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Article

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Research in Globalization

Provided in Cooperation with:
Elsevier

Suggested Citation: Oyadeyi, Oluwadamilola A.; Oyadeyi, Olajide O. (2025) : Towards inclusive and sustainable strategies in smart cities: A comparative analysis of Zurich, Oslo, and Copenhagen, Research in Globalization, ISSN 2590-051X, Elsevier, Amsterdam, Vol. 10, pp. 1-18, https://doi.org/10.1016/j.resglo.2025.100271

Research in Globalization 10 (2025) 100271

Contents lists available at ScienceDirect

Research in Globalization

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

Towards inclusive and sustainable strategies in smart cities: A comparative analysis of Zurich, Oslo, and Copenhagen☆

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ARTICLE INFO

JEL classification:
R58
O18
Q56

Keywords:
Smart cities
Urban development
Sustainability
Sustainable urbanisation
Technology integration
Smart city models

ABSTRACT

Urbanisation has increased the need for sustainable urban development by positioning smart cities as critical frameworks for addressing environmental, economic, and social challenges. This study evaluates the sustainability strategies of three leading smart cities Zurich, Oslo, and Copenhagen by examining their environmental footprint, energy consumption, waste management, and air quality. The study uses a PRISMA-based systematic literature review to put together evidence from peer-reviewed articles published between 2017 and 2024. The Critical Appraisal Skills Program (CASP) was used to assess the quality of the articles. The study reveals that smart mobility and waste-to-energy systems drive Zurich's strengths in urban densification and public transportation, Oslo's leadership in renewable energy and electric mobility, and Copenhagen's ambitious carbon–neutral initiatives. Despite these achievements, challenges such as high implementation costs, slow technological adoption, and social equity issues persist, emphasising the complexity of achieving inclusive and sustainable urban evolution. To address these challenges, this study recommends increasing public participation through inclusive urban planning and digital platforms, strengthening policy frameworks, and funding for sustainability projects, and investing in data collection technologies to monitor real-time environmental impacts. Furthermore, fostering cross-city collaboration and addressing energy consumption challenges associated with AI and IoT are essential for scaling successful models globally. These insights offer actionable guidance for policymakers and urban planners to improve sustainability strategies and ensure long-term benefits.

Introduction

The rapid pace of urbanisation has led cities to seek innovative solutions to improve urban living while addressing pressing environmental challenges. In response, the concept of "smart cities" has gained prominence as a framework for integrating technology with urban development to improve communication, transport, energy efficiency, infrastructure, and connectivity (Caragliu et al., 2011; Albino et al., 2015; Bibri & Krogstie, 2017). Smart cities refer to urban areas that integrate digital technologies into municipal services to improve sustainability, connectivity, and quality of life (Kumar et al., 2022). These cities aim to create sustainable environments that reduce environmental impacts while promoting economic growth and improving the quality of life for residents. These cities can optimize resource use, streamline urban services, and reduce waste through advanced technologies such as the Internet of Things (IoT), big data analytics, and artificial intelligence (Mora & Bolici, 2017; Kumar et al., 2020). The development of smart cities is critical to ensuring the sustainability of urban areas for future generations, given the urgent need to mitigate climate change and manage limited resources (Caird & Hallett, 2019). Thus, for a successful transition there is need to implement sustainability strategies which involve specific measures aimed at reducing environmental footprints while fostering economic and social resilience.

This study employs the Triple Bottom Line (TBL) Theory as a theoretical framework to assess how smart city strategies balance environmental, economic, and social sustainability dimensions. TBL, developed by John Elkington (1999), emphasises that sustainable development requires an integrated approach to these three pillars. Environmental sustainability focuses on reducing negative ecological impacts through practices like renewable energy adoption and pollution control

☆ This article is part of a special issue entitled: 'Smart Cities' published in Research in Globalization.

