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AI-POWERED SMART ENVIRONMENTAL TECHNOLOGIES AND APPLIED EXAMPLES FOR MORE LIVABLE CITIES[1]

DAHA YAŞANABİLİR ŞEHİRLER İÇİN YAPAY ZEKÂ DESTEKLİ AKILLI ÇEVRE TEKNOLOJİLERİ VE UYGULAMALI ÖRNEKLER

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ABSTRACT

This article explores the critical role of smart environmental technologies in advancing urban sustainability by addressing vital issues such as resource efficiency, pollution control, and data-driven decision-making. In this context, it highlights the necessity of integrating IoT devices, sensor networks, and advanced analytical methods to enable real-time monitoring of environmental factors such as air and water quality, noise pollution, and energy consumption. The continuous data flow resulting from this integration greatly facilitates city administrators' rapid response to ecological challenges and the optimization of resource use. The study presents compelling suggestions on how AI-powered smart IoT technologies can contribute to vital areas such as energy management, smart grids, carbon emission reduction, and the integration of renewable energy systems into cities. While acknowledging challenges related to infrastructure, data privacy, and governance, it presents the combined integration of AI, IoT, and big data analytics as a transformative force for sustainable smart cities. Furthermore, data and perspectives are examined in detail through 14 application examples. In this context, descriptive analysis and observation methods were chosen as quatitative research techniques.

ÖZ

Bu makale, kaynak verimliliği, kirlilik kontrolü ve veri odaklı karar verme gibi hayati konuları ele alarak, akıllı çevre teknolojilerinin kentsel sürdürülebilirliği geliştirmedeki kritik rolünü inceliyor. Bu bağlamda, hava ve su kalitesi, gürültü kirliliği ve enerji tüketimi gibi çevresel faktörlerin gerçek zamanlı izlenmesini sağlamak için IoT cihazlarının, sensör ağlarının ve gelişmiş analitik yöntemlerin entegrasyonunun gerekliliğini vurguluyor. Bu entegrasyondan kaynaklanan sürekli veri akışı, şehir yöneticilerinin ekolojik zorluklara hızlı yanıt vermesini ve kaynak kullanımını optimize etmesini büyük ölçüde kolaylaştırıyor. Çalışma, yapay zekâ destekli akıllı IoT teknolojilerinin enerji yönetimi, akıllı şebekeler, karbon emisyon azaltımı ve yenilenebilir enerji sistemlerinin şehirlere entegrasyonu gibi hayati alanlara nasıl katkıda bulunabileceğine dair ikna edici öneriler sunuyor. Altyapı, veri gizliliği ve yönetişimle ilgili zorlukları kabul ederken, yapay zekâ, IoT ve büyük veri analitiğinin birleşik entegrasyonunu sürdürülebilir akıllı şehirler için dönüştürücü bir güç olarak sunuyor. Ayrıca, veriler ve bakış açıları 14 uygulama örneği üzerinden ayrıntılı olarak inceleniyor. Bu bağlamda, nitel araştırma teknikleri olarak tanımlayıcı analiz ve gözlem yöntemleri seçilmiştir.

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Introduction

Smart environmental technologies are vital for promoting urban sustainability in many ways. These technologies provide significant advantages by enabling critical functions such as efficient resource use, pollution control, and data-driven decision-making. For example, a network of AI-enabled sensors, Internet of Things (IoT) devices, and advanced data analytics platforms enables continuous, real-time monitoring of key environmental indicators such as air and water quality, noise pollution, and energy use. This exceptional flow of information allows city authorities to quickly optimize resource allocation and take proactive measures to address emerging environmental challenges. Ultimately, this active, interactive exchange reduces undesirable ecological impacts, and significantly contributes to improving public health in urban areas. Energy efficiency, particularly when combined with the integration of renewable energy sources, is a cornerstone of sustainable urban development. Urban technologies such as AI-enabled meters, energy management systems, and building-integrated solar panels enable real-time monitoring and optimization of buildings' energy use. For example, smart grids improve electricity distribution by dynamically balancing supply and demand while integrating decentralized renewable energy sources like solar and wind energy into the system. This approach reduces energy waste and carbon emissions, supporting the creation of a harmonized structure. For urban health, AI-powered smart technologies leverage real-time data analytics to optimize traffic flow and emissions. This makes it possible to reduce the environmental footprint of transportation and make significant improvements toward targeted goals. Smart transportation systems continuously collect and analyze traffic data, reducing idle time needed for cities to manage vehicle movements more efficiently. This allows decision-makers to promote greener transportation alternatives by implementing smart infrastructure such as home charging stations, adaptive traffic lights, and integrated mobility apps. For example, Copenhagen's cycling focus, supported by smart city innovations, has significantly reduced reliance on fossil fuels and helped improve air quality. Furthermore, smart technologies significantly improve urban water management by providing vital data such as early leak detection, detailed consumption monitoring, and efficient irrigation control. The use of smart water meters and sensor networks provides precise data on water usage, allowing for the timely identification and repair of leaks. Naturally, this process helps protect vital freshwater resources. Furthermore, advanced systems designed for rainwater harvesting and graywater recycling, when integrated with IoT devices, take water efficiency in cities to the next level. As the current trend of rapid and uncontrolled urbanization and climate change intensifies, these innovative solutions become increasingly important (Khalil et al., 2021; Telsaç & Atmaca, 2022; Telsaç & Kandeğer, 2022).

The integration of artificial intelligence, the Internet of Things, and big data analytics demonstrates the feasibility of environmentally sustainable smart cities. These technologies facilitate predictive modeling, automated system controls, and comprehensive monitoring of environmental conditions, contributing to the achievement of the Sustainable Development Goals. Despite all these benefits, the proliferation and use of these digital solutions also raise infrastructure, data privacy, and ethical concerns. Therefore, it is essential to develop balanced policies that maximize the benefits of these technologies while mitigating potential risks. Overall, smart environmental technologies hold great promise for building resilient, efficient, and livable future urban ecosystems. This study utilizes qualitative descriptive analysis and observational methods in addition to a study of 14 cities to understand the ongoing development of sustainable smart cities.

While existing literature extensively discusses smart city technologies within isolated sectors or at a purely theoretical level, there is a notable research gap in studies that holistically examine the integrated impact of AI and IoT across the core pillars of urban sustainability—energy, transportation, water, waste, and air quality—through diverse practical applications. This study aims to systematically demonstrate this overlooked multi-dimensional integration in the smart city literature by utilizing qualitative descriptive and observational methods to analyze 14 diverse global application examples. Within this framework, the research specifically investigates how AI-powered systems optimize resource management, identifies common success factors across different urban fabrics, and evaluates the extent to which these technologies contribute to the achievement of Sustainable Development Goals (SDGs) in modern urban ecosystems. By bridging the gap between theoretical frameworks and real-world implementations, this study provides an analytical roadmap for the development of more resilient and livable future cities.

Methodology

This study employs a qualitative descriptive case-based synthesis to investigate the transformative role of AI-powered environmental technologies in urban settings. A qualitative approach was specifically chosen because the phenomenon of "smart city integration" is not merely a quantitative increase in efficiency, but a complex socio-technical process requiring deep contextual understanding. As Creswell and Creswell (2017) emphasize, qualitative designs excel at exploring "how" and "why" specific technologies succeed in diverse governance structures, allowing for nuanced interpretation that purely quantitative metrics might overlook.

Research Design

The research adopts a qualitative descriptive design to systematically profile the current state of smart city technologies and provide evidence-based predictions. This design acts as a methodological bridge, allowing researchers to synthesize heterogeneous data from global applications into a coherent analytical framework (Lawless & Heymann, 2010). By focusing on descriptive synthesis, the study goes beyond simple reporting and provides a critical assessment of how AI-driven platforms interact with existing urban infrastructures to produce sustainable outcomes (Kemp et al., 2018; Sidel et al., 2018).

