages IoT devices and data analytics to monitor soil health, weather, and crop conditions. This approach enables more efficient use of water, fertilizers, and pesticides, reducing environmental impact while enhancing yields. Supported by smart technologies, sustainable farming practices ensure food security and the preservation of natural resources (Hossain *et al.*, 2019). Smart cities, which combine multiple smart technologies, are designed to improve urban living. With IoT and big data analytics, they optimize infrastructure systems for transportation, energy, water, and waste management (Ahad *et al.*, 2020). These initiatives aim to create sustainable and resilient urban environments. While the benefits of smart technologies are immense, challenges such as high costs, technological complexity, and regulatory barriers remain. Nevertheless, ongoing advancements and supportive policies can help overcome these hurdles, paving the way for a more sustainable future (Jatinkumar *et al.*, 2018). In summary, smart technologies are revolutionizing resource management and addressing environmental issues. By integrating these technologies into various sectors, we can establish more sustainable and resilient systems that benefit both society and the environment (Agarwal *et al.*, 2022). Their adoption holds tremendous potential for shaping a sustainable future and ensuring the well-being of future generations.

2. Importance of Environmental Sustainability

Environmental sustainability is a vital concept focused on safeguarding natural resources and ecosystems for the benefit of future generations. It involves a comprehensive set of principles and practices aimed at minimizing human impact on the environment, enhancing ecosystem health, and ensuring the long-term availability of natural resources (Azlan *et al.*, 2023). Its significance lies in its foundational role in maintaining the well-being of the planet and its inhabitants. One key aspect of environmental sustainability is the preservation of natural resources. Essential resources such as water, soil, minerals, and forests are finite and critical for human survival. Overuse and unsustainable practices threaten their availability for future generations (Kermeli *et al.*, 2019). Adopting sustainable approaches like responsible water use, sustainable farming methods, and forest conservation helps safeguard these resources for long-term use. Ecosystems provide indispensable services, including clean air and water, crop

pollination, and climate regulation. Biodiversity, which reflects the variety of life forms on Earth, is central to maintaining robust ecosystems. Environmental sustainability prioritizes protecting and restoring ecosystems and biodiversity by reducing pollution, curbing habitat destruction, and fostering conservation (Lee *et al.*, 2018). Resilient ecosystems are better equipped to adapt to environmental changes and sustain human life. Climate change, driven by human activities such as burning fossil fuels, deforestation, and industrial processes, is among the most urgent environmental challenges. Environmental sustainability addresses this issue by promoting renewable energy adoption, energy efficiency, and sustainable land management. Reducing greenhouse gas emissions is critical to mitigating climate change's adverse effects, including shifts in weather patterns, rising sea levels, and threats to biodiversity (Li *et al.*, 2018).

Human health is closely tied to environmental sustainability. Pollution of air, water, and soil contributes to respiratory illnesses, waterborne diseases, and exposure to hazardous substances. Sustainable practices, such as minimizing emissions, managing waste effectively, and ensuring access to clean water, support healthier living conditions (Mohapatra *et al.*, 2017). Moreover, sustainable agriculture reduces reliance on harmful chemicals, leading to safer food and water supplies. Economic benefits also arise from sustainability efforts. Energy efficiency measures lower costs for businesses and households, while renewable energy development generates jobs and drives economic growth. Sustainable agriculture enhances crop productivity and reduces expenses related to soil degradation and water scarcity (Stuit *et al.*, 2022). Additionally, conserving natural resources and ecosystems bolsters industries like tourism and fisheries, which depend on a healthy environment. Social equity is intrinsically linked to environmental sustainability. Unsustainable practices disproportionately affect vulnerable communities, which often lack the resources to adapt to environmental challenges or recover from disasters (Tanyer *et al.*, 2018). Promoting sustainability ensures equitable access to clean air, water, and resources, addressing issues such as environmental injustice. It also involves creating policies that prevent deepening inequalities and foster fair distribution of sustainable development benefits.

At its heart, environmental sustainability embodies a commitment to intergenerational responsibility. It acknowledges that today's actions shape the future health of the planet. By adopting sustainable practices, we can ensure future generations inherit a world capable of supporting life and meeting their needs. This ethical perspective underscores the importance of balancing present-day demands with the planet's long-term well-being. In conclusion,

environmental sustainability is crucial for conserving natural resources, protecting ecosystems and biodiversity, combating climate change, enhancing human health, and fostering economic and social progress. It requires collective action from individuals, communities, businesses, and governments. Prioritizing sustainability enables the creation of a resilient, equitable world for current and future generations (Bibri, 2018). Ultimately, environmental sustainability is indispensable for ensuring the continued health and prosperity of the planet and all its inhabitants.

