***Review Article***

**Smart Infrastructure Systems: A Review of IoT-Enabled Monitoring and Automation in Civil and Agricultural Engineering**

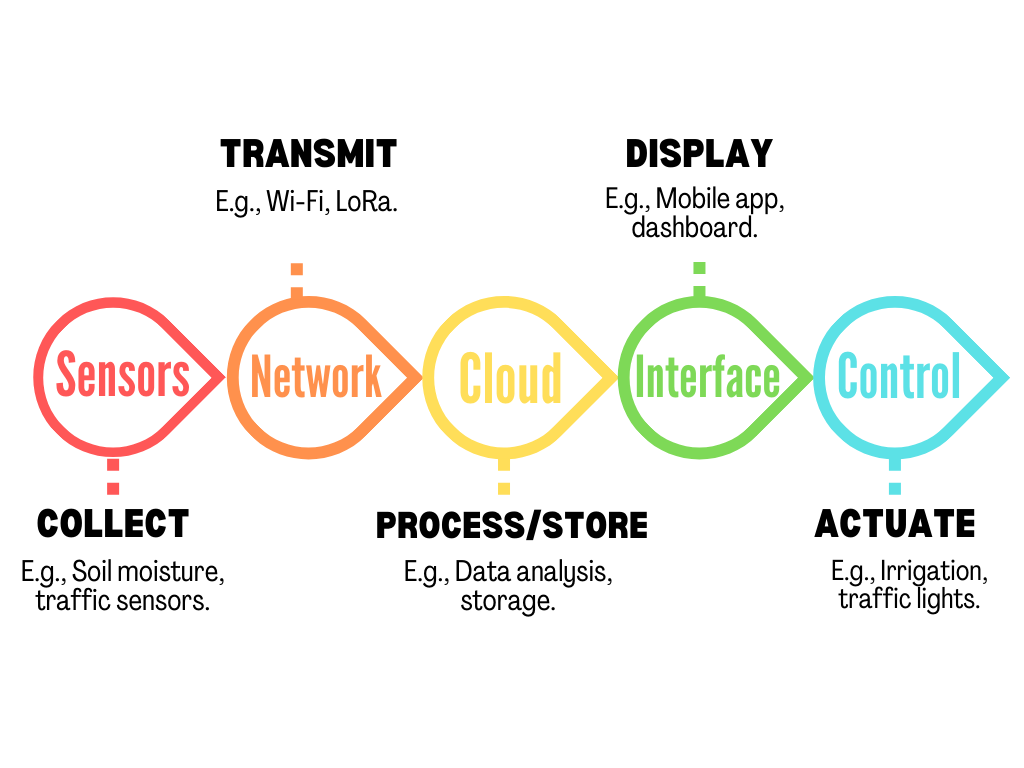
**ABSTRACT**

The Internet of Things (IoT) significantly influences the advancement of smart infrastructure systems in civil and agricultural engineering. IoT technologies have reshaped the management of urban infrastructure and agricultural operations through real-time monitoring, predictive maintenance, and automated control. In civil engineering, IoT sensors help monitor structural integrity, environmental conditions, and urban utilities, enhancing safety and efficiency in areas like traffic and waste management. IoT enhances agriculture through precision farming methods, including automatic irrigation, monitoring of crop and soil health, and resource optimization, leading to sustainable practices and increasing yields. This study analyzes IoT applications in rural and remote areas, focusing on the integration and challenges of IoT deployment. This also employs a case study approach to analyze IoT applications, highlighting key technological, economic, and policy challenges in remote and rural regions where connectivity and integration are critical. The findings suggest that IoT-driven infrastructure improves efficiency, sustainability, and resilience, but require more comprehensive analysis and integration in remote and rural areas. Future possibilities for IoT are discussed, focusing on advancements in edge computing, the use of renewable energy, and the development of smart rural infrastructure that meets both urban and agricultural needs. The paper urges for ongoing research and supportive policies that optimize the potential of IoT-integrated infrastructure systems, which are expected to improve efficiency, sustainability, and resilience in both sectors.

**Keywords**: Smart infrastructure, Internet of things (IoT), Civil engineering, Agricultural engineering, Precision farming, automation

1. **INTRODUCTION**
   1. **Background**

Intelligent infrastructure systems signify a progression in the design, monitoring, and maintenance of infrastructure within civil and agricultural domains. Conventional infrastructure systems such as buildings, highways, irrigation networks, and drainage systems frequently depend on routine maintenance and manual evaluations, resulting in delayed reactions and inefficiencies (Iradukunda et al., 2023). On the other hand, intelligent infrastructure employs sophisticated technologies for real-time monitoring, automated regulation, and predictive management. The technique is crucial for modern civil engineering as it allows infrastructure to respond to varying environmental and operational circumstances, therefore prolonging its durability and enhancing resource efficiency.