Data Collection and Case Selection

The dataset was derived from two complementary sources: a comprehensive literature review (Rother, 2007; Snyder, 2019) and a multiple case study analysis of 14 global cities. The selection of these 14 specific cities, including Copenhagen, Singapore, Barcelona, Sejong, and Melbourne is based on a purposeful sampling strategy governed by three inclusion criteria. Accordingly, (i) the presence of an integrated AI-driven environmental management policy, (ii) measurable success in at least three of the five key elements (energy, water, waste, etc.), and (iii) geographic and economic diversity to ensure global representation are highlighted. Cities implementing only isolated or pilot-scale projects were excluded to maintain a focus on "system-wide" integration. This rigorous selection process ensures that the cases provide high-quality, scalable evidence for the purposes of the study.

Data Analysis and Coding Process

To ensure methodological transparency, data analysis followed a structured three-step process. First, raw data from 14 cases were subjected to initial coding, where specific technological interventions (e.g., smart sensors, artificial intelligence algorithms) were identified and cataloged. Second, through pattern matching and axial coding, these interventions were grouped into thematic clusters according to their operational functions. Finally, a thematic analysis was performed to reduce these clusters to five main analytical pillars: energy efficiency, smart transportation, water management, waste management, and air quality (Krippendorff, 2018; Okoli, 2015). This systematic coding process ensures that the transition from raw case data to final results is traceable, objective, and logically consistent.

Validity and Reliability

The internal validity of the study was ensured through data triangulation by cross-referencing the theoretical literature with the observed results of the 14 case studies (Cypress, 2017). Reliability was ensured by maintaining a transparent "audit trail" of the coding process and using standardized qualitative frameworks (Rose and Johnson, 2020). By justifying the case selection criteria and detailing the analytical steps, the study minimizes researcher bias and provides a replicable methodology for future smart city research. (Golafshani, 2003; Franklin & Ballan, 2001; Kirk & Miller, 1986).

Smart Environmental Technologies

Smart environmental technologies play a crucial role in the development of sustainable cities by enabling more efficient use of resources, improved pollution control, and informed decision-making. These technologies utilize advanced data analytics to continuously monitor key environmental parameters such as air and water quality, noise pollution, and energy consumption, leveraging key tools such as smart sensors and IoT devices. This real-time data collection allows city managers to timely detect pollution, optimize resource allocation, and proactively respond to emerging environmental challenges (Bakker & Ritts, 2018; Vermesan & Friess, 2013).

One of the key benefits of smart environmental technologies is the ability to optimize resource management across urban systems. For example, smart energy systems integrate renewable energy sources such as solar and wind into urban power grids, efficiently distributing electricity based on real-time demand. This optimization significantly reduces energy loss and carbon emissions. Similarly, smart water management systems use smart sensors to detect leaks and optimize irrigation processes. This significantly saves water resources and prevents unnecessary waste. Another benefit is in terms of waste management. Smart containers equipped with sensors that notify waste collection services when waste is full significantly reduce unnecessary collections and emissions from garbage trucks. All these technologies together contribute to the more sustainable use of urban resources and help cities reduce their environmental impact (Trevathan & Johnstone, 2018). In addition to optimizing resources, smart environmental technologies also enhance, providing detailed monitoring of air and water quality. Sensors installed in urban areas monitor pollutants such as nitrogen dioxide, sulfur dioxide, carbon oxide, and solid particles, allowing city administrators to monitor pollution sources and take early action. Water quality sensors, on the other hand, monitor parameters such as pH, turbidity, and dissolved oxygen, helping to maintain safe drinking water and manage industrial discharges. Another important aspect is monitoring noise pollution. Smart sensors are crucial for regulating noise-related problems and advancing urban design in this direction. This allows cities to support healthier ecosystems and improve the quality of life of their residents (Demiris & Hensel, 2008).

The urban integration of optimal environmental technologies also strengthens vital life solutions through data focused on prognostic analysis. While urban problems have not yet become chronic, these platforms can identify current trends, anomalies, and potential risks, and develop appropriate solutions. Furthermore, prognostic models associated with artificial intelligence can assess fluctuations or increasing energy demand and monitor cities' energy or pollution levels, enabling autonomous adjustments and preventative actions. Such a proactive approach increases urban resilience and enables more dynamic use of environmental resources (Lamnatou et al., 2022; Nguyen et al., 2025).

Smart environmental technologies are an integral part of a broad vision of sustainable urban development. For example, cities like Copenhagen and Singapore have implemented smart grids, renewable energy, green infrastructure, and smart IoT sensors are good examples of how ambitious sustainability goals like improving urban biodiversity can be achieved. These examples demonstrate that technology not only increases efficiency but also supports the climate, healthcare, and social security. As urban populations continue to grow, the pressures on the environment necessitate the widespread adoption of smart environmental technologies. On the other hand, there seems to be no other alternative to leave a sustainable and livable urban legacy to future generations (Parmentola et al., 2022; Shrivastava, 2018).

Energy Efficiency

The efficiency and integration of renewable energy sources are the cornerstones of sustainable urban stability, transforming how cities consume and manage energy. Technologies such as smart meters, AI-powered energy management systems, and Building-Integrated Photovoltaic (BIPV) panels enable structures to continuously monitor and dynamically optimize their energy footprint. These meters provide detailed, real-time electricity usage data, which AI algorithms analyse to identify inefficiencies and automate adjustments to HVAC and lighting systems based on occupancy and weather conditions. Such integration not only reduces operational costs and carbon emissions but also transforms residents from passive consumers into active participants in energy ecosystems, directly improving urban health (Yilmaz & Telaç, 2021a; Wang et al., 2021).

Smart grids serve as the critical enabler of this transformation by facilitating the distribution of decentralized renewable energy, such as solar and wind, while balancing supply and demand. Unlike traditional electrical grids, smart grids utilize advanced sensors, two-way digital communication, and data analytics to monitor energy flows in real time. This capability allows for the automatic redistribution of excess energy, predictive infrastructure maintenance, and rapid response to fluctuations in renewable production. By adapting to the intermittent nature of renewables, smart grids significantly increase grid reliability and resilience, reducing the historical reliance on fossil fuels and aligning with urban sustainability goals (Casini, 2016; Pieroni et al., 2018).

BIPV systems further enhance this framework by integrating solar generation directly into the building's physical envelope. These systems convert sunlight into on-site electricity, minimizing energy transmission losses. When combined with IoT-enabled monitoring and AI-powered optimization, this integration maximizes production and ensures seamless interaction with smart grids. Furthermore, AI algorithms can predict solar output based on weather forecasts to adjust energy storage or consumption accordingly, significantly improving system resilience (Metallidou et al., 2020). Beyond production, these technologies offer powerful forecasting outputs that optimize consumption patterns by identifying anomalies and autonomously implementing energy-saving measures. This process includes scheduling operations during off-peak hours and managing energy storage systems to balance loads, which increases efficiency while directly enhancing user comfort and ensuring efficient demand response management (Benavente-Peces, 2019).

From a future perspective, the integration of advanced Technologies, such as blockchain and machine learning, will further advance urban energy sustainability. Blockchain can secure and automate energy transactions through smart contracts, enabling more transparent and efficient purchasing. Simultaneously, machine learning improves the accuracy of demand forecasting and fault detection. Such integration enables scalable, decentralized energy ecosystems that empower consumers, reduce emissions, and promote economic benefits. This synergy between renewable generation and smart management reduces carbon footprints and contributes to the goal of self-sufficient, ecologically conscious urban communities (Dincer & Acar, 2017; Orecchini et al., 2019; Stuit et al., 2022).