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https://doi.org/10.1016/j.resglo.2025.100271
Received 8 September 2024; Received in revised form 4 January 2025; Accepted 18 January 2025
Available online 20 January 2025

(Srivastava et al., 2022). Economic sustainability involves resource-efficient strategies that support long-term growth, while social sustainability aims to improve quality of life and equity among residents (Elkington, 1999; Bibri & Krogstie, 2017). The application of this framework allows for a holistic evaluation of sustainability initiatives in smart cities.

While smart cities have become a focal point for urban planners and policymakers, there is still much to learn about the effectiveness of their sustainability initiatives. Studies show that smart city technologies have the potential to improve energy efficiency, reduce carbon emissions, and improve waste management systems (Kramers et al., 2014; Ahvenniemi et al., 2017). However, empirical evidence on the real-world impact of these initiatives on reducing the environmental footprint of cities remains limited (Manville et al., 2014; Silva et al., 2018). Moreover, questions remain about how these initiatives affect key urban factors such as energy consumption, air quality, and waste management (Angelidou, 2015; Joss et al., 2019).

Against this backdrop, this study explored the sustainability strategies implemented in leading smart cities Zurich, Oslo, and Copenhagen over the past several years. The research will focus on three key questions: (1) To what extent have the sustainability strategies in these cities contributed to reducing their environmental footprint? (2) How have these initiatives impacted energy consumption, waste management, and air quality? (3) Have these cities achieved their sustainability goals, and if not, what are the primary challenges hindering their progress?

Zurich, Oslo, and Copenhagen have consistently ranked among the top five smart cities globally due to their comprehensive and long-standing sustainability programs (Bibri & Krogstie, 2020; IMD, 2023). These cities offer valuable insights into how smart city strategies can drive environmental improvements while fostering economic and social growth (Marsal-Llacuna et al., 2015). Evidence in existing literature reveals that Zurich's energy initiatives have focused on renewable energy sources and reducing fossil fuel dependence, while Oslo has made strides in electrifying transportation and promoting green infrastructure (Angelidou, 2015; Bibri, 2020). Copenhagen is renowned for its waste-to-energy programs and innovative water management systems (Ahvenniemi et al., 2017; Bibri, 2020). Despite their achievements, these cities continue to face challenges such as balancing economic growth with environmental objectives and addressing the social implications of smart city developments (Ahvenniemi et al., 2017).

Evidence from leading global cities has revealed how smart city initiatives drive sustainability and innovation, addressing critical climate goals through transformative strategies. Zurich has adopted measures aligned with Switzerland's climate targets, including a 50 % reduction in greenhouse gas (GHG) emissions by 2030 and achieving net-zero emissions by 2050, supported by programs like the Smart City Lab and innovation grants that foster collaboration and pilot projects (IMF, 2023; Smart City Zurich Strategy, 2018). Oslo has showcased leadership in sustainable urban development with its early adoption of zero-emission mobility solutions such as electric buses and ferries, reducing both emissions and noise pollution despite harsh winters. Investments in green spaces, renewable energy, and a dedicated annual climate budget further align Oslo with Nordic carbon-neutrality ambitions (Johnson, 2020; Julsrud & Krogstad, 2020).

Similarly, Copenhagen has committed to becoming the first carbon–neutral capital by 2025 through its Copenhagen Climate Plan, integrating sustainable mobility initiatives like intelligent traffic systems and smart streetlights, which have achieved 76 % energy savings. With significant investments, including 2.7 billion Danish kroner (363 million euros) across 65 sustainability projects, Copenhagen exemplifies how strategic collaboration among public, private, and academic stakeholders can transform urban environments (Quélin & Smadja, 2021).

In light of the foregoing, this study adopts a systematic structure to evaluate how Zurich, Oslo, and Copenhagen have implemented technologies and policies aimed at reducing their environmental footprints. It examined the extent to which these initiatives have improved energy efficiency, waste management, and air quality, alongside the challenges encountered in achieving sustainability goals. The study offers a comparative approach, drawing lessons from these cities' experiences to inform global efforts toward sustainable urbanization and contributes to the growing discourse on creating more inclusive, sustainable, and technologically advanced urban futures. The novelty of this study lies in its comparative analysis, revealing best practices and identifying areas for further innovation in sustainability strategies.

