Digital Twin for Climate Resilience: Transforming Smart Cities for a Sustainable Future

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Keywords: Digital Twin, Climate Change, Smart Cities, Decarbonization, Urban Heat Island, Resilience, Green Building, Agriculture, Internet of Things (IoT).

Abstract

The urgency of climate change demands innovative solutions that transcend traditional mitigation and adaptation strategies. In this context, Digital Twins (DTs) have emerged as a transformative tool for integrating real-time data, advanced simulation, and predictive analytics across diverse domains. This paper presents a comprehensive review of DT applications that bolster climate resilience, emphasizing how the technology can drive decarbonization, enhance resource efficiency, and mitigate urban heat island effects. We categorize DT implementations into three spatial scales—small-scale assets, city-level systems, and global or Earth-level networks—illustrating the versatility and scalability of DT-driven interventions. Subsequently, we delve into key sectoral applications, including green building practices, climate-responsive construction, and precision agriculture, illustrating how DTs can optimize operational processes and reduce greenhouse gas emissions. By synthesizing findings from leading studies and real-world case examples, we highlight both the current achievements and the challenges—such as data standardization, computational demands, and stakeholder engagement—that hamper wider DT adoption. We argue that addressing these hurdles through cross-disciplinary collaboration, regulatory support, and technological innovation is critical for fully leveraging DTs' potential in climate resilience. Overall, this paper underscores DTs as a promising catalyst for transformative change, offering data-driven insights that guide policy and practice toward a more sustainable, equitable, and climate-resilient future.

1. Introduction

The escalating crisis of climate change necessitates urgent attention and decisive action. Its severity is evident in the increasing frequency and intensity of extreme weather events, rising global temperatures, and accelerating biodiversity loss Kumler et al. (2025). Recently, many countries have experienced a significant increase in the frequency and severity of wildfires, a trend that has been exacerbated by climate change Senande-Rivera et al. (2025). In 2024, the Western Megafires collectively burned vast areas from Western Canada to the Southwestern United States, with several fires exceeding 10,000 hectares in size Senande-Rivera et al. (2025). Similarly, the Pioneer Fire in Washington state burned 38,735 acres between June and October 2024, threatening communities and leading to significant evacuations Senande-Rivera et al. (2025). These events underscore the escalating wildfire risks associated with climate change. Beyond environmental concerns, climate change poses significant threats to human health, food security, economic stability, and social cohesion Hassoun (2025).

Consequently, there is an imperative for prioritizing both adaptation and mitigation approaches. Conventional approaches, nevertheless, cannot address both the dimensions and complexity of the problem of climate. Instead, new, emerging technology, scientific, and multidisciplinary collaboration-based approaches are a must. One such technology, DT technology, developed for use in industrial production and spacecraft engineering, possesses tremendous potential for complex system optimization through real-time integration and simulation Kumler et al. (2025). Applied in programs for climate change, DTs embody a powerful, transformational tool for investigating, predicting, and countering climate impacts Dale et al. (2023). By utilizing real-time information and high-fidelity simulations, DTs allow decision-makers to make fact-based, critical decisions in formulating effective climate mitigation and adaptation approaches.

A DT is a virtual model of a real entity, system, or process, dynamically depicting real-life scenarios in a virtual environment Shafik (2025). By fusing information derived from sensors, IoT, and complex analysis, DTs enable high-fidelity tracking, modeling, and analysis of complex systems. With such capabilities, DTs enable researchers, policymakers, and stakeholders to develop new strategies, conduct focused interventions, and make fact-based decisions in an attempt to mitigate the consequences of climate change. With its simulation capability, DTs usher in new avenues in forecasting, disaster preparedness, and prudent use of resources. DTs have numerous applications in a variety of sectors: in urban planning, DTs model city operations under scenarios of changing climates, driving improvements in infrastructure, use of energy, and transportation networks Shafik (2025). With the integration of environment-related information Mansour and Chen (2022), such city-scale simulations can underpin flood risk management, urban heat islands (UHI) mitigation, and efficient management of air quality Channi et al. (2025). In agriculture, DTs enable precision agriculture through optimized irrigation, selection of crops, and management of pests, ultimately increasing yields and reducing resource waste Ghandar et al. (2021). In renewable energy, DTs maximize solar farms, wind farms, and smart grids, producing cleaner and more efficient energy. Real-time tracking of such assets also enables predictive maintenance, minimizing downtime and operational costs Ghandar et al. (2021).