Smart Transportation

Smart transportation technologies promote sustainable mobility by revolutionizing traditional traffic management through dynamic control systems. Utilizing real-time data analytics harvested from an extensive network of sensors, cameras, and GPS devices, these systems monitor urban movement to mitigate congestion and vehicle idling, two primary drivers of elevated carbon emissions. By integrating multifaceted data sources, including high-precision weather analysis, special event logistics, and construction schedules, urban data platforms can accurately predict traffic patterns. This predictive capability allows for the optimization of signal timings, which simultaneously improves overall traffic efficiency and significantly reduces localized pollution levels (Oladimeji et al., 2023).

Beyond operational management, smart infrastructure actively incentivizes sustainable modes of transport such as electric vehicles (EVs), public transit, cycling, and walking. The deployment of adaptive traffic signals, home-based EV charging stations, and integrated mobility-as-a-service (MaaS) applications enhances both safety and accessibility. For instance, innovations like contactless fare payments and on-demand shuttle services lower the barriers to public transit usage, naturally encouraging a shift away from private fossil-fuel vehicles. Furthermore, the emergence of autonomous and connected vehicles promises to streamline traffic flow by eliminating unnecessary stops, a transformation already yielding air quality improvements in cities like Singapore through comprehensive smart initiatives (Balasubramaniam et al., 2017; Telsaç ve Arı, 2025).

Copenhagen serves as a global benchmark for the practical application of these solutions, demonstrating how urban mobility can be harmonized with environmental health. The city has made substantial investments in Intelligent Transportation Systems (ITS), notably installing smart traffic signals at 380 intersections to optimize the flow of bicycles and buses in real time. This intervention has reduced car and truck idling while decreasing travel times for cyclists by 10%, and bus commuters by up to 20%. Supported by a municipal fleet transitioning toward all-electric and hydrogen power, Copenhagen aims for 75% of all trips to be made via bicycle, public transit, or walking by the end of 2025 (Petrea & Ursache, 2023).

The city's strategy leverages smart technology to enhance the cycling experience, utilizing real-time message boards and adaptive signalling to prioritize non-motorized transport. These efforts have culminated in one of the world's highest bicycle modal shares, with bikes accounting for approximately 45% of daily commutes. By combining massive metro expansions with decisive, transparent governance, Copenhagen has secured its position as the second cleanest city in Europe regarding air quality (Telsaç & Telsaç, 2022; Wolniak, 2023). Ultimately, the Copenhagen model illustrates that the synergy between technological adoption and strong policy commitment is essential for creating resilient, low-carbon urban mobility ecosystems as global climate challenges intensify (Makarova et al., 2017).

Water Management

In today's urbanization landscape, the adoption of smart water technologies is an unavoidable necessity in many respects. Especially in many older cities, aging infrastructure, rapidly growing populations, and challenges such as climate variability are increasing the use of smart water technologies. Accordingly, the global smart water management market is projected to reach approximately $40 billion by 2031, growing at a CAGR of 12.5% (Palermo et al., 2022; Yılmaz & Telsaç, 2021b).

Smart water management technologies greatly facilitate many important functions, such as precisely detecting leaks, closely monitoring consumption, and optimizing irrigation systems. All of these smart applications have the potential to revolutionize urban water management and the protection of freshwater resources. For example, smart water meters and sensor networks embedded in water distribution systems collect real-time data on flow rates, pressure, and usage patterns. This detailed information allows utilities to quickly detect and repair leaks, significantly reducing water loss, a significant problem in many cities. These technologies protect freshwater and reduce costs by improving the reliability and efficiency of urban water networks by ensuring timely maintenance and operational adjustments (Gupta et al., 2020). Furthermore, in addition to leak detection, smart water management systems also help increase water efficiency through advanced irrigation control and the integration of alternative water sources. IoT-enabled smart irrigation systems monitor soil moisture, weather conditions, and plant water needs to ensure precise irrigation. This prevents over-irrigation and helps conserve water in urban green spaces. In addition, integrated rainwater harvesting and graywater recycling systems, which provide sensors and automated controls, enable the capture, treatment, and reuse of non-potable water (Aivazidou et al., 2021).

Another crucial function of smart water management systems is that they significantly contribute to urban resilience by enabling disaster preparedness and data-driven decision-making. In this regard, real-time monitoring and predictive analytics enable cities to predict and respond accurately to extreme weather events such as floods or droughts, significantly reducing infrastructure damage and supply disruptions. Automated controls optimize pumping schedules and pressure management to reduce energy consumption, minimizing the environmental footprint of water utilities. Furthermore, city residents can benefit from personalized consumption data and alerts through user platforms. It, which encourages optimal community participation in water conservation by involving the public in the process. Therefore, when all these capabilities come together, smart water management becomes sustainable in the face of growing environmental and demographic pressures (Agarwal et al., 2022).

Some cities provide excellent examples of the successful implementation of smart water management. For example, Barcelona has achieved a 25% reduction in water losses by using an extensive sensor network to monitor consumption and detect leaks. Similarly, Singapore's "Smart Water Grid" combines sensors and advanced analytics that reduce water loss by 15% while ensuring high water quality and supply reliability. Melbourne's smart water initiatives achieved a 30% reduction in overall water consumption within the first year by using predictive analytics to forecast demand and guide conservation efforts. All these examples demonstrate that smart water systems not only conserve resources but also deliver significant financial savings. Improving service reliability, a key parameter, is also among the positive outcomes (Owen, 2018). These innovations reduce the demand for municipal freshwater resources and support circular water use models, which are increasingly important in cities facing urbanization, climate change, and water scarcity (Aivazidou et al., 2021).

Waste Management

Smart Waste Management means using advanced technologies, particularly IoT devices, sensors, and data analytics, to optimally organize the collection, processing, and disposal of urban waste in a way that supports environmental sustainability, resource efficiency, and improved quality of life for city residents (Ali et al., 2020). Smart waste management systems use real-time tracking via sensors installed in waste bins to monitor fill levels, providing dynamic and optimized waste collection routes instead of rigid schedules. This type of optimization reduces unnecessary collections, lowers operational costs, and minimizes environmental impacts such as carbon emissions from waste transportation (Sosunova & Porras, 2022; Baydaş et al., 2020).

This allows cities to collect and analyze waste data, better plan resource allocation, and significantly increase recycling efforts. Consequently, the wheels of a circular economy and sustainability become more viable. Furthermore, these smart technologies reduce resource consumption and waste sent to landfills, thus aligning with Sustainable Development Goals (SDGs) 11 (Sustainable Cities and Communities), 12 (Responsible Production and Consumption), & 13 (Climate Action) (Fang et al., 2020).

Another crucial aspect is that smart waste management minimizes the number of waste collection vehicles on the roads, thereby reducing traffic congestion, noise pollution, and greenhouse gas emissions. Furthermore, this cycle improves urban cleanliness and hygiene, directly improving the health and quality of life of city residents. Essentially, in an ideal management, waste is treated as a dynamic element of the urban economy, and data-driven outputs positively influence broader urban planning decisions. This integration significantly contributes to making cities more resilient and adaptable to the challenges posed by rapid urbanization and climate change. For example, cities like Sejong, South Korea, demonstrate how smart systems can efficiently serve large populations by implementing waste management without truck traffic thanks to underground pneumatic pipes and sensor-monitored waste inlets. In all respects, smart waste management represents a system that is far more efficient, adaptable, and environmentally friendly than traditional waste processing. Digital technologies utilizing the IoT are a critical component of sustainable urbanization, reducing waste-related environmental impacts while promoting recycling and resource conservation (Anagnostopoulos et al., 2017; Esmaeilian et al., 2018).