### ****Fig.1** Overview of IoT-enabled smart infrastructure system**

In smart farming, intelligent infrastructure improves the management of agricultural resources, facilitating accuracy in water and fertilizer application, crop health monitoring, and field condition maintenance (Kowalska & Ashraf, 2023; Padhiary, Kumar, & Sethi, 2024). Smart infrastructure enhances operating efficiency through the implementation of sensors, data analytics, and automation, while also promoting sustainability and resistance to environmental issues (Padhiary & Kumar, 2024). Hence, intelligent infrastructure solutions bridge the standards of civil and agricultural engineering, enhancing functionality, ecological responsibility, and economic viability (**Fig.1**). The article provides a comprehensive review of IoT applications in infrastructure, focusing on both civil and agricultural sectors. It highlights the interconnected nature of infrastructure in mixed urban-rural settings and the unique constraints faced by rural and remote areas. The review aims to fill the gap by integrating both civil and agricultural IoT applications, with a particular focus on challenges and opportunities in rural infrastructure. It analyzes recent technological advancements, policy developments, and future prospects like edge computing and renewable energy integration, offering a holistic perspective on the role of IoT in shaping smart, sustainable infrastructure across diverse environments.

* 1. **IoT in Infrastructure Monitoring and Automation**

IoT has redefined infrastructure monitoring and automation through the integration of physical systems with digital intelligence (Kumar et al., 2024). It enables continuous monitoring of civil infrastructure components such as bridges, buildings, and roadways through connected sensors and devices that provide real-time data accumulating and processing. IoT systems can identify fluctuations in structural integrity, environmental conditions, and operating load, issuing alerts and facilitating automatic solutions that eliminate any problems (Ye et al., 2024).

In agriculture, IoT-integrated solutions are important in precision farming. IoT sensors quantify soil moisture, temperature, and nutrient concentrations, enabling farmers to allocate resources with precision (Adinarayana et al., 2024; Padhiary, 2024d). Moreover, computerized irrigation systems regulate water levels according to real-time data, conserving water while maintaining optimal conditions for crop development. The IoT promotes a networked infrastructure that facilitates proactive maintenance, resource efficiency, and adaptation in urban and rural environments, assisting both civic and agricultural sectors in addressing the needs of a growing, energy-conscious global population (Simionescu & Strielkowski, 2024).

* 1. **Scope and Objectives**

This study addresses the utilization of IoT in monitoring, predictive maintenance, and automation within smart infrastructure systems in civil and agricultural engineering. It analyzes case studies, technological innovations, and industry-specific applications to offer a thorough comprehension of the role of IoT technologies in the modernization of infrastructure systems. It considers applications in civil engineering, including structural health monitoring and environmental monitoring, as well as in agricultural engineering, emphasizing precision farming, automated irrigation, and resource management. It evaluates the integration of civil and agricultural infrastructure, especially in rural regions, and outlines the obstacles and constraints associated with IoT implementation. The study seeks to demonstrate how IoT facilitates linked, resilient, and sustainable infrastructure systems.

1. **METHODOLOGY**

This study systematically selected peer-reviewed articles from Scopus, Web of Science, IEEE Xplore, and Google Scholar published between 2019–2024, ensuring a balance between civil engineering (55%) and agricultural engineering (45%) applications. Articles were chosen based on their empirical relevance to IoT-driven infrastructure monitoring, automation, and precision farming, excluding purely theoretical studies. Data justification relied on real-world case studies, such as IoT-based structural health monitoring (SHM) in bridges and tunnels and precision farming techniques using smart irrigation and soil sensors, highlighting their impact on predictive maintenance, resource optimization, and sustainability (Bhogayata & Sata, 2025). Economic feasibility was analyzed, revealing high initial costs as a major barrier for small-scale farmers, while policy challenges emphasized the need for standardized IoT security regulations. Future research should focus on AI-integrated IoT for autonomous decision-making, cybersecurity frameworks to protect critical infrastructure, and renewable energy solutions like solar-powered IoT sensors for sustainable applications (Miller et al., 2024). Also, smart rural infrastructure development must be explored to bridge the gap between urban and agricultural IoT systems, ensuring efficient, resilient, and interconnected smart infrastructure solutions.

1. **IoT TECHNOLOGIES FOR MONITORING AND AUTOMATION**
   1. **Types of IoT Sensors and Devices**

IoT sensors and devices are the foundation of intelligent infrastructure systems, facilitating real-time data acquisition and monitoring across diverse parameters in civil and agricultural engineering (**Fig.2**).