Despite such transformative potential, research specifically examining DTs' role in climate resilience remains limited. While various studies have explored DT usage in numerous industries, there is a notable gap regarding how DTs directly advance climate change mitigation and adaptation. Addressing this gap is vital to fully harness DT technology in creating more sustainable, resilient systems. This paper tackles that need by conducting a thorough review of existing literature on DT applications for climate resilience. It highlights key challenges, explores emerging opportunities, and distills best practices to maximize the impact of DTs in a rapidly changing global climate. Specifically, the key contributions of this study can be summarized as follows.

1. First, we provide a systematic review of how DTs contribute to achieving zero-carbon communities, analyzing their impact across multiple scales, from individual buildings to entire cities and even global systems.

2. Second, we present concrete case studies demonstrating the practical implementation of DTs in decarbonization efforts. This includes applications in buildings and construction, where DTs facilitate green building (GB) practices and energy efficiency optimization, as well as their role in mitigating UHI effects and improving urban climate resilience. Additionally, we explore how DTs are revolutionizing agricultural practices by enabling climate-smart solutions that enhance food security while reducing environmental footprints.

The remainder of this paper is organized as follows: Section II explores how DTs can drive decarbonization by reducing carbon emissions and improving energy efficiency. Section III examines their role in sustainable construction, particularly in advancing green building technologies. Section IV discusses how DTs contribute to urban climate adaptation, helping to mitigate UHI effects and enhance resilience. Section V focuses on their impact on agriculture, with an emphasis on optimizing resource use and strengthening climate adaptation strategies. Section VI identifies key challenges in implementing DT solutions and outlines future research directions to maximize their potential in climate resilience. Finally, Section VII offers concluding reflections, highlighting the transformative role of DTs in shaping a more sustainable and climate-resilient future.

2. Accelerating Decarbonization with DTs

DTs hold remarkable potential for driving down carbon emissions and hastening the shift toward net-zero communities. By creating digital replicas of physical assets and processes, DTs enable stakeholders to identify inefficiencies, simulate potential interventions, and implement targeted strategies for reducing greenhouse gas (GHG) emissions. In this section, we explore how DTs contribute to decarbonization across three scales: *small-scale* deployments (e.g., buildings and ships), *city-level* initiatives, and *global or Earth-level* undertakings. Categorizing DT applications in this way allows us to appreciate both the range of use cases and the cumulative impact they can achieve.

2.1 Small-Scale Level Applications

On the small-scale level, DTs introduce innovative methods for cutting carbon footprints and advancing sustainability within localized systems, such as individual buildings or transport assets. Typically, these DT frameworks merge real-time sensor data with advanced machine learning (ML) algorithms, delivering insights that inform resource allocation and operational efficiency. Two recent studies exemplify the effectiveness of DT-based solutions at this granular scale.

First, Arsiwala et al. (2023) introduce a DT model—augmented with ML algorithms—that observes and forecasts CO_2 emissions in present buildings. With real-time data about energy consumption, water usage, and waste generated through IoT sensors Alshami et al. (2024), the model periodically evaluates a building's performance in terms of its environmental impact. Based on the collected data, it also proposes countermeasures, such as optimizing HVAC controls or altering occupant behavior, to reduce carbon emissions. This data-driven, proactive approach not only helps lower energy costs but also fosters a deeper understanding of the interconnections between building operations and their environmental footprint.

Second, Wei et al. (2023) demonstrate how DTs can accelerate shipping decarbonization. They present a real-time ship-routing system that integrates live vessel data with a predictive emission model to forecast compliance with various carbon regulations throughout a voyage. By continuously analyzing fuel consumption, shipping routes, and operational parameters, the system determines the most efficient routes that minimize both emissions and costs. This example highlights how DTs can drive real-time, measurable improvements in operational settings—whether on land or at sea—by identifying opportunities to reduce energy consumption and ensuring compliance with evolving environmental regulations.

Collectively, these examples illustrate how DTs, through predictive analysis and smart monitoring, enable decision-makers to make timely, well-informed choices. In turn, they help individual transportation networks and buildings align with broader decarbonization goals, paving the way for city-wide and global sustainability efforts.