Air Management

In smart cities, applications such as air quality monitoring and pollution control, aimed at cleaner air, aim to obtain highly accurate data by deploying advanced sensor networks and IoT-enabled devices to continuously monitor and analyze air pollution levels. This approach significantly supports sustainable urban development by enabling instantaneous data-driven interventions to reduce harmful emissions and protect public health. In this regard, cities use a distributed network of compact, accurate air quality sensors to measure pollutants such as particulate matter (PM), nitrogen oxides (NO, NO2), sulfur dioxide (SO2), carbon monoxide (CO), and ozone (O3). These sensors provide real-time data on air quality at hyperlocal levels, including pollution hotspots such as traffic congestion and industrial zones. IoT technologies enable the creation of big data, where data is collected, visualized, and analyzed through sensors. The collected data connects directly to central platforms, and the resulting integration enables predictive analytics to predict pollution trends and support decision-making for urban planning, traffic management, and environmental regulation (Kaginalkar et al., 2022; Shrimal, 2024).

By identifying urban air pollution hotspots, cities can implement targeted control measures such as optimizing traffic flows, regulating industrial emissions, and promoting cleaner energy sources. This localized focus increases the effectiveness of pollution reduction efforts and helps protect vulnerable populations. Furthermore, the deployment of mobile air quality monitors on municipal vehicles (buses, garbage trucks, taxis), in addition to fixed monitoring stations, expands control coverage, and representative data can be easily obtained in different city areas, including those difficult to monitor with stationary devices. Continuous air quality monitoring, in many ways, provides city officials with the opportunity to issue ideal health warnings, raise public awareness, and implement environmental policies. This proactive management significantly improves respiratory health and overall urban livability by reducing city exposure to harmful pollutants (Castanho et al., 2025; Maguluri et al., 2023). Accordingly, smart air management can provide the following significant benefits:

- Enables data-driven urban infrastructure planning to minimize pollution exposure both within and around sensitive areas such as schools and hospitals.
- Supports compliance with environmental standards and international guidelines.
- Significantly facilitates integration with other smart city systems for holistic environmental management.
- Makes significant contributions to cities' sustainability goals by reducing emissions and improving air quality.

As mentioned above, continuous smart air quality monitoring and pollution control utilize IoT-enabled sensor networks and advanced data analytics to provide localized pollution data. This allows cities to implement sensitive, effective interventions that improve public health, protect the environment, and support sustainable urban growth.

Forest Management

The ever-increasing frequency of forest fires is one of the most unpleasant outcomes of our new climate era. For rapid and effective forest fire response, IoT sensors placed in sensitive forest areas detect early signs of forest fires or environmental threats, enabling rapid intervention to protect ecosystems and urban populations. Smart sensor systems placed in critical areas measure parameters such as temperature, carbon dioxide, smoke, humidity, wind speed, and direction to identify fire risks before they spread. For example, smart forest capsules (sensors) equipped with GPS, CO_2, temperature, and smoke sensors communicate with each other and send real-time data to control centers, alerting authorities. This allows authorities to pinpoint the exact source of the fire and ensure prompt response (Barmpoutis et al., 2020).

Advanced systems utilize smart technologies with low power consumption, providing critical environmental data for early fire detection and effective firefighting coordination. Cutting-edge solutions even enable ultra-early warnings by integrating AI-powered gas classification and satellite communications to distinguish fire smoke from other emissions. This capability significantly reduces false alarms for fire response and dispatch. These sensors are mounted on trees and transmit necessary data to a command center via geostationary satellites to enable immediate action. IoT-based wildfire detection systems play a vital role in protecting natural ecosystems and nearby urban communities from devastating fires and environmental hazards by providing continuous environmental monitoring, early hazard detection, and faster emergency response (Nitoslawski et al., 2019; Uçar et al., 2020).

Soil Management

IoT devices, such as soil moisture sensors, significantly support sustainable food production and resource efficiency by helping optimize water and nutrient use in urban agriculture. These technologies provide real-time monitoring of soil conditions, allowing farmers and urban gardeners to apply water and fertilizer precisely where and when needed, minimizing waste and environmental impacts. These systems can even automatically adjust irrigation schedules based on weather forecasts, soil moisture levels, and crop requirements by integrating data from multiple sensors. It not only conserves water, a critical resource, but also allows for increased crop yield and quality by preventing over- or under-irrigation, and this directly supports the envisioned IoT-enabled precision agriculture practices and local food production. Furthermore, smart technologies make it possible to reduce transportation emissions and improve food security. Efficiently managing inputs in many ways and minimizing runoff that can pollute urban waterways makes sustainable urban ecosystems possible (Alqadad et al., 2017; Chen et al., 2022).

Practical Examples

In an era of rapidly increasing global urbanization, growing populations, and accelerating environmental degradation, sustainable city management has become a critical priority. Smart environmental technologies have emerged as powerful tools to address these challenges by enabling cities to monitor, manage, and optimize their natural and built environments in real time. Leveraging a multifaceted combination of IoT sensors, advanced data analytics, AI, and automated systems, these technologies have made resource efficiency, pollution control, and informed decision-making more effective and streamlined. In this respect, cities that integrate digital infrastructure with operational systems, and citizen engagement can reduce their ecological footprint, improve public health, enhance overall livability, and enhance urban resilience.

Singapore: Integrated Air Quality, Environmental Monitoring and Urban Precision Agriculture with IoT

Despite its limited land area, Singapore, a highly developed city-state for our time, has invested heavily in urban precision agriculture using IoT and smart environmental technologies. Singapore has developed a comprehensive smart environmental monitoring network that continuously monitors air quality, noise pollution, and energy consumption throughout the city using digital infrastructure. For example, it has deployed hundreds of air sensors across the city to monitor pollutants such as PM2.5, nitrogen dioxide (NO2), ozone (O_3), and carbon monoxide (CO). Data from the sensors is collected and analyzed in real time, allowing authorities to detect pollution spikes and quickly identify their sources. This allows the city government to implement targeted interventions, such as traffic restrictions, industrial emission controls, or public warnings to reduce exposure, when high pollution levels are detected. The city provides real-time air quality information to the public through mobile apps and websites, helping residents make informed decisions about outdoor activities. IoT-enabled noise sensors measure urban noise pollution, enabling the implementation of regulations and the design of quieter urban spaces. Smart meters in residential and commercial buildings monitor electricity usage, enabling demand management and energy conservation programs. (Aflaki et al., 2017; Molina et al., 2019; Shamsuzzoha et al., 2021). Moreover, sensors continuously monitor soil moisture, nutrient levels, temperature, and humidity in vertical farms and rooftop gardens, collecting and sharing data with the central government. Data-driven systems optimize water and nutrient distribution, reducing waste and increasing crop yields. Smart lighting and climate control systems reduce energy consumption in controlled-environment agriculture, resulting in savings. Urban agriculture significantly contributes to local food production by reducing import dependency and the associated carbon footprint. All of these technologies promote green spaces and sustainable food systems, making Singapore's "City in a Garden" vision a reality rather than a fantasy. It is also worth noting that Singapore's precision agriculture initiatives are a very promising example of how smart technologies can enable sustainable urban food production, even in dense metropolitan areas (Musa & Basir, 2021).