3. Overview of the Intersection between Smart Technologies and Environmental Sustainability

The convergence of smart technologies and environmental sustainability marks a critical frontier in tackling global environmental challenges. Technologies such as the Internet of Things (IoT), artificial intelligence (AI), and big data analytics provide groundbreaking solutions to reduce environmental degradation and foster sustainable practices (Wang *et al.*, 2019). These innovations enable efficient resource management, minimize waste, and improve the monitoring and mitigation of environmental impacts. For example, IoT devices can optimize energy use in buildings by adjusting lighting and temperature based on occupancy, while AI algorithms enhance energy demand forecasting and management. One of the most impactful areas where smart technologies contribute to environmental sustainability is renewable energy (Hilty *et al.*, 2014). Advanced sensors and data analytics support the seamless integration of renewable energy sources like wind and solar into power grids, ensuring a stable and dependable energy supply. Smart grids utilize real-time data to balance energy supply and demand, minimizing wastage and improving distribution efficiency. Furthermore, AI-driven predictive maintenance extends the lifespan of renewable energy systems, increasing their overall sustainability. Smart technologies also play an essential role in promoting sustainable urban development. In smart cities, IoT, AI, and data analytics optimize urban planning, transportation, and waste management (Xu *et al.*, 2019). For instance, intelligent traffic management systems help reduce congestion and emissions by streamlining traffic flow, while smart waste management systems boost recycling rates and decrease reliance on landfills. These advancements not only enhance urban residents' quality of life but also contribute to the sustainability of cities. In agriculture, the application of smart technologies commonly referred to as precision farming has the potential to transform food production. IoT sensors and drones enable real-time monitoring of soil health, crop conditions, and weather patterns, allowing farmers to use water, fertilizers, and pesticides

more precisely and efficiently. This approach increases agricultural productivity while minimizing the environmental impact of farming activities. In summary, integrating smart technologies into sustainability initiatives offers tremendous potential to create a more sustainable future. These technologies improve resource efficiency, reduce waste, and facilitate better environmental monitoring and management, addressing critical environmental challenges. However, it is vital to ensure their deployment aligns with sustainability principles to maximize their positive impact on the environment (Venanzi *et al.*, 2023).

4. Smart Technologies in Agriculture

Smart technologies are transforming agriculture by introducing innovative tools and systems that enhance efficiency, productivity, and sustainability. These technologies encompass a range of applications, including precision farming, the Internet of Things (IoT), and sustainable water management, each contributing to more effective and environmentally friendly agricultural practices (Kavga *et al.*, 2021).

4.1 Precision Farming

Precision farming, often referred to as precision agriculture, employs advanced technologies to enable precise management of agricultural practices at a granular level. Through tools such as GPS, remote sensing, IoT-enabled sensors, and data analytics, farmers can monitor and respond to variations across their fields with exceptional accuracy. This technology-driven approach facilitates targeted interventions, such as applying fertilizers, pesticides, and water only where and when they are needed, ensuring efficient resource utilization and minimizing environmental harm. The benefits of precision farming extend beyond resource optimization. By tailoring inputs to specific field conditions, it reduces over-application of chemicals, lowering costs and preventing runoff that can pollute water sources. Advanced monitoring systems also provide real-time insights into soil health, crop conditions, and weather patterns, enabling proactive decision-making and reducing the risk of crop failures (Zhao *et al.*, 2019).

In addition to improving crop yields and reducing waste, precision farming supports long-term sustainability by conserving vital resources like water and soil. For example, smart irrigation systems ensure optimal water delivery, while soil monitoring helps prevent degradation and maintain fertility. Precision farming also contributes to food security by increasing agricultural productivity without expanding farmland, thus preserving natural ecosystems. Moreover, this innovative approach aligns with the broader goals of sustainable

development, addressing challenges such as climate change and resource scarcity (Maksimovic, 2017). By integrating precision farming techniques, agriculture can transition toward a more environmentally responsible and economically viable model, supporting both farmers and the global population. Ultimately, precision farming represents a transformative shift in agriculture, blending traditional farming knowledge with cutting-edge technology to achieve a balance between productivity, environmental stewardship, and sustainability.

4.2 IoT in Agriculture

The Internet of Things (IoT) has become a cornerstone of modern agriculture, transforming traditional farming methods by interconnecting devices and systems to enable real-time data collection and analysis. IoT sensors strategically placed in fields can monitor critical parameters such as soil moisture, temperature, nutrient content, and weather conditions. These insights empower farmers to make informed decisions about irrigation, fertilization, and planting schedules, optimizing resource use and minimizing environmental impact. By adopting this data-driven approach, farmers can conserve water, reduce reliance on chemical inputs, and promote healthier, more robust crops (Mondejat *et al.*, 2021). Beyond stationary sensors, IoT-enabled devices such as drones and autonomous tractors are revolutionizing field operations. Drones equipped with multispectral cameras can survey large areas quickly, identifying issues like pest infestations or nutrient deficiencies.