The following sections of the paper discuss the theoretical framework and methodology, present findings on the sustainability strategies implemented in Zurich, Oslo, and Copenhagen, analyse the environmental impacts of these strategies, evaluate the progress made in achieving sustainability goals, highlight ongoing challenges, and identify lessons that can inform global efforts toward sustainable urbanisation. The paper concludes with recommendations for future research and practical strategies for policy development.

Theoretical framework

The Triple Bottom Line (TBL) Theory serves as the foundation for understanding how sustainability initiatives in smart cities contribute to urban development. This theory, developed by John Elkington (1999), emphasises the need to balance three core dimensions of sustainability: environmental, economic, and social. Each of these dimensions plays a crucial role in ensuring that cities can grow and develop without compromising the needs of future generations (Žak, 2015; Oyadeyi et al., 2024a). This study uses the TBL framework to evaluate how smart cities like Zurich, Oslo, and Copenhagen manage these three aspects through the implementation of smart technologies and sustainability initiatives.

The first key concept of the TBL theory is environmental sustainability, which refers to the responsible management of natural resources and reducing the negative environmental impacts of human activity (Srivastava et al., 2022). In the context of smart cities, this includes efforts such as reducing greenhouse gas emissions, improving air quality, and promoting renewable energy (Kumar et al., 2020; Adediran et al., 2024). Zurich's focus on clean energy and Oslo's investment in electric transportation are prime examples of how these cities implement environmental sustainability (Boulouchos et al., 2008; Aasness & Odeck, 2023). Thus, environmental sustainability is critical because it directly addresses the urgent need to combat climate change and reduce ecological damage (Uralovich et al., 2023).

Emerging technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), Blockchain, and Digital Twin systems play transformative roles in advancing environmental goals within smart cities. Bibri et al. (2023) highlight how the convergence of AI, IoT, and Big Data drives environmentally sustainable urbanism by optimizing energy use, waste management, and transportation systems. Similarly, David et al. (2024) illustrate AI's potential to achieve net-zero sustainability through intelligent climate modelling, emissions monitoring, and renewable energy integration. Bibri et al. (2023), also revealed that AI enables predictive analytics for urban planning, while Blockchain ensures transparency in resource management (Brain & Oyadeyi, 2023; Oyadeyi et al., 2024b). This synergy accelerates progress toward the Sustainable Development Goals (SDGs), especially in cities striving for environmental sustainability.

Another key concept in the TBL theory is economic sustainability, which involves ensuring long-term economic growth while minimising environmental harm and maintaining resource efficiency (Nogueira et al., 2022). Smart cities aim to achieve economic sustainability by integrating technologies that increase operational efficiency and reduce costs, such as optimising energy usage or improving waste management (Manville et al., 2014). Lucciarini and Galdini (2024), found that Copenhagen's waste-to-energy initiatives not only address waste management issues but also contribute to the city's economic growth by generating energy from waste.

Social sustainability is the third key concept of the TBL theory, which focuses on improving the quality of life for all citizens, ensuring equitable access to resources, and addressing social inequalities (Elkington, 1999; Farooq et al., 2021). In smart cities, social sustainability involves using technology to improve public services, healthcare, and overall urban liveability (Bibri & Krogstie, 2017). Copenhagen, for example, is known for its focus on social inclusion in its smart city strategies, ensuring that residents benefit equally from improvements in air quality and access to clean energy (Angelidou, 2015). Smart cities use technologies to foster inclusivity, improve public services, and promote equitable access to resources. Sidani et al. (2022) emphasize the role of smart city strategies in reducing social exclusion and fostering community engagement through tailored solutions.

The TBL theory, with its key concepts, serves as a widely recognised comprehensive framework for evaluating sustainability, emphasising the need for sustainable development to balance environmental, economic, and social goals (Elkington, 1999). Traditional models of urban development often prioritise economic growth at the expense of the environment or social equity. However, the TBL theory emphasises the interconnectedness of all three dimensions. For instance, neglecting social equity can lead to disparities that undermine economic progress, and environmental degradation can eventually lead to higher costs, reducing long-term economic sustainability (Ahvenniemi et al., 2017). In this way, the TBL framework allows for a holistic evaluation of smart city initiatives by ensuring that they do not favour one aspect of sustainability over the others.