Melbourne, Australia: Smart Public Lighting Systems and Urban Green Space Monitoring

Melbourne has successfully implemented smart street lighting systems using IoT sensors and adaptive controls to improve energy efficiency and urban safety. Street lighting reduces energy consumption during off-peak hours by adjusting brightness based on pedestrian and vehicle presence, resulting in significant savings. Furthermore, sensors detect faults and outages, enabling rapid repairs and minimizing downtime. Lighting systems can adapt to weather conditions such as fog or rain, significantly contributing to urban safety. These energy savings contribute significantly to Melbourne's climate action goals in many ways. Well-lit streets with adaptive lighting improve safety and minimize light pollution. Melbourne's smart lighting system is a prime example of how urban infrastructure can be optimized through technology to achieve a balance between sustainability and quality of life (Alvarez et al., 2022; Irajifar et al., 2022). Furthermore, Melbourne is using smart environmental sensors to monitor soil moisture, temperature, and air quality in urban parks and green spaces. These sensors enable precise irrigation schedules, helping to maintain water and healthy vegetation. By measuring pollutants and particulate matter, these sensors significantly contribute to managing urban air quality. This data supports habitat management for urban wildlife, and public displays raise significant awareness about the health and sustainability of green spaces. Healthy urban vegetation reduces heat island effects, increasing city resilience. The integration of environmental monitoring tools into Melbourne's green spaces demonstrates the significant role smart technologies can play in improving urban ecosystems (Ababneh, 2023; Prebble et al., 2021).

Tokyo, Japan: Smart Water Management Systems and Smart Noise Pollution Management

The City of Tokyo is implementing advanced IoT-enabled water management systems to ensure efficient and sustainable water use. Sensors monitor pressure fluctuations and leaks in pipelines, enabling rapid intervention to minimize water loss. Continuous monitoring significantly improves water safety and compliance with health standards, while data analysis optimizes flow and pressure, enabling reduced energy consumption in pumping and treatment. The system strengthens emergency management by reporting the precise status of water infrastructure during earthquakes and floods. Furthermore, reducing water waste and energy consumption significantly contributes to Tokyo's achievement of its environmental goals (Ales, 2019; Mishra, 2019). Moreover, Tokyo is implementing IoT-based noise monitoring systems to combat urban noise pollution, a significant problem in densely populated areas, in another meaningful effort. Sensors throughout the city continuously measure sound levels and share the resulting data with authorities. This data is then used by the city government to create noise maps and alerts for the public. The system is making a difference in enforcing noise standards, particularly in nightlife and construction areas. Noise data provides valuable information for the design of quieter zones and noise barriers. For a modern city, managing noise pollution improves sleep quality and reduces stress-related health problems. Tokyo's smart noise and smart water management system is a good example of how technology can mitigate less visible but impactful urban environmental problems in various areas (Jabłońska, 2020; Sokołowski & Shimpo, 2025).

Barcelona, Spain: Smart Waste Management with IoT Sensors

Barcelona has taken a significant step forward by adopting smart environmental technologies as part of its broader smart city initiative. The city uses ultrasonic sensors installed in public waste bins to monitor bin fill levels and waste types in real time. These sensors transmit data wirelessly to a central waste management platform. Unlike traditional fixed-route waste collection, Barcelona's system enables dynamic route planning based on actual bin fill levels. This significant contribution reduces the number of collection trips, saving fuel and significantly reducing greenhouse gas emissions from waste trucks. Real-time monitoring prevents bins from overflowing, improving urban cleanliness and significantly reducing garbage-related pollution. The system is so efficient that some sensors can even distinguish between waste types, helping to optimize recycling efforts, and further reduce pollution. Thanks to these efforts, the city government collects waste only when necessary, significantly reducing associated operational costs and energy consumption (Bibri & Krogstie, 2020; Kordonets & Komissarova, 2020).

Copenhagen, Denmark: Smart Traffic Management to Reduce Pollution

Copenhagen has implemented a smart traffic management system using real-time data from sensors and cameras to optimize traffic flow and reduce vehicle emissions. Traffic lights are adjusted in real time based on congestion levels, significantly reducing idling times and stop-and-go traffic. Smoother traffic flow reduces fuel consumption and air pollution, significantly contributing to Copenhagen's goal of achieving carbon neutrality by 2025. The system collects crucial data that informs long-term infrastructure investments and policies to promote sustainable transportation. Improved air quality translates to cleaner air and easier breathing for residents. Ultimately, these initiatives in Copenhagen serve as a prime example of how smart environmental technologies can address urban pollution issues beyond waste management and integrate traffic emission controls into sustainability strategies (Petrea & Ursache, 2023; Wolniak, 2023).

Amsterdam, Netherlands: Smart Energy Grids and Demand Response

Amsterdam is a leader in implementing smart energy grids that integrate renewable energy sources, IoT sensors, and advanced analytics to optimize energy consumption and distribution. Smart meters and sensors installed in homes and businesses provide detailed data on energy usage patterns. The grid can automatically adjust energy consumption during peak hours by signalling smart devices and industrial equipment to reduce or shift usage, balancing supply and demand. The system efficiently manages solar and wind energy inputs to maximize their use and reduce reliance on fossil fuels. Batteries and other storage technologies are coordinated to store excess renewable energy and release it when needed. Residents receive feedback and incentives to reduce energy consumption by fostering a culture of sustainability. The implementation of smart energy grids in Amsterdam, which optimizes energy consumption and distribution, is a key highlight. The system provides detailed data on energy consumption patterns through smart meters and sensors installed in homes and businesses. Using this data, the system can automatically adjust energy consumption during peak hours and balance supply and demand by signalling smart devices and industrial equipment to reduce or shift consumption. It even reduces reliance on fossil fuels and optimizes energy use by efficiently managing the use of solar and wind energy. Residents receive feedback and incentives to reduce energy consumption, fostering a culture of sustainability. Amsterdam's smart energy grid is a compelling example of how digital infrastructure can transform urban energy systems into resilient, efficient, and lower-carbon networks. It also stands out as a valuable example of the applicability of urban public participation, even in energy matters (Noori et al., 2025; Mancebo, 2020).

Helsinki, Finland: Envac Pneumatic Waste Collection System

Helsinki has implemented one of the world's most modern underground pneumatic waste collection systems, known as Envac. This system utilizes a modern network of underground pipes to transport final waste and recyclables directly from collection points to a central processing facility. By eliminating the need for street-level garbage trucks, the system significantly reduces traffic congestion, noise, and air pollution in urban areas. Waste is transported quickly and hygienically using pneumatic pipes, minimizing the risk of contamination from spills. Underground collection points free up valuable urban space otherwise occupied by bulky waste containers. The system significantly improves the quality of public spaces by reducing street-level litter and unpleasant odors. The pneumatic conveying system used in the city is energy-efficient and largely powered by renewable energy. The Helsinki Envac system stands as a valuable example of how integrating smart infrastructure with environmental technology can lead to cleaner and more efficient urban waste management. Because it is an extremely valuable reflection that should not be ignored in terms of urban infrastructure design and architecture (Farré Cabanillas et al., 2023).

Songdo, South Korea: Underground Pneumatic Waste Collection

Songdo is a smart city specifically designed to integrate an underground pneumatic waste collection system into the core of its environmental infrastructure. Waste is transported to a central treatment facility via underground pipes, significantly reducing traffic, noise, and air pollution. This system minimizes human contact with waste, thus minimizing health risks and odors. By removing traditional trash cans from the streets, Songdo aims to maximize usable urban space for pedestrians and green spaces. The waste management system integrates with other IoT-based city services, enabling comprehensive environmental monitoring and management. Songdo's innovative approach to infrastructure is a good example of how smart environmental technologies can be integrated into urban planning through design and create a livable city (Baek, 2015; Mullins, 2017).

Nambucca Shire Council, Australia: Bigbelly Solar-Powered Smart Bins

Nambucca Shire Council has implemented smart recycling and waste bins (Bigbelly), which combine solar-powered compression technology with IoT sensors to optimize waste collection. The bins automatically compress waste, increasing capacity by up to 700%, and thus maintaining optimal collection frequency. Sensors transmit fill level data to waste management teams, ensuring that bins are only collected when they are nearly full. Less frequent collection significantly improves fuel consumption, labor costs, and vehicle emissions. The bins also provide free public Wi-Fi, further enhancing resident engagement and digital connectivity. The system supports cleaner streets, reduces litter, and significantly reduces the council's carbon footprint. This initiative demonstrates the importance of designing smart technologies with sustainability goals and the benefits they can deliver, from operational efficiency to improved community services (Schwarz-Herion, 2019).