A diagram of different types of sensors

Description automatically generated

### ****Fig.2** IoT sensors and devices**

Temperature sensors are extensively utilized in civil engineering to monitor variations in structural temperature, which can impact material integrity, particularly under extreme weather conditions. In agriculture, they enhance environmental conditions for optimal crop growth. Crucial in agricultural applications, humidity sensors assess soil moisture and ambient humidity, facilitating accurate irrigation control (Ikram et al., 2024). In civil infrastructure, ambient moisture levels are monitored, as they might affect structural integrity (Vasconcelos et al., 2024a). Pressure sensors are utilized in civil infrastructure to assess stress and load on constructions such as bridges, tunnels, and skyscrapers (De Oliveira et al., 2024). These sensors provide the early detection of wear, ensuring prompt maintenance and safety. Vibration sensors (Accelerometers) are essential in civil engineering for structural health monitoring, especially in identifying displacements and vibrations in key infrastructure like bridges and buildings (Crognale et al., 2024). They notify engineers of structural instability, facilitating preventive measures.

Soil moisture Sensors are mainly utilized in agriculture to assess soil moisture content. This data is essential for precision irrigation, reducing water consumption while ensuring ideal crop conditions (Kumar et al., 2020). pH and nutrient sensors are employed in agriculture to assess soil conditions and nutrient concentrations, facilitating sustainable crop management by maintaining optimal fertilizer balance (Anjaneyulu et al., 2024; Padhiary, Kyndiah, Kumar, et al., 2024). In both domains, devices with cameras can acquire visual data for AI-based applications. In civil engineering, they facilitate structural inspections, whereas in agriculture, they aid in monitoring crop health, detecting weeds, and identifying pests (Padhiary et al., 2023; Singh et al., 2024). The implementation of IoT sensors in civil and agricultural engineering significantly enhances real-time monitoring, automation, and efficiency. Various sensor types, including temperature, humidity, pressure, and vibration sensors, play distinct roles in each sector, optimizing infrastructure resilience and agricultural productivity. **Table 1** provides a comparative analysis of IoT sensor applications across both fields, highlighting their functionality and sector-specific adaptations.

**Table 1.** IoT sensor applications in civil and agricultural engineering

|  |  |  |  |
| --- | --- | --- | --- |
| **Sensor Type** | **Application in Civil Engineering** | **Application in Agricultural Engineering** | **References** |
| **Temperature sensors** | Monitor thermal expansion and contraction in buildings | Optimize greenhouse climate for controlled crop growth | (El-Gayar et al., 2018) |
| **Humidity sensors** | Track environmental moisture affecting material integrity | Measure soil moisture for precision irrigation | (Vasconcelos et al., 2024b) |
| **Pressure sensors** | Assess stress and load on bridges and tunnels | Optimize water pressure in irrigation systems | (Bado & Casas, 2021) |
| **Vibration sensors** | Detect instability and microcracks in buildings | Monitor livestock movement and stress levels | (Hamed et al., 2023) |
| **PH & nutrient sensors** | Not commonly used in civil infrastructure | Measure soil quality for fertilizer optimization | (Saha & Bhardwaj, 2025) |
| **Air quality sensors** | Detect pollutants and environmental hazards in cities | Assess pesticide residue impact on crops | (Boonupara et al., 2023) |
| **Optical & camera sensors** | AI-driven infrastructure inspections via imaging | Detect crop health issues, pests, and nutrient deficiencies | (Verma & Kishor, 2024) |
| **Acoustic sensors** | Detect structural changes in tunnels and bridges | Monitor animal sounds for disease detection | (Yang & Zhao, 2023) |
| **GPS & geolocation sensors** | Enable smart city planning, real-time urban navigation | Track livestock and optimize field operations | (Rana & Bhambri, 2024) |
| **Multi-spectral sensors** | Analyze structural wear and tear through remote sensing | Assess crop health using remote imaging techniques | (Hayat, 2023) |

* 1. **Communication Protocols**

Efficient communication protocols are crucial for IoT devices to relay data from sensors to centralized systems or cloud storage. Various protocols facilitate data transmission in urban and rural environments:

LoRa (Long Range): Renowned for its little power consumption and extensive range, LoRa is used in rural and remote agricultural regions where cellular service may be inadequate (Aldhaheri et al., 2024). It is appropriate for conveying minimal data across extensive distances, rendering it optimal for agricultural surveillance.

Zigbee is frequently utilized in short-range, low-power Internet of Things applications, including building automation and smart city infrastructure (Alaba, 2024). In civil engineering, it facilitates communication among sensors within a confined region, such as within buildings or bridge constructions.

NB-IoT (Narrowband IoT): A low-power wide-area (LPWA) technology, NB-IoT is extensively utilized in urban and rural settings where numerous devices require internet connectivity (Routray & Mohanty, 2024). It is especially advantageous for subterranean and isolated sensors in civil and agricultural infrastructure.

5G: As a rapid protocol with minimal latency, 5G is revolutionizing IoT functionalities, particularly urban infrastructure. Its capacity to manage substantial data volumes and facilitate real-time processing is advantageous for applications such as autonomous farm machinery and urban traffic control systems (Hoque et al., 2025; Majumdar et al., 2024).

Wi-Fi and Cellular (4G, LTE) are popular protocols in IoT systems necessitating high-speed data transport. They are prevalent in smart buildings and agricultural environments with Wi-Fi connectivity, facilitating remote monitoring and control (Daousis et al., 2024).