One of the strengths of the TBL theory is its adaptability to different urban contexts, making it particularly relevant for evaluating the diverse strategies employed by smart cities such as Zurich, Oslo, and Copenhagen. According to Caird and Hallett (2019), these cities use technology not only to reduce environmental impacts but also to boost economic development and improve the well-being of their residents. Thus, the TBL theory provides a balanced approach for assessing their sustainability strategies, as it considers multiple dimensions of impact.

This study applies the TBL theory to assess the sustainability initiatives in Zurich, Oslo, and Copenhagen. In a practical sense, Zurich's focus on energy efficiency and reducing carbon emissions fits into the environmental dimension, while Oslo's investments in electric transport systems relate to both economic and environmental sustainability (Boulouchos et al., 2008; Aasness & Odeck, 2023). Copenhagen's waste-to-energy systems and its efforts to provide equitable access to clean energy resources address both the economic and social pillars of the TBL framework (Lucciarini & Galdini, 2024).

This research contributes to the literature by providing an in-depth, comparative analysis of how these leading smart cities have applied the TBL theory in their sustainability strategies. Although several studies have explored the environmental impacts of smart cities, few have adopted the holistic approach advocated by the TBL theory, which considers the interconnectedness of environmental, economic, and social outcomes. This study fills that gap by analysing how well Zurich, Oslo, and Copenhagen have achieved balanced outcomes across all three dimensions of sustainability. Moreover, the research will identify the challenges these cities face in maintaining this balance and offer recommendations for other cities seeking to implement similar sustainability strategies. This research not only contributes to the academic understanding of smart cities but also offers practical insights for policymakers and urban planners seeking to create more sustainable, inclusive urban environments.

Methodology

Research design

This study employs *a* qualitative research approach, specifically a systematic literature review (SLR), to examine sustainability strategies employed by smart cities and assess their impacts on environmental footprint, energy consumption, waste management, and air quality. The adoption of a systematic literature review is justified by the need for a rigorous and transparent method to evaluate the effectiveness of sustainability strategies in smart cities. Another justification for the use of this approach enables the integration of findings from various studies, providing a holistic view that would not be achievable through other methodologies. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework was followed to ensure that the review process was rigorous and transparent.

Previous studies have demonstrated the effectiveness of using a systematic literature review (SLR) to examine sustainability initiatives in smart cities. Authors like Cocchia (2014) used a systematic literature review method to examine the concepts of smart and digital cities, while Lim et al. (2019) identified the outcomes of smart city development. Similarly, Ruhlandt (2018) investigated the governance of smart cities, Tomor et al. explored smart governance for sustainable cities, and Myeong et al. (2022) analyzed research models and methodologies related to smart cities. These studies highlight the suitability of SLR for consolidating diverse evidence, making it an ideal method for identifying patterns, addressing gaps, and exploring challenges in the existing literature on sustainability initiatives. This method is advantageous because it systematically consolidates diverse evidence, facilitating the identification of patterns, gaps, and challenges in the literature.

Prisma framework

The PRISMA framework was used to guide the selection and screening of studies to ensure transparency and consistency throughout the review process. This framework includes four main stages: identification, screening, eligibility, and inclusion. In the identification stage, relevant studies were found through database searches. In the screening stage, duplicates and irrelevant studies were removed based on their titles and abstracts. The eligibility stage involved a detailed review of the full text of the studies to ensure they met the inclusion criteria. The review finally included studies that met all criteria, and a PRISMA flow diagram was used to track the number of studies reviewed at each stage, making the process clear and reproducible (see Fig. 1).