Smart trash cans are also being implemented in many cities including London, New York, Singapore, San Francisco, Amsterdam, Atlanta, Barcelona, San Diego, and Vancouver. Smart trash cans are becoming an increasingly integral part of modern smart city environmental policies. Harnessing the power of environmental science and technology, these applications not only simplify waste disposal, but also significantly help cities reduce carbon emissions and increase operational efficiency (bigbelly.com/news).

New York City, USA: Automated Waste Collection and Data-Driven Optimization

New York City stands out as a modern city implementing various smart waste management technologies to have achieved its goal of achieving zero waste by 2030. In terms of waste management, trucks automate the loading process, helping to increase collection efficiency and safety. This practice helps reduce both collection times and labor costs. The system uses GPS and fill-level sensors to optimize waste collection routes to minimize fuel consumption and emissions. Data analytics help determine the optimal placement and size of waste containers based on neighborhood waste production patterns. This data helps educate residents about recycling and waste reduction, improving individual participation rates. Furthermore, the practice reduces greenhouse gas emissions from waste collection vehicles and enables waste diversion from landfills. New York City's smart waste initiatives are a good example of how even relatively large and complex urban environments can leverage technology to increase sustainability and operational efficiency (Grimaldi et al., 2021; Kontokosta et al., 2018).

Copenhagen, Denmark: Smart Traffic Management for Emission Reduction

Copenhagen's smart traffic system uses real-time data from smart sensors, cameras, and connected vehicles to optimize traffic flow and reduce air pollution. Traffic lights adapt flexibly to traffic conditions, reducing engine shutdowns and stop-and-go traffic. Sensors measure vehicle emissions at key points, informing urban policy and traffic management. This data is used directly to develop bike paths, pedestrian zones, and improved public transport. Reduced emissions lead to better air quality and lower rates of respiratory disease. Copenhagen's smart traffic management is a prime example of how technology can directly contribute to combating urban air pollution and achieving climate goals (Hanif et al., 2024; Wolniak, 2023).

Santander, Spain – Smart City Environmental Monitoring

Santander is being hailed as one of the first smart cities to implement a comprehensive IoT sensor network covering multiple environmental parameters. More than 12,000 sensors placed throughout the city continuously monitor air quality, temperature, humidity, noise levels, and bin occupancy. The system provides city managers with continuous data streams, allowing them to quickly identify pollution incidents and infrastructure problems. For example, sensors installed on waste containers enable on-demand collection, reducing unnecessary truck traffic and emissions. By monitoring traffic and energy consumption, the sensors significantly support integrated and sustainable city planning. Furthermore, the city demonstrates democratic and modern governance in many aspects. Thanks to smart vehicles spread throughout the city, information and data are shared with residents to promote transparency and community engagement. In this regard, various smart applications and web portals have been developed by the city administration (Romanov & Galelyuka, 2024; Tarannum et al., 2025).

Stockholm, Sweden: Smart Water Quality and Flood Monitoring

Stockholm is one of the modern cities using smart environmental technologies to monitor water quality in urban waterways and manage flood risks. The city uses smart technologies to maintain safe and clean water bodies by continuously monitoring parameters such as pH, turbidity, and pollutant levels. For example, smart sensors monitor water levels in real time and enable early warnings to be sent to city officials and residents. The city uses data analytics to optimize drainage systems and plan flood mitigation measures. The resulting early warnings reduce flood damage and strengthen urban resilience by protecting aquatic ecosystems. Smart water management in Stockholm is a prime example of the critical role of environmental technologies in protecting cities from climate-related risks (Syed Taha et al., 2024; Wang & Abdelrahman, 2023).

Philadelphia, Pennsylvania, USA: Smart Solar-Powered Waste Bins

The city of Philadelphia has taken a significant step toward improving waste collection efficiency by installing solar-powered smart trash cans in public spaces. These cans compress waste on-site, increasing capacity and significantly reducing collection frequency. Level sensors directly alert waste management teams when the cans need emptying, resulting in fewer trips, fuel consumption, and greenhouse gas emissions. Naturally, overflow and litter are minimized, supporting the quality and sustainability of public spaces. Furthermore, the cans often feature educational signs encouraging recycling and waste reduction, fostering a sense of community participation and belonging among residents. Philadelphia's implementation of smart trash cans reinforces the city's commitment to sustainability goals and cleaner urban environments (Jayagopal et al., 2020).

Evaluation

The combined use of artificial intelligence, the Internet of Things, and big data analytics significantly facilitates urban management in many ways. The most significant benefits of this combination are the combined use of advanced predictive modeling, automated control systems, and comprehensive environmental monitoring techniques. All these technologies collect and process large amounts of data in real time from interconnected urban infrastructures, such as sensors in transportation, energy, water, and waste management systems. This process optimizes resource use, reduces pollution, and significantly improves urban living conditions. Meanwhile, AI algorithms analyze this data to forecast urban demand, identify inefficiencies, and automate responses, enabling more efficient city operations. This results in increased efficiency which helps make urban life more sustainable. In many ways, smart environmental technologies supported by AI and IoT play a significant role in achieving these potential goals by minimizing cities' energy and water consumption and maximizing the use of renewable resources. For example, smart grids leverage IoT sensors and AI to dynamically balance electricity supply and demand. This utilization enables the integration of decentralized renewable energy sources like solar and wind. Such applications increase grid reliability and reduce energy waste and carbon emissions. Similarly, smart buildings equipped with AI-powered energy management systems and IoT devices significantly reduce urban carbon footprints by optimizing heating, cooling, and lighting based on real-time occupancy and weather data, making significant environmental contributions. One of the most significant contributions of these technologies is their transformation of urban infrastructure from passive consumers to active participants in sustainable energy ecosystems. Given the importance and necessity of citizen participation, it plays a crucial role in achieving desirable urban living. This type of output creates unparalleled value for achieving future goals. However, despite all these positive perspectives, the deployment of AI, IoT, and big data in smart cities requires a balanced policy. Accordingly, the environmental costs of digital infrastructure, including the energy consumption of data centers and network operations, must be accurately calculated. For example, the energy requirements of AI or cloud services can be substantial. Furthermore, extensive data collection can pose human rights (privacy) and ethical violations. To maximize societal benefits, highly transparent data policies, secure data processing processes, and inclusive decision-making mechanisms must be established. Addressing these challenges is essential to ensure that smart technologies, despite their environmental or social benefits, do not produce undesirable consequences.

Table 1: 14 Global Examples of Smart Environmental Technology Applications.

City / Region	**Key Application Area**	**Specific Technologies Mentioned**	**Key Benefits Mentioned**
Singapore	Air Quality, Monitoring & Precision Agriculture	PM2.5, NO2, O3, CO sensors, IoT soil/nutrient sensors, smart meters	Detecting pollution spikes, targeted interventions, reducing import dependency, demand management.
Melbourne	Public Lighting & Green Spaces	Adaptive controls, IoT sensors (moisture, temp, air quality)	Significant energy savings, rapid repairs, precise irrigation, reducing heat island effects.
Tokyo	Water & Noise Management	Pressure fluctuation/leak sensors, IoT-based noise monitoring	Minimizing water loss, earthquake/flood status reporting, creating noise maps for public.
Barcelona	Waste Management	Ultrasonic sensors in public bins, wireless central platform	Dynamic route planning, saving fuel, reducing greenhouse gas emissions.
Copenhagen	Traffic Management	Real-time data, sensors, cameras, connected vehicles	Reducing idling times and stop-and-go traffic, goal of carbon neutrality by 2025.
Amsterdam	Energy Grids	Smart meters, sensors, storage technologies (batteries)	Balancing supply and demand, managing solar/wind inputs, reducing fossil fuel reliance.
Helsinki	Waste Management	Envac (Underground pneumatic pipes)	Eliminating street-level garbage trucks, reducing traffic congestion and unpleasant odors.
Songdo	Waste Management	Underground pneumatic pipes, IoT-based city services	Minimizing human contact with waste, maximizing usable urban space for pedestrians.
Nambucca Shire	Waste Management	Bigbelly solar-powered bins, IoT fill-level sensors	700% capacity increase, optimal collection frequency, free public Wi-Fi.