Selecting the appropriate communication protocol is essential for ensuring dependable data transmission and connectivity in diverse environments, especially in rural regions where coverage may be constrained.

* 1. **Data Processing and Edge Computing**

The significant data produced by IoT devices requires prompt processing to gain valuable insights. Data processing unfolds through two primary methods: centralized cloud processing and edge computing.

*Centralized Cloud Processing:* In conventional IoT configurations, sensor data is transmitted to centralized cloud servers for analysis and storage (Antonius Alijoyo et al., 2024). This method is appropriate for applications where latency is not a primary concern and substantial computational resources are necessary. In civil infrastructure, extensive data from various sensors monitoring urban systems can be centrally processed for thorough analysis and planning.

*Edge Computing:* Edge computing facilitates the proximity of data processing to the sensor, enabling instantaneous data analysis and decision-making (Nalayini et al., 2024). Edge computing lowers latency and minimizes the necessity for continuous internet connectivity by processing data locally. This is particularly beneficial in rural agricultural environments where connectivity may be problematic. Edge computing devices can analyze soil conditions, weather data, or livestock health on-site, enabling immediate actions such as adjusting irrigation or alerting farmers to potential issues (Sathya et al., 2024).

In civil engineering, edge computing is advantageous for important infrastructure such as bridges and tunnels, where prompt responses to sensor data (e.g., pressure or vibration abnormalities) are essential for safety. Furthermore, edge computing optimizes bandwidth utilization and eliminates data transmission expenses, making it an economical alternative for extensive IoT networks.

1. **IOT APPLICATIONS IN CIVIL AND AGRICULTURAL ENGINEERING**

The Internet of Things is developing civil and agricultural engineering by enabling real-time monitoring, automation, and data-driven decision-making. In civil engineering, IoT is predominantly used for structural health monitoring, smart traffic management, and environmental assessment. Whereas, in agriculture, IoT applications focus on precision farming, automated irrigation, and livestock management. A comparative analysis of IoT applications in these fields highlights their shared technological foundation, while also emphasizing sector-specific adaptations and challenges. **Table 2** provides a structured comparison of these IoT applications.

**Table 2.** Comparison of IoT applications in civil and agricultural engineering

|  |  |  |  |
| --- | --- | --- | --- |
| **Aspect** | **IoT in Civil Engineering** | **IoT in Agricultural Engineering** | **References** |
| **Primary focus** | Infrastructure monitoring, urban automation | Precision farming, resource optimization | (Atalla et al., 2023; Wang & Yin, 2022) |
| **Key technologies** | Structural health sensors, smart traffic management, AI-based monitoring | Soil sensors, smart irrigation, livestock tracking, AI-driven yield prediction | (Aarif K. O. et al., 2025; Plevris & Papazafeiropoulos, 2024) |
| **Real-time monitoring** | Bridges, tunnels, and roadways for structural integrity | Soil moisture, crop health, and livestock behavior | (Farooq et al., 2022; Selvaprasanth & Malathy, 2025) |
| **Automation level** | Smart cities, automated traffic control, energy-efficient buildings | Automated irrigation, AI-driven crop management | (Apanavičienė & Shahrabani, 2023; Chithra et al., 2024) |
| **Data collection & analysis** | Sensors collect environmental and structural data, analyzed by AI | IoT devices analyze soil, weather, and crop conditions | (Chamara et al., 2022; Kapoor et al., 2024) |
| **Main benefits** | Improved safety, cost savings in maintenance, real-time data-driven decisions | Efficient water use, increased crop yield, sustainable resource management | (Chen et al., 2023; Et-taibi et al., 2024) |
| **Challenges** | High deployment cost, cybersecurity risks, integration issues | Connectivity issues, affordability for small farmers, sensor durability | (Dhanaraju et al., 2022; Mohammed et al., 2022) |
| **Energy source** | Grid-powered, renewable (solar IoT in remote areas) | Solar-powered IoT, smart irrigation with energy efficiency | (Rosabal et al., 2023; Yadav et al., 2024) |
| **Economic feasibility** | Expensive initial investment but cost-saving long-term benefits | Initial setup cost is high but leads to higher agricultural productivity | (Quy et al., 2022; Vijayan et al., 2023a) |
| **Future trends** | AI-driven predictive maintenance, blockchain for infrastructure data security | AI-driven robotic farming, digital twins for real-time farm management | (Bali & Singh, 2024; Mai et al., 2024) |

* 1. **IoT Applications in Civil Engineering**
     1. **Structural Health Monitoring**

In civil engineering, structural health monitoring (SHM) is an important use of IoT (Vijayan et al., 2023b). This means constantly checking infrastructure to find problems and fix them before they get worse. IoT-enabled structural health monitoring systems utilize diverse sensors (e.g., strain gauges, accelerometers, displacement sensors) installed onto major infrastructure components such as bridges, buildings, tunnels, and dams. These sensors record real-time data on variables including load, vibration, deformation, temperature, and stress.