Search strategy

A comprehensive search was conducted using academic databases such as Google Scholar, Scopus, and Web of Science. The search terms used included "sustainability strategies," "smart cities," "environmental footprint," "energy efficiency," "waste management," "air quality," and "sustainability challenges." The search was limited to peer-reviewed journal articles and conference papers, published between 2017 and 2024 to ensure the relevance of the literature. Additionally, manual searches of reference lists were conducted to find further relevant studies. The initial search resulted in 320 studies, which were then screened for relevance to the research questions.

Inclusion and exclusion criteria

To determine which studies were relevant, inclusion and exclusion criteria were applied. Studies were included if they focused on sustainability strategies in smart cities, contained empirical data on environmental impacts such as energy consumption, waste management, or green transitions, and were published in English. Particular emphasis was placed on studies analysing European cities, notably Zurich, Oslo, and Copenhagen, given their prominence in sustainability and smart city development. This focus aligns with the classification framework provided by Cantuarias-Villessuzanne et al. (2021), which categorises European cities into three clusters: cities with emerging smart strategies, technology-orientated cities, and quality-of-life-orientated smart cities.

According to Cantuarias-Villessuzanne et al. (2021), Zurich, Oslo,

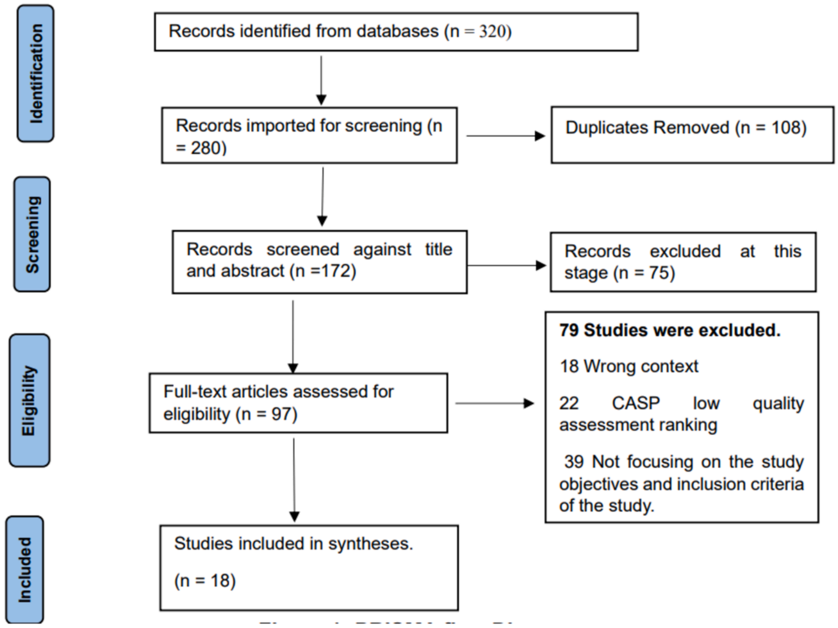

Fig. 1. PRISMA flow Diagram.

and Copenhagen fall within the "quality-of-life-orientated" cluster, distinguished by their focus on environmental sustainability, energy efficiency, and urban resilience. These cities exemplify strategic leadership in leveraging their dynamic capabilities to address local environmental challenges and improve residents' quality of life. By incorporating these classifications, the analysis gains depth and enables the identification of common patterns and divergences among cities with similar sustainability goals. Conversely, studies that were purely theoretical, lacked empirical data, or were not peer-reviewed were excluded. This stringent approach ensured the inclusion of only high-quality and relevant studies, enabling robust data synthesis. Furthermore, the inclusion of the classifications by Cantuarias-Villessuzanne et al. (2021) adds valuable insights into the strategic variations among smart cities, particularly the contrast between emerging strategies, technology-orientated approaches, and quality-of-life-focused initiatives. This categorisation provides a foundational framework for comparing sustainability strategies across diverse urban contexts, thereby enhancing the analytical rigour of the review.

Data extraction process

After screening, relevant studies were selected, and data were extracted using a structured form. The extracted data included the study ID, authors, year, title, city, sustainability strategies, and the impacts of these strategies on the environment, energy, waste management, and air quality. Data on the achievement of sustainability goals and challenges hindering progress were also recorded. Two reviewers independently extracted data to ensure consistency, and any disagreements were resolved through discussion. In total, 18 studies were included for data synthesis (see Appendix).