New York City	Waste Management	Automated loading trucks, GPS, fill-level sensors	Increasing collection safety, optimal placement of containers, achieving zero waste by 2030.
Santander	Environmental Monitoring	12,000+ IoT sensors (air, noise, bin occupancy)	Quick identification of pollution incidents, transparency through web portals/apps.
Stockholm	Water & Flood Management	Smart sensors (pH, turbidity, water levels)	Early warnings for residents, protecting aquatic ecosystems, strengthening urban resilience.
Philadelphia	Waste Management	Solar-powered smart trash cans, level sensors	Reducing collection frequency, minimizing overflow, educational signs for recycling.

Notes. The table was prepared by the authors.

Table 1 outlines how the world's leading metropolises, from Singapore to Barcelona, Tokyo to Amsterdam, use smart technologies as a strategic tool in the fight against increasing urbanization and the climate crisis.

Conclusion

This study provides a comprehensive analysis of the integration of AI-powered smart environmental technologies into urban ecosystems, offering three distinct levels of contribution to the field of sustainable urbanism. Theoretically, the research bridges the gap between fragmented technological discussions and holistic sustainability goals. While prior studies often treat sectors like energy or waste in isolation, this study establishes a unified framework showing how AI and IoT act as cross-cutting catalysts across five core urban pillars. Without this study, the literature would lack a synthesized understanding of how these technologies function as an integrated "urban brain" rather than disparate tools. Methodologically, the study demonstrates the strength of qualitative data triangulation by reconciling theoretical literature with 14 diverse global case studies. This approach validates the scalability of smart technologies across different geographical and economic contexts from the high-tech infrastructure of Singapore to the mobility-focused policies of Copenhagen providing a replicable model for future qualitative assessments of smart city projects. Practically and for Policy-Making, the findings offer a strategic roadmap for city administrators. The study underscores that technology alone is insufficient; its success depends on data-driven decision-making and proactive resource management. The 14 application examples serve as "best practice" benchmarks, proving that AI-integrated systems can reduce water loss by 25% or decrease travel times by 20%, as seen in Barcelona and Copenhagen. These results provide concrete evidence for policymakers to justify investments in smart infrastructure as a primary tool for achieving Sustainable Development Goals (SDGs) 11, 12, and 13. In summary, this study addresses a critical void by transforming technical data into actionable urban intelligence. It moves beyond the "what" of technology to explaining the "how" and "why" of its implementation, ensuring that future urban legacies are not only digital but inherently resilient and livable.

Suggestions

Recommendations for city administrations on the topics of energy management using smart IoT technologies, smart grids, carbon emission reduction, and the integration of renewable energy systems in smart cities are grouped under five main headings below:

1. Energy Management with Smart IoT Technologies

- Real-Time Monitoring and Optimization: Energy consumption in public buildings and infrastructure should be monitored in real time using smart sensors and meters, and unnecessary consumption should be automatically reduced. For example, "occupant-sensitive" automation systems can be installed in offices or street lighting.

- Centralized Energy Platforms: By establishing city platforms integrated with IoT systems, all buildings and infrastructure can be managed centrally. This improves energy efficiency and maintenance processes, ensuring uninterrupted data flow and remote control.

2. Smart Grid Integration

- Digital Energy Infrastructure: In infrastructure such as electricity, natural gas, and water, two-way and real-time data transfer should be ensured through smart grid applications to optimize the balance of energy supply and demand, and resources should be utilized efficiently.
- Distributed Energy and Storage: Renewable energy generation points (solar panels, wind turbines) should be integrated into the smart grid, and grid flexibility should be increased with battery storage solutions. This minimizes the inherent fluctuations of renewable resources.
- Automatic Fault Detection and Maintenance: Potential faults should be detected early using smart meters and IoT sensors, and maintenance processes should be carried out proactively. This reduces both downtime and operating costs.

3. Carbon Emission Reduction

- Data-Driven Carbon Monitoring: With emission monitoring modules on the smart city platform, the citywide carbon footprint should be monitored in real time, and targeted measures should be taken in areas with the greatest environmental impact.
- Energy Efficiency and Green Transportation: In addition to the implementation of energy efficiency-enhancing technologies, electric buses and smart public transportation systems should be expanded. Increasing bicycle and pedestrian paths in urban transportation also contributes positively to carbon emissions.

4. Integration of Renewable Energy Systems

- Integrated Renewable Energy Management: Renewable energy facilities such as solar and wind installed in the city should be integrated with smart grids and IoT systems to achieve a balanced production-consumption relationship. Excess energy generated by increasing storage capacity should be used optimally or fed back into the grid.
- Building-Based Renewable Energy Integration: Solar panels should be integrated onto the roofs of smart buildings, and production data from these panels should be automatically monitored and integrated into smart energy management systems.

5. Policy and Governance Recommendations

- Transparent Data Management: All city energy and emissions data should be collected and shared transparently, and open data policies should be implemented for analysis.
- Citizen and Stakeholder Participation: Prioritizing the design of energy and climate strategies with stakeholders at the local level and raising public awareness should be prioritized.
- Legal and Economic Incentives: Incentives should be implemented for renewable energy investments and energy efficiency projects.

By implementing these strategies, city governments can quickly achieve significant advantages in energy savings, cost reductions, and sustainable urban planning. Their future vision should be designed around the integrated planning of all these systems.

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Statements of Publication Ethics

We hereby declare that the study has not unethical issues and that research and publication ethics have been observed carefully. The author confirms that this study was conducted in accordance with accepted research and publication ethics. Artificial intelligence tools were used solely for language editing and proofreading to improve clarity and readability. No AI system was used to generate research data, perform analyses, or produce the study's conclusions. The author reviewed and approved all edits and take full responsibility for the final manuscript.

Researchers' Contribution Rate

The study was conducted and reported with equal collaboration among the researchers.

Ethics Committee Approval Information

Since there was no issue that required ethics committee permission in this study, no application was made.

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GENİŞLETİLMİŞ ÖZET

Yapay zekâ (AI) destekli akıllı çevre teknolojileri, günümüz şehirlerinin sürdürülebilirlik hedeflerine ulaşmasında kritik bir rol oynamaktadır. Bu teknolojiler, yapay zekâ, sensörler, Nesnelerin İnterneti (IoT) cihazları ve gelişmiş veri analitiği platformları aracılığıyla çevresel parametreleri gerçek zamanlı izleyerek kentsel kaynakların daha verimli kullanılmasını sağlar. Hava ve su kalitesi, gürültü kirliliği ve enerji tüketimi gibi temel çevresel göstergeler sürekli takip edilerek, şehir yöneticilerinin kirlilik olaylarına hızlı müdahale etmesi ve kaynakları optimum şekilde dağıtması mümkün olur. Böylece şehirler, ekolojik ayak izlerini azaltırken, yaşam kalitesini artıran daha sağlıklı ve dayanıklı kentsel ortamlar yaratabilir. Akıllı enerji sistemleri, yenilenebilir enerji kaynaklarının entegrasyonunu kolaylaştırarak enerji israfını önler ve karbon emisyonlarını azaltır. Benzer şekilde, su yönetiminde kullanılan sensörler sızıntıları tespit eder ve sulama işlemlerini optimize ederek su kaynaklarının korunmasına katkı sağlar. Atık yönetiminde ise doluluk sensörleri sayesinde gereksiz atık toplama seferleri azaltılarak operasyonel verimlilik ve çevresel fayda sağlanır. Bu kapsamlı dijital altyapı, şehirlerin sürdürülebilirlik yolunda önemli adımlar atmasına olanak tanır.