IoT technology also contributes to predictive farming by integrating data from various sources, including weather forecasts and historical field performance, to predict potential challenges and recommend proactive solutions. For example, smart irrigation systems can adjust watering schedules based on weather patterns and soil conditions, preventing overwatering and saving vital resources. Similarly, livestock monitoring systems can track animal health and behavior, ensuring timely interventions and improving overall productivity.

Ultimately, the IoT is driving a technological evolution in agriculture, empowering farmers to adopt precision techniques that address the growing demand for food while safeguarding natural resources. This interconnected ecosystem of devices and data represents a critical step toward achieving sustainable and efficient farming practices in the face of global challenges such as climate change and population growth.

4.3 Sustainable Water Management

Water is an indispensable resource in agriculture, and its sustainable management is crucial for maintaining long-term productivity and preserving environmental health. Smart technologies provide innovative approaches to using water efficiently. IoT sensors can track soil moisture levels and weather patterns, enabling farmers to schedule irrigation precisely and reduce water waste. Advanced systems like drip irrigation and automated sprinklers, which can be remotely controlled, deliver water directly to plant root zones, minimizing evaporation and runoff. These solutions not only conserve water resources but also enhance crop yields and lower the environmental impact of agricultural practices. In summary, the adoption of smart technologies in agriculture, including precision farming, IoT applications, and sustainable water management practices, offers immense potential for boosting sustainability and productivity. By utilizing these advanced tools, farmers can make informed, data-driven decisions that optimize resource utilization, improve agricultural outputs, and minimize environmental harm. As these technologies continue to advance, they are poised to become increasingly critical in addressing global challenges such as food security and environmental conservation (Ahad *et al.*, 2020).

5. Smart Technologies in Urban Development

5.1 Smart Cities

Smart cities leverage advanced technologies to improve urban living standards, boost operational efficiency, and support sustainability. IoT sensors are extensively used to monitor key metrics such as air quality, traffic flow, noise levels, and energy consumption, providing valuable data for informed decision-making in city management. Digital communication technologies power smart grids, enhancing the reliability and efficiency of electricity distribution by quickly detecting and addressing changes in local usage patterns.

E-governance platforms simplify citizen interactions with government services by enabling online access to tasks such as bill payments, permit applications, and public records retrieval. These platforms enhance transparency and streamline processes, reducing bureaucratic delays (Zhou *et al.*, 2024). Smart lighting systems equipped with motion sensors adjust brightness based on pedestrian or vehicular activity, conserving energy and minimizing light pollution. Public safety is bolstered through integrated systems, including surveillance cameras and emergency response technologies, which enable rapid responses to incidents. Together, these innovations contribute to more sustainable, efficient, and liveable urban environments (Venkatramanan and Shah, 2019).

5.2 Smart Transportation Systems

Smart transportation systems are designed to enhance the efficiency, safety, and sustainability of urban mobility. Intelligent traffic management systems utilize real-time data from traffic cameras, sensors, and GPS devices to optimize traffic signal timing, alleviate congestion, and provide drivers with up-to-date traffic information. Public transit applications deliver real-time updates on bus and train schedules, delays, and alternative routes, enabling commuters to plan their travel more effectively. The adoption of electric vehicles (EVs) helps lower greenhouse gas emissions and reduces dependence on fossil fuels, while autonomous vehicles (AVs) have the potential to enhance road safety and decrease traffic congestion by eliminating human errors. Eco-friendly transportation alternatives, such as bike-sharing programs and e-scooter services, offer convenient options that help mitigate traffic and reduce air pollution. Additionally, smart parking systems provide real-time data on available parking spaces, cutting down on the time spent searching for parking and easing traffic flow (Hui *et al.*, 2023).

5.3 Waste Management Solutions

Innovative waste management technologies are transforming how cities handle waste, making the process more efficient and sustainable. Smart bins equipped with sensors can detect their fill levels and notify waste collection services when they need to be emptied. This approach streamlines collection routes, reduces operational costs, and minimizes unnecessary trips. Advanced recycling systems, including AI-powered robots and optical sorting machines, enhance the precision and efficiency of recycling operations, allowing for higher recycling rates and less contamination in recyclable materials. Waste-to-energy solutions convert waste into usable energy through methods such as incineration, anaerobic digestion, and gasification. These technologies help reduce the volume of waste sent to landfills while generating renewable energy. Composting technologies enable the processing of organic waste into nutrient-rich compost, which can be used as a natural fertilizer in agriculture and landscaping. Additionally, circular economy strategies emphasize the reuse, repurposing, and recycling of materials, decreasing overall waste generation and conserving natural resources.