2.2 City-Level Applications

At the city level, DTs offer powerful tools for tackling carbon emissions and promoting sustainable urban growth. Cities play a decisive role in global decarbonization efforts, as they are responsible for a substantial proportion of greenhouse gas emissions. Leveraging DT technology at this scale allows for a better understanding, analysis, and optimization of urban systems to achieve emission-reduction targets.

A notable case is the study conducted in Bertam City, Malaysia, by Zaidi and Haw (2023). Given the rapid pace of urbanization and increasing carbon emissions, the Malaysian government has committed to lowering its carbon footprint and ultimately reaching carbon neutrality. The authors employed the Intelligent Communities Lifecycle software to develop a DT model of Bertam City. They simulated various scenarios to examine energy consumption and associated carbon emissions in a virtual environment. Findings suggest that both active and passive design strategies, including optimizing building envelopes and HVAC systems, significantly reduce energy usage and emissions (an estimated 8.6% decrease for Bertam City). This research highlights how DT technologies can support the decarbonization of tropical cities by informing energy-efficient strategies.

Moreover, many cities worldwide have launched ambitious climate mitigation programs to curb emissions, as shown in Table 1. By leveraging DT solutions, municipal authorities can monitor, model, and optimize infrastructure and resource usage, contributing to accelerated decarbonization. DT adoption at the city level also facilitates data-driven decision-making, the identification of energy-saving opportunities, and the development of sustainable urban planning strategies.

2.3 Global or Planet-Level Applications

At the planetary level, DTs play a vital role in understanding and managing carbon emissions on a much larger scale. Their application at this level involves connecting DTs across cities, regions, and ecosystems to provide deeper insights into the planet's interconnected natural and human subsystems. By integrating high-resolution observations and simulations, global DTs achieve greater physical accuracy and support long-term monitoring and forecasting over multiple decades.

A notable example of large-scale DT initiatives is the collaboration between the European Space Agency (ESA) and NASA on the Earth System Digital Twins (ESDT) project (Bauer et al., 2021). These agencies aim to create high-resolution models of Earth's interconnected environments—including forests, climate systems, and other critical natural processes—producing unified forecasts based on real-time observations and advanced computational simulations. At the same time, the European Union (EU) continues to drive DT advancements through programs like GreenData4All and Destination Earth. Launched in 2021, Destination Earth focuses on developing high-priority DTs to predict extreme weather events and enhance climate adaptation planning, with implementation beginning in 2023 (Bauer et al., 2021).

By integrating diverse data sources, advanced modeling techniques, and state-of-the-art observational tools, these global DT initiatives empower scientists and policymakers to make data-driven, evidence-based decisions regarding carbon emissions and climate resilience. In doing so, they reinforce international sustainability goals and help mitigate some of the most significant consequences of climate change on a global scale.

3. Addressing Urban Heat Islands with DTs: Enhancing Climate Resilience

Urban heat islands (UHIs) have become a growing concern in modern cities, where extensive urban development, high-density infrastructure, and heat-absorbing surfaces such as asphalt and concrete contribute to significantly higher temperatures compared to surrounding rural areas (Jabbar et al., 2023). These elevated temperatures increase energy demand for cooling, degrade air quality, and present serious public health risks—especially during increasingly severe heatwaves driven by climate change (Kumler et al., 2025). Traditional mitigation strategies often fail to account for the full complexity of urban microclimates, highlighting the need for advanced, data-driven solutions.

DT technology is emerging as a transformative tool for visualizing, analyzing, and mitigating UHI effects. By integrating real-time environmental data with high-performance computational models, DTs provide urban planners with valuable insights into localized heat distribution and the effectiveness of different mitigation strategies (Channi et al., 2025; Shafik, 2025). In this section, we examine the role of DTs in UHI analysis, predictive heat mitigation, and adaptive urban design.

3.1 Understanding Urban Heat Islands with DTs

DTs integrate a wide range of environmental datasets—such as urban form, land surface temperature, and air pollution indicators—into dynamic simulations that model microclimate conditions (Ketzler et al., 2020). This comprehensive view allows for the identification of heat hotspots, enabling more precise and effective climate adaptation strategies. For instance, Singapore utilizes Digital Urban Climate Twins (DUCTs), which combine thermal imaging and meteorological data to assess how green spaces, reflective materials, and building orientation contribute to localized heat retention (Lin et al., 2021). Similarly, Helsinki's 3D city model incorporates solar radiation and airflow simulations to identify optimal locations for cooling interventions.