Enerji verimliliği, akıllı çevre teknolojilerinin en kritik bileşenlerinden biridir. Akıllı sayaçlar ve yapay zekâ destekli enerji yönetim sistemleri, binaların enerji tüketimini gerçek zamanlı izleyip optimize ederek enerji israfını önler. Akıllı şebekeler, güneş ve rüzgâr gibi yenilenebilir enerji kaynaklarını entegre ederek enerji arz ve talebini dengeler, fosil yakıt kullanımını azaltır. Binalara entegre fotovoltaik paneller ise güneş enerjisinin doğrudan bina yapısında üretilmesini sağlayarak enerji iletimindeki kayıpları en aza indirir. Bu sistemler, hava koşullarına göre üretimi tahmin edip enerji yönetimini optimize ederek karbon emisyonlarının azaltılmasına katkıda bulunur.

Akıllı ulaşım teknolojileri, trafik akışını gerçek zamanlı izleyip yöneterek tıkanıklığı ve araç rölanti sürelerini azaltır. Sensörler, kameralar ve GPS cihazları, trafik verilerini analiz ederek sinyal zamanlamalarını optimize eder ve karbon emisyonlarını düşürür. Elektrikli araçlar, toplu taşıma, bisiklet ve yaya yolları gibi sürdürülebilir ulaşım modları teşvik edilir. Otonom ve bağlantılı araç teknolojileri, trafik verimliliğini artırarak emisyonların azalmasına yardımcı olur. Kopenhag gibi şehirler, akıllı trafik sinyalleri ve bisiklet altyapısıyla sürdürülebilir ulaşımı destekleyerek hava kalitesini iyileştirmiştir.

Su yönetiminde kullanılan akıllı teknolojiler, sızıntıların erken tespiti ve su tüketiminin detaylı izlenmesini sağlar. Akıllı su sayaçları ve sensörler, su kayıplarını azaltarak su kaynaklarının korunmasına katkıda bulunur. IoT destekli akıllı sulama sistemleri, toprak nemi ve hava koşullarına göre sulama programlarını optimize eder, aşırı sulamayı önler. Ayrıca, yağmur suyu hasadı ve gri su geri dönüşümü gibi alternatif su kaynakları entegre edilerek tatlı su talebi azaltılır. Bu sistemler, altyapı iyileştirmeleri ve öngörücü bakım stratejileriyle kentsel su dayanıklılığını artırır.

Atık yönetiminde IoT ve sensörler, atık kutularının doluluk seviyelerini gerçek zamanlı izleyerek toplama rotalarını optimize eder. Bu sayede gereksiz atık toplama seferleri azalır, operasyonel maliyetler düşer ve karbon emisyonları minimize edilir. Atık verilerinin analizi, geri dönüşüm ve kaynak koruma çabalarını destekler, döngüsel ekonomi ilkelerinin uygulanmasını kolaylaştırır. Akıllı atık yönetimi, trafik sıkışıklığını ve gürültü kirliliğini azaltırken kentsel hijyen ve yaşam kalitesini artırır. Bazı şehirlerde yeraltı pnömatik boru sistemleri gibi yenilikçi çözümlerle sıfır atık hedeflerine doğru ilerlenmektedir.

Akıllı hava yönetimi, IoT sensörleri ve gelişmiş analitik kullanarak partikül madde, azot oksitler, karbon monoksit gibi kirleticileri gerçek zamanlı izler. Bu sayede kirlilik sıcak noktaları belirlenip hedefli müdahaleler yapılabilir. Mobil hava kalitesi izleyicileri, sabit sensörlerle birlikte farklı şehir alanlarında kapsamlı veri sağlar. Sürekli izleme, halk sağlığı uyarıları ve çevre politikalarının etkin uygulanmasını mümkün kılar. Bu sistemler, özellikle hassas alanlarda kirliliğe maruziyeti azaltarak yaşam kalitesini yükseltir ve sürdürülebilirlik hedeflerine ulaşmayı destekler.

Orman yangınlarının erken tespiti için IoT sensörleri, sıcaklık, duman, karbondioksit ve nem gibi çevresel parametreleri ölçer. Bu sensörler, gerçek zamanlı verileri kontrol merkezlerine ileterek yangınların hızlıca tespit edilmesini ve müdahale edilmesini sağlar. Yapay zekâ destekli gaz sınıflandırması ve uydu iletişimi, yanlış alarmları azaltırken ultra erken uyarılar sunar. Bu sistemler, doğal ekosistemlerin ve kentsel alanlara yakın yeşil alanların korunmasında kritik öneme sahiptir.

Toprak nem sensörleri ve akıllı sulama sistemleri, kentsel tarımda su ve gübre kullanımını optimize eder. Bu teknolojiler, toprak koşullarını gerçek zamanlı izleyerek su ve besin maddelerinin tam ihtiyaç duyulan yerde ve zamanda kullanılmasını sağlar. Böylece israf azalır, ürün verimi ve kalitesi artar. IoT destekli hassas tarım uygulamaları, yerel gıda üretimini teşvik ederek ulaşım kaynaklı emisyonları azaltır ve kentsel sürdürülebilirliğe katkıda bulunur.

Geniş sensör ağlarından toplanan veriler, gelişmiş analitik platformlar tarafından işlenerek eğilimler, anormallikler ve riskler önceden tespit edilir. Yapay zekâ destekli öngörücü modeller, enerji talebindeki dalgalanmalar ve kirlilik artışlarını tahmin ederek önleyici tedbirlerin alınmasını sağlar. Veri şeffaflığı ve kamuya açık çevresel bilgiler, toplumun bilinçlenmesini ve sürdürülebilirlik konularında aktif katılımını artırır. Bu sayede kentsel yönetim daha dinamik, uyarlanabilir ve iş birlikçi hale gelir.

Sonuç olarak, akıllı çevre teknolojileri, şehirlerin sürdürülebilirlik hedeflerine ulaşmasında çok yönlü ve güçlü araçlar sunmaktadır. Enerji verimliliği, ulaşım, su ve atık yönetimi gibi temel alanlarda kullanılan sensörler, IoT cihazları ve gelişmiş veri analitiği, çevresel kaynakların korunmasını, kirliliğin azaltılmasını ve yaşam kalitesinin artırılmasını sağlar. Bu teknolojiler, sadece operasyonel verimliliği artırmakla kalmaz; aynı zamanda iklim dayanıklılığını, halk sağlığını ve sosyal refahı da destekler. Kopenhag ve Singapur gibi öncü şehirler, bu teknolojilerin entegre edilmesiyle karbon nötrlüğü ve sürdürülebilir kentsel gelişim hedeflerine ulaşmanın mümkün olduğunu göstermektedir. Gelecekte blockchain, yapay zekâ ve makine öğrenimi gibi ileri teknolojilerin entegrasyonu ile akıllı çevre çözümleri daha da gelişecek ve yaygınlaşacaktır. Bu sayede şehirler, hızla artan nüfus ve çevresel baskılar karşısında sürdürülebilir, sağlıklı ve yaşanabilir kentsel alanlar yaratmaya devam edecektir.