*Bridges:* IoT sensors monitor dynamic loads, vibrations, and structural displacement, detecting early indicators of degradation or stress caused by traffic, weather, or seismic events (Deng et al., 2023). Data analysis systems can forecast maintenance requirements and avert disastrous failures.

*Structures:* IoT sensors monitor structural deformations, foundation stability, and material integrity (Yosefi & Nasseri, 2024). In skyscrapers, sensors quantify oscillations and other motions resulting from wind, temperature fluctuations, or adjacent construction activity.

*IoT sensors* in tunnels monitor changes, cracks, water infiltration, and other structural issues that could affect stability (Luo et al., 2024). This data facilitates preventive maintenance for avoiding collapses or hazardous events.

*IoT-based SHM* systems facilitate predictive maintenance through continuous data collection, optimizing repair schedules, prolonging structural lifespan, saving costs, and improving safety (Yosefi & Nasseri, 2024).

* + 1. **Automation in Urban Infrastructure**

The automation of urban infrastructure via IoT enhances the efficiency of municipal services and enhances the quality of life. Principal applications consist of:

*Traffic Management:* IoT-enabled traffic systems employ cameras, sensors, and interconnected cars to oversee traffic flow, dynamically regulate signals, and enhance route utilization (Aderibigbe & Gumbo, 2024a). Information from these systems aids in alleviating congestion, minimizing emissions, and enhancing road safety. Certain systems can prioritize emergency vehicles or public transportation, thereby improving overall traffic efficiency.

*Waste Management:* Intelligent garbage bins integrated with IoT sensors track fill levels and transmit data to waste management facilities, facilitating optimized collection routes and schedules (Addas et al., 2024). This decreases fuel consumption, mitigates overflow problems, and guarantees prompt waste disposal. Advanced technologies can amalgamate recycling sorting and furnish real-time data on trash patterns for resource allocation.

*Utilities Management (Water and Power)*: IoT sensors and automated controls enhance the efficiency of water and power distribution systems (García-Martín et al., 2023). Smart meters and leak detection systems in water networks provide accurate monitoring of water consumption and prompt notifications on leaks, hence promoting water conservation and timely maintenance. IoT-enabled solutions in power grids optimize load balancing, control peak demand, and mitigate power outages (Tabassum et al., 2024). Moreover, IoT improves energy management in buildings by overseeing HVAC systems, lighting, and other utilities, thereby fostering sustainable resource utilization (Dahmani, 2024).

* + 1. **Environmental Monitoring**

Environmental monitoring has become increasingly vital for urban infrastructure development and maintenance as cities seek to establish healthier, more sustainable ecosystems. IoT technologies facilitate environmental monitoring by acquiring information on air quality, noise levels, water quality, and other characteristics impacting public health and urban infrastructure (Narayana et al., 2024). Key IoT applications in environmental monitoring includes the following:

Air Quality Monitoring: IoT sensors identify contaminants like CO₂, particulate matter (PM 2.5 and PM 10), nitrogen dioxide, and sulfur dioxide (Samal et al., 2023). By monitoring air quality in real-time, municipalities may identify pollution hotspots, communicate notifications to the public, and execute targeted strategies that reduce emissions. This data also guides strategies aimed at enhancing air quality and facilitates adherence to environmental standards.

Noise Monitoring: IoT noise sensors assess sound levels in metropolitan environments, detecting elevated noise pollution from vehicular traffic, construction, or industrial operations (Govea et al., 2024). Noise data allows municipalities to implement noise regulations, design calmer urban areas, and tackle noise-related health issues for inhabitants.

Water Quality and Flood Monitoring: IoT sensors in aquatic environments and distribution systems assess parameters like pH, turbidity, temperature, and contaminant concentrations (Sugiharto et al., 2024). Sensors in rivers and drainage systems can monitor water levels, facilitating early flood alerts and mitigating disaster risks. IoT systems safeguard public health and ensure the integrity of water supplies for urban and agricultural applications by facilitating immediate responses to alterations in water quality (Ramakrishnan et al., 2024).

IoT-based environmental monitoring safeguards public health and aids in the conservation of urban and natural ecosystems. By incorporating IoT-driven environmental data, cities may develop more sustainable and resilient infrastructures that adjust to environmental changes and facilitate long-term urban development.