By integrating these datasets into a unified platform, DTs enhance the accuracy of heat exposure assessments and improve the effectiveness of interventions such as increasing urban greenery, using high-reflectance materials, and optimizing building layouts for better ventilation (Dale et al., 2023). With these capabilities, urban planners can develop more comprehensive, scalable, and environmentally sustainable strategies for cooling cities.

3.2 Simulation and Decision-Making for Heat Mitigation

A key advantage of DTs is their ability to run predictive simulations, allowing urban planners and stakeholders to assess various UHI mitigation strategies in a virtual environment before implementing them in reality. This enables them to evaluate the potential effectiveness of different approaches—such as increasing vegetation, applying high-albedo coatings, improving urban airflow, or rethinking city layouts—and select the solutions that provide the most significant thermal relief and energy savings.

Green infrastructure stands out as a powerful nature-based solution for combating UHIs. With DTs, planners can model where expanding tree canopies, green roofs, and vertical gardens will have the largest impact, leveraging real-time microclimatic data to optimize locations and design parameters (Ghandar et al., 2021). Tools like GIS and remote sensing further refine these analyses by measuring shading effects, evapotranspiration rates, and vegetation density to maximize cooling outcomes. In Singapore, a DT-driven urban forestry initiative significantly lowered surface temperatures in hot spots (Lin et al., 2021). Los Angeles' "Cool Streets" program similarly relies on DT simulations to guide strategic tree planting along key pedestrian routes, effectively reducing local heat stress and improving air quality (Omrany and Al-Obaidi, 2024). In addition to vegetation-based strategies, DTs assess the effectiveness of high-albedo surfaces in reducing heat absorption across urban environments. Cool roofs and reflective pavements enhance solar reflectivity, minimizing heat retention. DT-driven simulations analyze material properties, color variations, and thermal emittance, helping planners optimize their deployment across different urban settings (Dale et al., 2023). New York City's "Cool Neighborhoods Initiative" applied DT-based heat mapping to prioritize areas for cool roof installations, achieving substantial reductions in peak summer surface temperatures. Likewise, in Tokyo, a DT-driven assessment guided the implementation of water-retentive pavements, which leverage evaporative cooling to reduce road surface temperatures by an average of 2.5°C (Omrany and Al-Obaidi, 2024).

Urban airflow is a critical factor in mitigating UHI effects, as efficient wind circulation helps disperse accumulated heat. To harness this potential, DTs integrate Computational Fluid Dynamics (CFD) models, enabling planners to simulate airflow patterns and refine city layouts for improved ventilation (Shafik, 2025).

Table 1. Climate action plans of selected cities (adapted from Woods and Freas 2019).

City	Country	Climate Action Plan
Boston	US	Reduce GHG emissions 25% by 2020; Carbon neutral by 2050
Cape Town	South Africa	Carbon neutral by 2050 (with eight other African cities)
Copenhagen	Denmark	Carbon neutral by 2025
Glasgow	UK	Carbon neutral by 2037 (proposal to move to 2030 target)
Houston	US	Carbon neutral by 2050
London	UK	Reduce CO_2 emissions 60% by 2025; Zero carbon by 2050
Melbourne	Australia	100% renewable energy, zero building and transport emissions by 2050
Munich	Germany	100% renewable energy by 2025
San Diego	US	100% renewable electricity by 2035
Stockholm	Sweden	Fossil-fuel-free by 2040
Sydney	Australia	Reduce GHG emissions 70% by 2030; Net zero emissions by 2050
Vancouver	Canada	100% city energy from renewables; Carbon neutral by 2050

These models pinpoint wind corridors and optimize building configurations to enhance natural airflow in dense neighborhoods. In Hong Kong, for instance, DT-driven urban ventilation assessments have guided street redesigns to alleviate localized heat buildup (Pan et al., 2022). Similarly, Tokyo's environmental planning framework incorporates CFD simulations to shape "wind tunnels" that channel air through high-density districts, thereby reducing heat concentrations (Omrany and Al-Obaidi, 2024).