6. Smart Technologies in Energy Management

6.1 Smart Grids

Smart grids are a major innovation in electricity management and distribution. These grids utilize digital technology to enable real-time monitoring and control of the entire electrical network. With the help of sensors and IoT devices, they gather data on energy consumption and grid performance, allowing utilities to quickly address fluctuations in demand and potential problems. A key feature of smart grids is their ability to implement demand response strategies, which adjust electricity supply based on real-time demand. This helps prevent blackouts and optimize energy consumption. Additionally, smart grids are designed to accommodate renewable energy sources like solar and wind, which can be variable. By employing advanced algorithms and real-time data, smart grids maintain a stable and reliable energy supply while supporting sustainability.

6.2 Renewable Energy Integration

Integrating renewable energy into the power grid is crucial for reducing dependence on fossil fuels and minimizing environmental impact. However, renewable sources like solar and wind are variable and intermittent by nature. To manage this, smart technologies are used to optimize their integration. Energy storage systems, such as batteries, are key in this process. They store surplus energy produced during peak times and release it when production is low, ensuring a steady energy supply (Viitanen and Kingston, 2014). Advanced forecasting methods, powered by predictive analytics and artificial intelligence, allow for more accurate predictions of renewable energy output. This enhances grid stability and facilitates better planning and management. Microgrids also play a vital role in integrating renewable energy. These localized grids can function independently or alongside the main grid, improving resilience and enabling more efficient use of local renewable energy sources.

6.3 Energy Efficiency in Buildings

Enhancing energy efficiency in buildings is a critical aspect of smart energy management. Smart technologies are utilized to monitor, control, and reduce energy usage within buildings. Devices like smart meters and sensors provide real-time data on energy consumption, helping building managers and occupants detect patterns and identify opportunities for energy savings. Automated systems, such as smart thermostats, lighting, and HVAC (heating, ventilation, and air conditioning) systems, adjust settings based on occupancy and usage trends, ensuring energy is used efficiently without sacrificing comfort. Building management systems (BMS) integrate various technologies to oversee and regulate energy consumption across the building (Nizetic *et al.*, 2019). These systems control lighting, heating, cooling,

and other energy-intensive processes, ensuring optimal energy efficiency throughout the building. By adopting these smart technologies, buildings can significantly cut down on energy use, reduce operational costs, and support environmental sustainability.

7. Benefits of Smart Technologies in Sustainability

Table 1: Benefits of Smart Technologies in Sustainability

Benefits	Explanation	References
Enhanced Energy Efficiency	Smart technologies like IoT sensors, smart thermostats, and automated lighting systems help optimize energy use by adjusting settings based on real-time data. For instance, smart thermostats learn user preferences and adjust heating and cooling systems accordingly, while automated lighting systems turn off lights in unoccupied rooms. This not only reduces energy consumption but also lowers utility bills and minimizes the environmental impact by reducing greenhouse gas emissions.	Albadi <i>et al.</i> , 2023
Integration of Renewable Energy	Smart grids and energy management systems are essential for integrating renewable energy sources such as solar and wind. These systems can balance the supply and demand of electricity, manage the variability of renewable sources, and store excess energy for later use.	Patnaik <i>et al.</i> , 2020
Improved Resource Management	Smart technologies enable more efficient use of natural resources. In agriculture, smart irrigation systems use sensors to monitor soil moisture levels and weather conditions, ensuring that crops receive the right amount of water at the right time. This reduces water waste and improves crop yields.	Nizetic <i>et al.</i> , 2022
Reduced Carbon Footprint	By enhancing energy efficiency and integrating renewable energy, smart technologies help reduce	Akintuyi, 2024

	<p>the carbon footprint of buildings, industries, and transportation systems. For example, smart buildings can reduce energy consumption by up to 30%, significantly lowering greenhouse gas emissions.</p>	
<p>Enhanced Grid Reliability and Resilience</p>	<p>Smart grids improve the reliability and resilience of the electricity supply by quickly responding to changes in demand and supply. They can detect and isolate faults in the grid, reducing the risk of blackouts and ensuring a consistent energy supply. This is particularly important in the face of increasing climate-related disruptions, such as extreme weather events, which can cause significant damage to traditional power grids.</p>	<p>Simo <i>et al.</i>, 2023</p>
<p>Data-Driven Decision Making</p>	<p>Smart technologies provide real-time data and analytics, enabling informed decision-making. This data can be used to identify inefficiencies, predict maintenance needs, and optimize operations. For example, in manufacturing, predictive maintenance systems use data from sensors to predict when equipment is likely to fail, allowing for timely maintenance and reducing downtime.</p>	<p>Sadeeq and Zeebaree, 2021</p>
<p>Economic Benefits</p>	<p>Investing in smart technologies can lead to significant cost savings and economic benefits. Energy-efficient buildings have lower operating costs, and integrating renewable energy can reduce energy bills. Additionally, the development and deployment of smart technologies create new job opportunities in fields such as engineering, data analysis, and renewable energy. This drives economic growth and supports the transition to a more sustainable economy.</p>	<p>Mohammadi <i>et al.</i>, 2018</p>