* 1. **IoT Applications in Agricultural Engineering**
     1. **Precision Farming and Crop Monitoring**

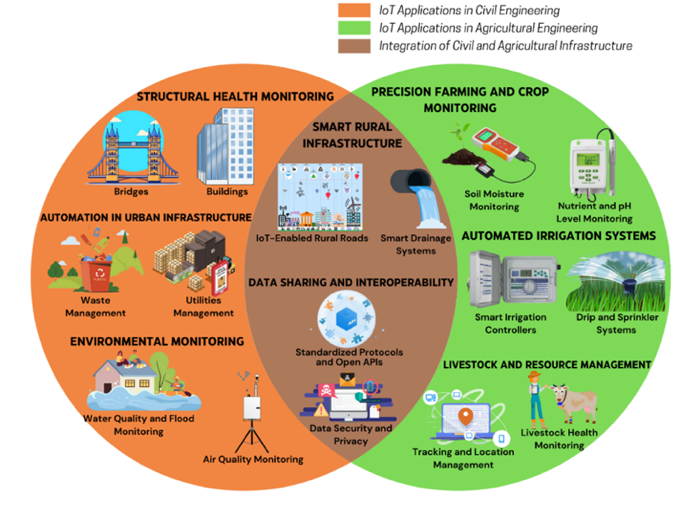
IoT-enabled precision agriculture utilizes real-time data to enhance farming techniques, increasing production, conserving resources, and minimizing environmental effects (Sharma & Shivandu, 2024). Primary uses involve soil moisture monitoring, facilitating efficient water management for farmers; nutrient and pH level monitoring, which informs accurate fertilizer delivery; and monitoring of crop health and pest activity. IoT devices, including drones and imaging sensors, identify indicators of nutrient deficits, illnesses, and insect infestations, enabling farmers to implement targeted interventions and avoid extensive crop loss (M E et al., 2024). AI evaluates these images, detecting possible problems promptly, enabling farmers to implement targeted measures and minimize extensive crop loss (Padhiary et al., 2025). Utilizing IoT sensors and imaging technology, precision agriculture improves resource efficiency, increases crop yield, and lowers expenses, eventually benefiting farmers (Hoque & Padhiary, 2024; Sahu, 2024). 3D printing technology revolutionizes the design of all-terrain vehicles, enabling more adaptable and efficient machinery for farming applications (Padhiary, Barbhuiya, Roy, et al., 2024; Padhiary & Roy, 2024).

* + 1. **Automated Irrigation Systems**

IoT-enabled irrigation systems combine real-time data from soil sensors, meteorological stations, and crop needs to automate water distribution, ensuring efficient application and flexibility in areas with constrained water resources or fluctuating weather conditions (Padmavathi et al., 2024). Intelligent irrigation controllers utilize data from these sensors to modify irrigation schedules, thereby conserving water. Weather-responsive irrigation systems employ IoT data to anticipate precipitation or drought, hence modifying water distribution accordingly. IoT-enabled drip and sprinkler systems provide water directly to the root zones of crops, optimizing efficiency while reducing evaporation and runoff (Qian et al., 2024). These systems conserve water and improve crop quality by sustaining ideal moisture levels, thus promoting sustainable agricultural practices. IoT-enabled irrigation systems are an essential component for sustainable agricultural practices.

* + 1. **Livestock and Resource Management**

IoT has improved livestock management and resource conservation by delivering real-time data on animal health, monitoring livestock locations, and enhancing energy and water efficiency. Wearable devices such as collars and ear tags monitor vital signs and activity levels, identifying early indicators of sickness or stress. GPS-enabled IoT devices monitor animal locations, enabling farmers to regulate grazing patterns, identify escapes, and deter theft. IoT sensors monitor resource utilization on farms, detecting inefficiencies and offering insights for optimization (Padhiary, Sethi, & Kumar, 2024). Pumps equipped with IoT technology modulate water distribution according to real-time requirements, thereby minimizing energy expenses and waste (Zakariazadeh et al., 2024). IoT systems regulate ventilation, lighting, and temperature in livestock facilities, ensuring optimal conditions with low energy consumption. These IoT applications enhance productivity and sustainability in agricultural engineering, improve animal care, and automate tedious tasks (**Fig.3**).



### ****Fig.3** IoT applications in civil and agricultural engineering**

1. **INTEGRATION OF CIVIL AND AGRICULTURAL INFRASTRUCTURE**
   1. **Smart Rural Infrastructure**

The application of IoT technology in rural infrastructure attempts to enhance the resilience and efficiency of communities through the combination of civil and agricultural engineering (Kalantzopoulos et al., 2024). This includes intelligent highways, drainage systems, and supply chain operations that improve accessibility and efficiency. Rural roads equipped with IoT sensors monitor road conditions, facilitating prompt maintenance and repair scheduling (Aderibigbe & Gumbo, 2024b). These systems monitor traffic, ambient conditions, and pavement status, mitigating road deterioration and enhancing transportation safety. IoT-based drainage systems regulate water flow, avert flooding, and facilitate efficient irrigation, thereby reducing flood risks during intense rainfall (Kalantzopoulos et al., 2024). IoT enhances agricultural supply chains by monitoring items from farm to market, regulating temperature in cold storage, and preventing spoilage. AI and IoT integration in smart cities enhance urban connectivity, enabling efficient infrastructure management (Padhiary, Roy, & Roy, 2024). Membrane technologies address wastewater treatment challenges in food processing, promoting sustainable industrial practices (Padhiary, 2024b). This improves logistics systems, enabling efficient and transparent food supply chains, advantageous for both farmers and consumers.