Beyond enhancing airflow, adjustments in urban design significantly broaden the potential for DT-driven climate adaptation. By examining factors such as street orientation, building height, and land use, DTs enable decision-makers to identify layouts that reduce solar exposure while maintaining energy efficiency. Strategies like restructuring street grids, integrating permeable surfaces, and developing green corridors contribute to long-term temperature moderation (Bianchini et al., 2023). For instance, in Barcelona, a redevelopment initiative utilized DT simulations to refine urban greening approaches, leading to a measurable decline in local UHI intensity. Similarly, Paris' 'Cool City" project leveraged DT insights to optimize the placement of permeable materials, effectively reducing urban heat stress while simultaneously improving stormwater management and biodiversity (Caprari et al., 2022).

3.3 Smart City DTs and Adaptive Heat Exposure Management

A major breakthrough in urban climate adaptation is the implementation of Smart City Digital Twins (SCDTs), which integrate environmental data with real-time human activity monitoring. Unlike traditional static models, SCDTs provide dynamic assessments of heat exposure by analyzing temperature, humidity, and pedestrian movement data. This real-time adaptability allows climate mitigation strategies to respond effectively to changing conditions (Shafik, 2025). SCDTs improve UHI adaptation by utilizing IoT sensor data to generate predictive heat exposure maps, pinpointing vulnerable areas and guiding mitigation efforts. These models also incorporate pedestrian flow simulations, enabling urban planners to optimize shaded pathways, cooling stations, and adaptive transit routes (Pan et al., 2022). For example, Barcelona's climate-aware DT platform integrates mobility data with heat stress indices to refine pedestrian routes, minimizing exposure to extreme temperatures (Bauer et al., 2021). Likewise, London's AI-enhanced DT framework recommends strategic placements for tree planting, permeable pavements, and green facades, reinforcing long-term resilience against extreme heat events (Opoku et al., 2021).

4. Digital Twins in Building and Construction: Advancing Green Building and Climate Resilience

DT technology has revolutionized the building and construction sector by integrating real-time data, advanced simulations, and predictive analytics. As climate change concerns intensify, DTs provide solutions for optimizing resource management, minimizing environmental impact, and enhancing buildings' adaptability to evolving climate conditions (Opoku et al., 2021; Shahzad et al., 2022). This section explores how DTs contribute to green building strategies, climate-responsive design, and large-scale urban sustainability.

4.1 Facilitating Green Building Initiatives

Green building (GB) initiatives aim to lower carbon emissions, enhance energy efficiency, and promote sustainable construction (Bortolini et al., 2022; Abdelkader et al., 2023). DTs play a crucial role in achieving these objectives by simulating building performance across various environmental conditions. By integrating Building Information Modeling (BIM) with IoT-enabled sensors Mansour et al. (2023), DTs empower architects and engineers to predict energy demand, analyze thermal conditions, and assess the ecological impact of different materials (Jiang et al., 2021; Kaewunruen et al., 2018).

Throughout the construction phase, DTs support real-time monitoring of materials, workforce efficiency, and energy consumption, helping project managers reduce waste, optimize workflows, and meet sustainability targets (Jiang et al., 2021; Ohueri et al., 2024). Once a building becomes operational, DTs serve as a continuous performance assessment tool, identifying inefficiencies and facilitating targeted upgrades to lower carbon footprints (Zhang et al., 2023). For instance, DT-driven predictive maintenance models enhance energy efficiency by regulating HVAC systems based on indoor air quality and occupant movement patterns (Arsiwala et al., 2023).

4.2 Supporting Climate-Responsive Design and Operations

Incorporating climate-responsive strategies is fundamental to sustainable architecture. DTs aid in this process by integrating historical climate trends, real-time environmental data, and predictive weather modeling (Shafik, 2025; Dale et al., 2023). These digital frameworks guide architects in refining building orientation, selecting energy-efficient facade materials, and optimizing ventilation systems to balance indoor comfort with reduced energy demand (Yang et al., 2022; Caprari et al., 2022).

A key DT application in climate adaptation is dynamic energy management. Enhanced by AI, DTs continuously analyze factors such as energy consumption, weather conditions, and occupant behavior to optimize heating, cooling, and lighting systems (Bianchini et al., 2023). In smart buildings, DTs further contribute by synchronizing with renewable energy grids, regulating solar and wind power usage in response to fluctuating demand and supply (Kumler et al., 2025). Additionally, DT simulations are increasingly used to assess building resilience against extreme climate events—such as heatwaves, hurricanes, and floods—enabling proactive design strategies that strengthen long-term sustainability (Bauer et al., 2021).