Improved Quality of Life	Smart technologies contribute to a higher quality of life by creating more comfortable and efficient living and working environments. For example, smart home systems can automate lighting, heating, and security, enhancing comfort and convenience. In transportation, smart systems can reduce traffic congestion, improve public transportation, and enhance air quality, making cities more liveable and reducing health risks associated with air pollution.	Ragazou <i>et al.</i> , 2022
--------------------------	---	---------------------------------

8. GOI's initiatives to promote smart technology in agriculture

1. Digital Agriculture Mission (DAM): The Digital Agriculture Mission (DAM) is a comprehensive initiative aimed at transforming the agricultural sector through the use of digital technologies. One of its key components is the India Digital Ecosystem of Agriculture (IDEA), which seeks to create a federated farmers' database. This database will integrate various agricultural schemes and services, providing a unified platform for farmers to access information and resources. Another important aspect is the Unified Farmers Service Interface (UFSI), which offers farmers a single interface to access multiple services, simplifying their interactions with various agricultural programs. Additionally, DAM provides funding for emerging technologies such as AI, IoT, and blockchain, supporting state governments in implementing innovative projects to enhance agricultural productivity and sustainability.

2. National e-Governance Plan in Agriculture (NeGP-A): The National e-Governance Plan in Agriculture (NeGP-A) aims to harness the power of digital technologies to improve agricultural practices and outcomes. By incorporating Artificial Intelligence (AI) and Machine Learning (ML), the plan enhances decision-making and predictive analytics, helping farmers make informed choices about crop management. The use of robotics and drones is promoted to improve precision farming and resource management, ensuring optimal use of inputs like water and fertilizers. Furthermore, data analytics and blockchain technologies are employed to ensure transparency and efficiency in agricultural supply chains, reducing wastage and improving traceability from farm to fork.

3. Sub-Mission on Agricultural Mechanization (SMAM)

The Sub-Mission on Agricultural Mechanization (SMAM) focuses on increasing the reach of farm mechanization, particularly among small and marginal farmers. One of its key strategies is the establishment of Custom Hiring Centres (CHCs), which provide farmers with access to high-tech and high-value farm equipment on a rental basis. This makes advanced machinery affordable and accessible to those who cannot afford to purchase it outright. SMAM also emphasizes awareness and training by conducting demonstrations and capacity-building activities. These initiatives aim to educate farmers about the benefits of modern machinery and encourage its adoption to improve productivity and reduce labour-intensive practices.

4. Pradhan Mantri Krishi Sinchayee Yojana (PMKSY): The "Per Drop More Crop" component of the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) is designed to enhance water use efficiency in agriculture. This initiative promotes the use of micro irrigation systems, such as drip and sprinkler irrigation, which optimize water usage at the farm level. By delivering water directly to the plant roots, these systems minimize water wastage and ensure that crops receive the right amount of moisture. This not only conserves water but also improves crop yields and quality, contributing to the overall sustainability of agricultural practices.

5. National Agriculture Market (e-NAM): The National Agriculture Market (e-NAM) is an electronic trading portal that connects Agricultural Produce Market Committee (APMC) mandis across India, creating a unified national market for agricultural commodities. Through digital trading services, e-NAM facilitates transactions between farmers, traders, and buyers, making the process more transparent and efficient. The platform also supports warehouse-based trading, allowing farmers to sell their produce directly from warehouses. This reduces the need for physical transportation to markets, cutting down on costs and post-harvest losses. e-NAM aims to empower farmers by providing them with better price discovery and access to a wider market.

6. Kisan Drones: The government is actively promoting the use of drones in agriculture through the Kisan Drones initiative. Drones are used for crop monitoring, enabling farmers to monitor crop health and detect issues such as pest infestations or nutrient deficiencies early. This allows for timely interventions and reduces crop losses. Additionally, drones facilitate precision agriculture by **applying fertilizers and pesticides more efficiently, ensuring that these inputs are used only where needed. This not only improves crop yields but also reduces the environmental impact of agricultural practices.**

7. Indian Council of Agricultural Research (ICAR) Initiatives: The Indian Council of Agricultural Research (ICAR) supports innovation and education in agriculture through various initiatives. One such initiative is the development of mobile apps for farming-related services, which are integrated into the KISAAN platform. These apps provide farmers with access to information on weather, crop management, market prices, and more, helping them make informed decisions. The Farmer FIRST Initiative aims to enhance the interface between farmers and scientists, promoting the exchange of knowledge and best practices. This initiative focuses on improving agricultural practices through collaborative efforts, ensuring that farmers benefit from the latest research and innovations.