* 1. **Data Sharing and Interoperability**

Intelligent infrastructure systems involve data exchange and compatibility across civil and agricultural IoT applications. This establishes a network ecosystem that facilitates data access and utilization across multiple domains, promoting cross-sector collaboration on environmental conditions, water consumption, soil quality, and infrastructure integrity (Aithal & Aithal, 2024). Standardized protocols and open APIs are essential for smooth interoperability, enabling varied IoT systems to communicate and function as a unified entity. Safeguarding data security and privacy is crucial for the dissemination of infrastructure data since it preserves user confidentiality and decreases intrusions (Jamal et al., 2024). Encryption and access control guarantee that only authorized individuals can access essential information, particularly when civic and agricultural data is consolidated on shared platforms.

* 1. **Integrated IoT Systems**

IoT has improved civil and agricultural infrastructure, establishing intelligent rural communities that connect urban conveniences with agricultural requirements. Semi-autonomous IoT-based sprayers reduce human labor and improve the precision of spraying operations in agricultural fields (Padhiary, Tikute, Saha, et al., 2024; D. Saha et al., 2023). Smart cities are expanding into rural regions, employing IoT-enabled technology to optimize the management of energy, water, and waste. Intelligent energy grids optimize electricity distribution according to real-time demand, and integrated waste systems mitigate environmental impact. Agricultural communities are integrating IoT-driven urban infrastructure, such as automated street lighting and air quality monitoring, with precision agricultural equipment (Debnath et al., 2024). IoT sensors assess air and soil quality, enhancing urban health and agricultural efficiency. Improved transportation, storage, and processing facilities that link agricultural logistics to urban infrastructure enhance these communities (Hoang, 2024). The transformative capacity of IoT is promoting economic expansion and sustainable development in rural regions.

1. **CHALLENGES AND LIMITATIONS**
   1. **Technical Challenges**

The use of IoT in civil and agricultural infrastructure poses numerous technical obstacles. Remote regions frequently experience inadequate internet or cellular connectivity, inhibiting IoT communication. Low-power wide-area networks and satellite IoT solutions are accessible but expensive and constrained (Stanco et al., 2024). The robustness of sensors is essential for IoT devices, which encounter severe environmental conditions. Power requirements pose a barrier, as numerous electronic devices depend on stable power sources, which can be expensive in off-grid rural environments (Mulenga et al., 2023). Integration across sectors necessitates seamless data exchange and compatibility across various technologies, ensuring interoperability between distinct systems and communication protocols.

* 1. **Data Privacy and Security**

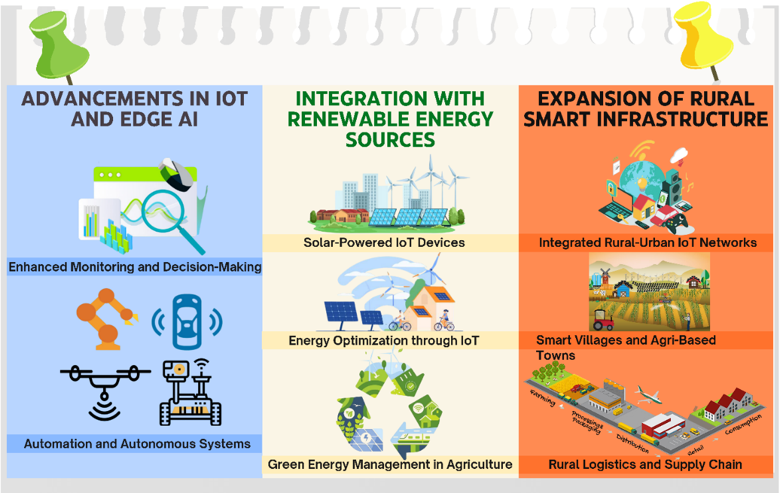
IoT networks have security vulnerabilities caused by the huge amount and sensitivity of data in civil and agricultural applications. Cyberattacks, including illegal access, data breaches, and viruses, may limit operations, compromise assets, and jeopardize public safety. Safeguarding critical agricultural and urban infrastructure data necessitates encryption, safe storage, and stringent access control. Regulatory compliance poses a hurdle since IoT systems managing sensitive data must adhere to several regional data protection standards, hence increasing complexity and costs associated with IoT adoption (Kaur et al., 2024). Compliance with privacy and data protection requirements is crucial for the effective implementation of IoT.