4.3 Scaling Up to Urban Environments

DTs extend beyond individual structures, playing a vital role in shaping sustainable, low-carbon cities (Channi et al., 2025). By unifying multiple building-level DTs into district-wide or city-scale models, planners can scrutinize energy consumption patterns, streamline transportation networks, and devise climate-resilient infrastructure (Lin et al., 2021; Pan et al., 2022). For example, the European Union’s “Destination Earth” program aims to develop a highly detailed DT of the entire planet, enabling urban climate scenario testing and decarbonization policy assessments (Bauer et al., 2021).

In smart cities, DTs also support the creation of energy-sharing ecosystems. Buildings that generate surplus renewable energy can distribute the excess to neighboring structures via an interconnected digital grid (Yang et al., 2022). At the same time, city-scale DTs help assess how green infrastructure—like additional tree canopies, urban wetlands, or reflective surfaces—might curb urban heat islands (Omrany and Al-Obaidi, 2024). Integrating air quality sensors and climate models further enhances policymakers’ ability to make data-driven decisions on land use and improve urban environmental conditions (Senande-Rivera et al., 2025).

5. Enhancing Climate Resilience Through DTs in Agriculture

DT technology is emerging as a transformative force in agriculture, enabling data-driven decision-making to enhance efficiency, mitigate environmental impacts, and improve resilience to climate change. While industries such as manufacturing and energy have widely embraced DTs, their adoption in agriculture remains relatively limited (Pylianidis et al., 2021; Purcell et al., 2023). This section explores how agricultural DTs contribute to optimizing resource management, reducing greenhouse gas (GHG) emissions, and strengthening climate adaptation—ultimately fostering more sustainable food systems.

5.1 Optimizing Resources and Reducing Emissions

One of the most significant advantages of DTs in agriculture is their ability to optimize resource allocation, particularly for water, fertilizers, and pesticides. By integrating real-time data on soil moisture, nutrient levels, and environmental conditions (Monteiro et al., 2018), DTs enable precise application of inputs, reducing both overuse and emissions linked to their production and transportation (Purcell and Neubauer, 2022). This precision-based approach not only prevents chemical runoff and water waste but also enhances agroecosystem resilience, helping farms better withstand climate extremes.

5.2 Precision Agriculture for Climate Health

DTs are central to precision agriculture, utilizing high-resolution data from sensors, drones, and satellites to monitor crop growth, detect pest activity, and predict yield variations (Pylianidis et al., 2021). These insights allow for targeted interventions, such as localized soil treatments and pest control strategies, which minimize environmental impact while promoting biodiversity. Additionally, data-driven automation in farm machinery significantly lowers fuel consumption, further reducing agriculture’s carbon footprint (Monteiro et al., 2022).

5.3 Forecasting, Adaptation, and Risk Management

Beyond daily farm operations, DTs play a crucial role in long-term climate adaptation (Bianchini et al., 2023). By integrating climate projections, historical yield records, and soil composition data, DTs can simulate how shifts in temperature, sand dune migration and desertification Ali et al. (2020), and precipitation patterns may impact crops. These predictive capabilities support proactive decision-making, allowing farmers to select climate-resilient crop varieties, adjust planting schedules, and modify irrigation practices ahead of extreme weather events. Ultimately, such measures enhance agricultural resilience, reducing crop losses and ensuring food security.

5.4 Collaboration and Technological Integration

The impact of DTs extends beyond individual farms, fostering collaborative innovation within the broader agricultural sector. Cloud-based platforms and open data networks facilitate knowledge exchange among farmers, agronomists, technology developers, and policymakers (Monteiro et al., 2018). This interconnected system accelerates the development of climate-smart agricultural practices, promotes standardized data collection methods, and enhances interoperability between different DT applications. Over time, such coordinated advancements drive widespread adoption of cutting-edge solutions.

5.5 Toward a Climate-Responsive Agricultural Future

By combining advanced technology with ecological awareness, DTs serve as a critical tool in the transition toward more sustainable and resilient agricultural systems. From optimizing resource use to forecasting climate impacts, DTs empower farmers to make informed decisions that enhance both productivity and environmental stewardship. As these technologies continue to evolve and become more accessible, they have the potential to reshape agricultural value chains worldwide, equipping communities with the tools needed to address the growing challenges of climate change.

6. Challenges and Future Directions

Despite the increased use of DTs in smart urban planning, decarbonization, and climate resilience, a range of obstacles present themselves. There is a lack of harmonization and gaps in data, computational overloads, governance, and budget constraints. Overcoming them is important in realizing DTs’ full potential in fighting climate change and contributing to sustainable development.