These initiatives collectively demonstrate the GOI's commitment to modernizing agriculture through smart technologies, ultimately aiming to increase productivity, sustainability, and farmer's incomes.

9. Conclusion

The integration of smart technologies in agriculture represents a transformative approach to achieving environmental sustainability. These technologies, including AI, IoT, drones, and precision farming tools, offer innovative solutions to some of the most pressing challenges in modern agriculture. By optimizing resource use, enhancing productivity, and reducing environmental impact, smart technologies pave the way for a more sustainable and resilient agricultural sector. One of the key benefits of smart technologies is their ability to improve resource efficiency. Precision agriculture techniques, such as the use of sensors and data analytics, enable farmers to apply water, fertilizers, and pesticides more judiciously. This not only enhances crop yields but also minimizes the overuse of inputs, reducing the risk of soil degradation and water pollution. Additionally, technologies like drip irrigation and automated irrigation systems ensure that water is used efficiently, addressing the critical issue of water scarcity in agriculture. Smart technologies also play a crucial role in mitigating the impacts of climate change. Climate-smart agricultural practices, supported by digital tools, help farmers adapt to changing weather patterns and extreme events. For instance, predictive analytics and weather forecasting models allow farmers to make informed decisions about planting and harvesting, reducing the risk of crop failure. Moreover, the adoption of climate-resilient crop varieties and sustainable soil management practices contributes to the long-term health of agricultural ecosystems. Furthermore, the use of drones and remote sensing technologies enhances the ability to monitor and manage agricultural landscapes. These tools provide real-

time data on crop health, soil conditions, and pest infestations, enabling timely interventions and reducing the need for chemical inputs. This not only improves the efficiency of farming operations but also promotes biodiversity and ecosystem health by minimizing the disruption caused by conventional farming practices. The role of agricultural extension services is pivotal in promoting the adoption of these smart technologies. By providing education, training, and support, extension agents ensure that farmers are equipped with the knowledge and skills needed to implement sustainable practices. They also facilitate access to technology and resources, helping to overcome financial and logistical barriers. Through continuous engagement and feedback, extension services contribute to the refinement and improvement of smart agricultural technologies, ensuring their relevance and effectiveness.

In conclusion, the adoption of smart technologies in agriculture is essential for achieving environmental sustainability. These technologies offer innovative solutions to optimize resource use, enhance productivity, and mitigate the impacts of climate change. With the support of agricultural extension services, farmers can effectively integrate these tools into their practices, leading to a more sustainable and resilient agricultural sector. As we move forward, it is crucial to continue investing in research, development, and dissemination of smart technologies to ensure a sustainable future for agriculture and the environment.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Option 2:

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology

Details of the AI usage are given below:

- 1.
- 2.
- 3.

References

1. Agarwal, P., Mittal, M., Ahmed, J., and Idrees, S. M. (2022). Smart technologies for energy and environmental sustainability. *Journal of Cleaner Production*, 217, 421-438
2. Ahad, M. A., Paiva, S., Tripathi, G., and Feroz, N. (2020). Enabling technologies and sustainable smart cities. *Sustainable cities and society*, 61, 102301.
3. Akintuyi, O. B. (2024). Vertical farming in urban environments: a review of architectural integration and food security. *Research Journal of Biology and Pharmacy*, 10(2), 114-126.
4. Alabdali, S. A., Pileggi, S. F., and Cetindamar, D. (2023). Influential factors, enablers, and barriers to adopting smart technology in rural regions: A literature review. *Sustainability*, 15(10), 7908.
5. Alzayani, F., Mohammed, A., and Shoaib, H. M. (2024). The impact of smart technologies on SMEs' sustainability: the mediation effect of sustainability strategy. *Competitiveness Review: An International Business Journal*, 34(1), 28-50.
6. Anagnostopoulos, T., Zaslavsky, A., Sosunova, I., Fedchenkov, P., Medvedev, A., Ntalianis, K., Skourlas, C., Rybin, A., and Khoruznikov, S. (2018). A stochastic multi-agent system for Internet of Things-enabled waste management in smart cities. *Waste Management and Research*, 36 (11), 1113-1121.
7. Ang, L. M., Seng, K. P., Zungeru, A. M., and Ijamaru, G. K. (2017). Big Sensor Data Systems for Smart Cities. *IEEE Internet of Things Journal*, 45, 1259–1271
8. Asaee, S.R., Ugursal, V.I., and Beausoleil-Morrison, I. (2019). Development and analysis of strategies to facilitate the conversion of Canadian houses into net zero energy buildings. *Energy Policy*, 118-130.
9. Azlan, Z. H. Z., Junaini, S. N., Bolhassan, N. A., Wahi, R., and Arip, M. A. (2023). Harvesting a sustainable future: An overview of smart agriculture's role in social, economic, and environmental sustainability. *Journal of Cleaner Production*, 140338.
10. Balaji, N., Li, Y., Sun, Z., and Qin, R. (2019). A Routing Algorithm for Inspecting Grid Transmission System Using Suspended Robot: Enhancing Cost-Effective and Energy Efficient Infrastructure Maintenance. *Journal of Cleaner Production*, 219, 622-638