* 1. **Economic and Policy Constraints**

Economic and policy considerations could hamper IoT implementation in infrastructure initiatives, particularly in agriculture, owing to financial limitations (Allioui & Mourdi, 2023). Financial obstacles, including substantial initial expenses for equipment, connectivity, and maintenance, are common among small farms and rural communities. Affordable solutions are necessary for making IoT technology accessible to these areas. Supportive policies, including government grants, subsidies, and tax incentives, may speed the adoption of IoT in civil and agricultural engineering (Bhat et al., 2024). AI-driven research on biogenic nanoparticles offers new opportunities in bioinformatics and nanobiotechnology for sustainable agriculture (Padhiary, Roy, & Dey, 2024). Nevertheless, numerous locations are devoid of policies that facilitate innovation and provide financial support for IoT initiatives. Establishing a definitive return on investment (ROI) for IoT infrastructure initiatives can be difficult, particularly in the agricultural sector (Bhatia et al., 2024). Overcoming these issues is essential for realizing the complete potential of IoT in civil and agricultural infrastructure. Overcoming technical and financial challenges, ensuring robust data security, and enacting supportive regulations are vital steps for enabling widespread and lasting IoT integration across various sectors.

1. **FUTURE DIRECTIONS**
   1. **Advancements in IoT and Edge AI**

The adoption of farm automation in India showcases emerging trends and the potential for scalable innovations in agricultural practices (Padhiary, 2024c). The combination of IoT with edge AI is anticipated to transform monitoring and automation in civil and agricultural systems, especially in remote or data-intensive regions (Alaba et al., 2024). Edge AI will facilitate real-time data analysis and predictive maintenance, cutting reliance on centralized cloud processing and enhancing system resilience (**Fig.4**). It can also enhance autonomous systems in infrastructure and agriculture, such as IoT-enabled autonomous tractors or drones that optimize navigation and resource distribution, adapting to real-time soil and weather conditions. In civil engineering, edge AI may facilitate autonomous vehicles in road maintenance and environmental monitoring, hence enhancing infrastructure management efficiency and safety (Rane, 2023). Collaborative marketing strategies enhances technology to facilitate global reach while addressing local agricultural challenges (Padhiary & Roy, 2025).



### ****Fig.4** Future directions in IoT for smart infrastructure**

* 1. **Integration with Renewable Energy Sources**

The integration of IoT infrastructure with renewable energy provides sustainable solutions for power and resource management in civil and agricultural systems. Solar-powered IoT devices are increasingly being used in agriculture, reducing dependence on non-renewable energy sources (Nath et al., 2023; Padhiary, 2024a). This extends to civil infrastructure, where solar-powered sensors oversee air quality, water usage, and structural integrity, promoting energy-efficient urban and rural systems. IoT-enabled energy monitoring systems may optimize renewable energy usage in both sectors, reducing waste and promoting energy efficiency. Agricultural operations may use IoT to manage renewable energy sources like biogas and wind, supporting sustainable agriculture and reducing the carbon footprint of farming (Jumoke Agbelusi et al., 2024; Kumar et al., 2024).

* 1. **Expansion of Rural Smart Infrastructure**

AI-driven automated decision-making in farm machinery optimizes agricultural operations and resource allocation (Padhiary, Roy, Dey, et al., 2024). Enhancing intelligent infrastructure in rural regions can close the urban-rural gap and address both agricultural and urban requirements, supporting sustainable development. Future rural smart infrastructure can establish integrated networks that address both urban water requirements and agricultural irrigation using IoT-based water management systems (Okoli & Kabaso, 2024). IoT-enabled infrastructure, such as energy-efficient street lighting, automatic drainage systems, and remote healthcare services, can enhance smart villages and agriculture-focused cities. These intelligent infrastructures can enhance rural living standards and economic prospects. Furthermore, IoT solutions can enhance agricultural supply chains, facilitating the efficient transportation of products and livestock (Rajabzadeh & Fatorachian, 2023). Intelligent rural roads integrated with sensors can assess road conditions, optimize logistics routes, and minimize waste, thereby guaranteeing the prompt transportation of fresh products to urban areas.

1. **CONCLUSION**

The Internet of Things (IoT) possesses the capacity to switch civil and agricultural engineering through real-time monitoring, automation, and predictive maintenance. This technique improves efficiency and resource preservation in civil infrastructure, including structural health monitoring and urban environmental assessment. IoT facilitates precision agriculture, automated irrigation, and resource management, hence improving production and conservation in agriculture. Integrating IoT in these areas is crucial for meeting increasing demands on urban and rural systems and promoting more intelligent, data-informed management techniques. IoT technologies enhance resource efficiency and minimize waste, in accordance with sustainability objectives. IoT-enabled solutions enhance the efficient utilization of resources, reduce emissions, and promote responsible oversight of essential infrastructure. Successful implementation necessitates continuous research and supportive policies. Challenges encompass connectivity in remote regions, compatibility across various IoT systems, and enhanced sensor durability. Standardized guidelines and security frameworks are essential for protecting sensitive data. Policy support, involving incentives and funds, is essential for facilitating universal and fair access to IoT technologies. As IoT progresses, it possesses significant potential for evolving infrastructure systems, enhancing their resilience, sustainability, and adaptability to societal demands.

Disclaimer (Artificial intelligence)

Author(s) hereby declares 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.

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