Data availability, integrity, and integration remain significant stumbling blocks. Differences in sensor accuracy, approaches to collecting data, and repository structures often cause DT model fragmentation. For instance, urban DTs require real-time information regarding infrastructure performance, traffic, and environment-related factors such as atmospheric conditions (air quality, for instance, in (Ketzler et al., 2020; Lin et al., 2021), whereas agricultural DTs require real-time updates regarding soil conditions and meteorological factors Pylianidis et al. (2021). Smooth integration of data will require uniform frameworks for data sharing, possibly supported through blockchain-based structures that will assure added security and real-time access. Integration of sensor networks and remote sensing capabilities, especially in underprivileged regions, will immensely contribute to enhancing data quality.

Beyond data, DTs face considerable complexity in multi-disciplinary and multi-scale environments. Plot and agricultural model constructions must integrate with larger urban and region simulations Bauer et al. (2021); Zaidi and Haw (2023). Communication between such layers is not an easy one, in that disparate modeling hypotheses and computational software are utilized between them. Overcoming such a challenge involves harmonization of simulation approaches, integration of physics and machine learning (pylianidis2021introducing), and establishment of common protocols for communicating between them in real-time.

Computational demands add another layer of complexity to deploying DTs. Detailed models that rely on vast, rapidly updating data—such as those tracking urban heat islands (UHI) or real-time wildfire threats—can strain infrastructure. To overcome these computational challenges, edge computing can help reduce delays, high-performance computing (HPC) clusters can support large-scale simulations, and surrogate modeling can strike a balance between accuracy and efficiency.

Beyond technical hurdles, trust, governance, and stakeholder involvement play a crucial role, particularly as DT-driven insights influence public policies and infrastructure projects. Transparency in data collection and validation, along with accountability structures, is essential for earning trust from communities and policymakers. While regulations can provide guidance, policies should also promote inclusive decision-making, ensuring that local voices help shape DT solutions.

Economic and policy barriers further complicate widespread DT adoption, especially in areas with limited funding or fragmented regulations. High initial costs may prevent smaller municipalities or agricultural sectors from leveraging these technologies, and inconsistent policies can stifle collaboration. Encouraging government incentives, fostering public-private partnerships, and streamlining regulations across regions could drive broader adoption and long-term success.

Looking ahead, there's a real opportunity to push DTs further in the fight for sustainability. With the right approach, AI could make these systems even more powerful—sharpening predictive models, automating real-time responses, and helping us stay ahead of environmental challenges. But technology alone isn't enough. Engineers, environmental scientists, and policymakers need to work together to develop solutions that don't just look good on paper but actually work in the real world.

Expanding DTs from local projects to global networks could completely change how we assess climate impacts, making our understanding deeper and our responses smarter. These systems could even serve as virtual "policy sandboxes," letting decision-makers test out sustainability ideas before they hit the real world—an invaluable tool for avoiding unintended consequences. But for any of this to work, we need clear, shared metrics for resilience and sustainability. Without them, it's impossible to measure progress or know which strategies are truly making a difference. If we can tackle these challenges head-on, DTs have the potential to drive real change—helping us manage resources more efficiently, protect the environment, and build a future that can withstand whatever comes next.

7. Conclusion

DTs provide a dynamic and integrated platform for addressing the growing challenges of climate change by optimizing resource use, reducing carbon emissions, and enhancing system resilience. In urban settings, DTs support decarbonization planning, mitigate urban heat islands, and guide climate-responsive infrastructure development. Similarly, in agriculture, DTs enable precision farming by optimizing water and fertilizer use, reducing environmental impacts while ensuring food security. On a global scale, interoperable DTs offer valuable insights for forecasting climate scenarios and shaping policy decisions. However, despite these advancements, several challenges hinder the widespread adoption of DTs, including the need for standardized data frameworks, high-performance computational resources, and secure, transparent data governance models. Achieving comprehensive solutions will require close collaboration among researchers, policymakers, and industry stakeholders, backed by appropriate funding mechanisms and clear regulatory structures. Through continued innovation and cross-sector cooperation, DTs have the potential to become a cornerstone of global climate resilience strategies, significantly enhancing adaptive capacity and environmental sustainability across industries and regions.

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