11. Bibri, S. E. (2018). The IoT for smart sustainable cities of the future: An analytical framework for sensor-based big data applications for environmental sustainability. *Sustainable cities and society*, 38, 230-253.
12. Cai, W., Lai, K.-H., Liu, C., Wei, F., Ma, M., Jia, S., and Jiang, Z. (2019). Promoting sustainability of manufacturing industry through the lean energy-saving and emission reduction strategy. *Science of the Total Environment*, 665,23-32.
13. Deb, D., and Brahmabhatt, N.L. (2018). Review of yield increase of solar panels through soiling prevention, and a proposed water-free automated cleaning solution. *Renewable and Sustainable Energy Reviews*, 82, 3306-3313.
14. Gharaibeh, A., Salahuddin, M. A., Hussini, S. J., Khreishah, A., Khalil, I., Guizani, M., and Al-Fuqaha, A. (2017). Smart Cities: A Survey on Data Management, Security, and Enabling Technologies. *IEEE Communications Surveys and Tutorials*, 19(4), 2456–2501.
15. Harkouss, F., Fardoun, F., and Biwole, P.H. (2018). Optimization approaches and climates investigations in NZEB: A review. *Applied Sciences*, 11(5), 923-952.
16. Hilty, L. M., Aebischer, B., and Rizzoli, A. E. (2014). Modeling and evaluating the sustainability of smart solutions. *Environmental Modelling & Software*, 56, 1-5.
17. Hossain, S.S., Mathur, L., Majhi, M.R., and Roy, P.K. (2019). Manufacturing of green building brick: recycling of waste for construction purpose. *Journal of Material Cycles and Waste Management*, 21(2), 281-292.
18. Hui, C. X., Dan, G., Alamri, S., and Toghraie, D. (2023). Greening smart cities: An investigation of the integration of urban natural resources and smart city technologies for promoting environmental sustainability. *Sustainable Cities and Society*, 99, 104985.
19. Jatinkumar Shah, P., Anagnostopoulos, T., Zaslavsky, A., and Behdad, S. (2018). A stochastic optimization framework for planning of waste collection and value recovery operations in smart and sustainable cities. *Waste Management*, 78, 104-114.
20. Kavga, A., Thomopoulos, V., Barouchas, P., Stefanakis, N., and Liopa-Tsakalidi, A. (2021). Research on innovative training on smart greenhouse technologies for economic and environmental sustainability. *Sustainability*, 13(19), 10536.
21. Kermeli, K., Edelenbosch, O.Y., Crijns-Graus, W., van Ruijven, B.J., Mima, S., van Vuuren, D.P., and Worrell, E. (2019). The scope for better industry representation in long-term energy models: Modeling the cement industry. *Applied Energy*, 240, 964-985.

22. Lee, C.T., Lim, J.S., Fan, Y.V., Liu, X., Fujiwara, T., and Klemes, J.J. (2018). Enabling low- carbon emissions for sustainable development in Asia and beyond. *Journal of Cleaner Production*, 176, 726-735.
23. Li, H., Zhao, J., Li, M., Deng, S., An, Q., and Wang, F. (2019). Performance analysis of passive cooling for photovoltaic modules and estimation of energy-saving potential. *Solar Energy*, 15, 70-82.
24. Maksimovic, M. (2017). The role of green internet of things (G-IoT) and big data in making cities smarter, safer and more sustainable. *International Journal of Computing and Digital Systems*, 6(04), 175-184.
25. Mohammadi, M., Noorollahi, Y., Mohammadi-ivatloo, B., Hosseinzadeh, M., Yousefi, H., and Khorasani, S. T. (2018). Optimal management of energy hubs and smart energy hubs—a review. *Renewable and Sustainable Energy Reviews*, 89, 33-50.
26. Mohapatra A., Nayak B., Das, P. and Mohanty, K.B. (2017). A review on MPPT techniques of PV system under partial shading condition. *Renewable and Sustainable Energy Reviews*, 80, 854- 867.
27. Mondejar, M. E., Avtar, R., Diaz, H. L. B., Dubey, R. K., Esteban, J., Gómez-Morales, A., and Garcia-Segura, S. (2021). Digitalization to achieve sustainable development goals: Steps towards a Smart Green Planet. *Science of The Total Environment*, 794, 148539.
28. Nizetic, S., Djilali, N., Papadopoulos, A., and Rodrigues, J. J. (2019). Smart technologies for promotion of energy efficiency, utilization of sustainable resources and waste management. *Journal of cleaner production*, 231, 565-591.
29. Nizetic, S., Oclon, P., and Tsoutsos, T. (2022). Progress in smart and sustainable technologies. *Journal of Cleaner Production*, 337, 130450.
30. Patnaik, S., Sen, S., and Mahmoud, M. S. (2020). Smart village technology. *Modeling and optimization in Science and Technologies*, 17, 181-189.
31. Popova, O., Chechel, A., Fomina, O., Myroshnychenko, G., Medvedieva, M., Hoholieva, N., and Molodchenko, O. (2023). Assessment of relationships between smart technologies, corporate sustainability, and economic behavior of companies. *Eastern-European Journal of Enterprise Technologies*, 122(13).
32. Ragazou, K., Garefalakis, A., Zafeiriou, E., and Passas, I. (2022). Agriculture 5.0: A new strategic management mode for a cut cost and an energy efficient agriculture sector. *Energies*, 15(9), 3113.

33. Sadeeq, M. A., and Zeebaree, S. (2021). Energy management for internet of things via distributed systems. *Journal of Applied Science and Technology Trends*, 2(02), 80-92.
34. Simo, A., Dzitac, S., Dușu, A., and Pandelica, I. (2023). Smart Agriculture in the Digital Age: A Comprehensive IoT-Driven Greenhouse Monitoring System. *International Journal of Computers Communications & Control*, 18(6).
35. Stuit, A., Brockington, D., and Corbera, E. (2022). Smart, commodified and encoded: Blockchain technology for environmental sustainability and nature conservation. *Conservation and Society*, 20(1), 12-23.
36. Tanyer, A.M., Tavukcuoglu, A., and Bekboliev, M. (2018). Assessing the airtightness performance of container houses in relation to its effect on energy efficiency. *Building and Environment*, 134, 59-73.
37. Uwaoma, P. U., Eboigbe, E. O., Kaggwa, S., Akinwolemiwa, D. I., and Eloghosa, S. O. (2023). Ecological economics in the age of 4IR: spotlight on sustainability initiatives in the global south. *International Journal of Advanced Economics*, 5(9), 271-284.
38. Venanzi, R., Latterini, F., Civitarese, V., and Picchio, R. (2023). Recent Applications of Smart Technologies for Monitoring the Sustainability of Forest Operations. *Forests*, 14(7), 1503.
39. Venkatramanan, V., and Shah, S. (2019). Climate smart agriculture technologies for environmental management: the intersection of sustainability, resilience, wellbeing and development. *Sustainable green technologies for environmental management*, 29-51.
40. Viitanen, J., and Kingston, R. (2014). Smart cities and green growth: Outsourcing democratic and environmental resilience to the global technology sector. *Environment and Planning A*, 46(4), 803-819.
41. Wang, S., Liu, Y., Gao, S., Xing, P., He, Y., Yan, S., and Yin, H. (2019). Purification and comprehensive utilization of sapphire kerf waste. *Journal of Cleaner Production*, 214, 248- 258.
42. Xu, X. Hu, H., Tan, Y., Yang, G., Zhu, P., and Jiang, B. (2019). Quantifying the impacts of climate variability and human interventions on crop production and food security in the Yangtze River Basin, China, 1990–2015. *Science of the Total Environment*, 665, 379-389.
43. Zhang, J., and He, S. (2020). Smart technologies and urban life: A behavioral and social perspective. *Sustainable Cities and Society*, 63, 102460.

44. Zhao, Y., Ren, Q., and Na, Y. (2019). Potential utilization of phosphorus in fly ash from industrial sewage sludge incineration with biomass. *Fuel Processing Technology* 188, 16-21.
45. Zhou, Y., and Liu, J. (2024). Advances in emerging digital technologies for energy efficiency and energy integration in smart cities. *Energy and Buildings*, 315, 114289.
46. Kojo, Nussetor Setsofia, Emmanuel Kofi Acquah, Ahadjie Bless, Kelvin Vensu, Kwadwo Safo, Djirackor Bernice Adzo, and Richard Essah. 2024. "Leveraging AI for Environmental Sustainability and Climate Action". *Asian Journal of Research in Computer Science* 17 (12):30-35. <https://doi.org/10.9734/ajrcos/2024/v17i12527>.
47. Choudhary, Akanksha, and Ankita Sharma. 2024. "Exploring the Role of Environmental Ethical Consideration in Advancing Green Growth: Perspectives from India". *Asian Journal of Agricultural Extension, Economics & Sociology* 42 (10):116-29. <https://doi.org/10.9734/ajaees/2024/v42i102567>.

UNDER PEER REVIEW