Quality assessment

The quality of each study was assessed using the Critical Appraisal Skills Programme (CASP) checklists. These checklists helped evaluate the methodological rigour of each study by examining aspects such as research design, clarity of objectives, and the appropriateness of the methodology used. Studies were rated as "high," "medium," or "low" quality based on how well they contributed to the understanding of sustainability strategies in smart cities. This process ensured that only credible and reliable studies were included in the final analysis.

Data synthesis

A thematic analysis was performed to synthesise the data extracted from the included studies. The sustainability strategies were categorised according to their impact on environmental footprint, energy consumption, waste management, and air quality. The analysis was organised by cities Zurich, Oslo, and Copenhagen to allow for comparisons across these cities. Additionally, common themes related to the challenges of implementing sustainability strategies were identified and analysed.

Results

Sustainability strategies of smart city

This section presents a thematic analysis of the sustainability strategies adopted by smart cities, focussing on Zurich, Oslo, and Copenhagen. Table 1 presents the extracted data from various studies, highlighting how these cities implement initiatives to promote environmental sustainability, improve urban living, and achieve long-term sustainability goals.

Sustainability strategies in Zurich

Zurich has adopted several sustainability strategies aimed at reducing its environmental footprint while promoting urban development. In a study conducted by Schrotter and Hürzeler (2020), it was discovered that the city emphasises urban densification, where it focuses on preserving its identity and minimising conflicts related to space usage. Complementary to this, the integration of information and communication technology (ICT) plays a significant role, with the presence of research institutions supporting the growth of the service sector (Duygan et al., 2021). As a result, these strategies balance Zurich's high urban density with sustainable practices.

Zurich has also made notable progress in the transportation sector. Menendez and Ambühl (2022) emphasise the city's efforts to reduce dependence on private cars by promoting public transportation and cycling. Moreover, these initiatives discourage motorised transport and

Table 1
Sustainable Development Strategies in Zurich, Oslo, and Copenhagen.

S/N	City	Planning Period	Main Components	Key Initiatives	Challenges
1.	Zurich	Targets 50 % reduction in GHG emissions by 2030 and net-zero by 2050	Urban densification, 2000-Watt Society strategy, digital twin tools, public transportation	Public participation in urban planning (e. g., Koch Area redevelopment)	High implementation costs, limited political
2.	Oslo	Aims for 50 % reduction in GHG emissions by 2020 and carbon neutrality by 2050	Electric mobility, renewable energy adoption, climate-smart urban areas	Electrification of public transport, biogas fuel adoption, Hoinbyen project	Barriers to zero-emission construction, addressing social equity
3.	Copenhagen	"Targets carbon neutrality by 2025″	Cycling infrastructure, smart mobility, waste-to-energy programs, smart energy grids	Traffic management systems, sensor networks for emissions monitoring, public–private collaborations	High implementation costs, slow technological adoption

Source: IMD Smart Cities Index Report (2023).

encourage residents to adopt human-powered mobility, which leads to a reduction in carbon emissions and an improvement in air quality. Furthermore,

Zurich's commitment to the green urban agenda is evident in projects that improve green spaces in densely populated areas, such as District 9 (Perić et al., 2023).

Another essential point is Zurich's focus on cooperative urban planning, which emphasises collaboration between stakeholders. According to Peric Momcilovic et al. (2022), the Koch Area redevelopment project in Zurich demonstrates this approach, where stakeholder engagement ensures that sustainable development goals are achieved. Nevertheless, challenges such as high costs and the need for increased public participation remain obstacles to fully realising these initiatives.

Sustainability strategies in Oslo

In comparison, Oslo has implemented a wide range of sustainability strategies to address climate change and promote urban sustainability. According to Hofsta and Torfing (2017), the city's climate and energy plan focuses on reducing its carbon footprint through collaboration across administrative sectors. Likewise, the use of mobility data to improve public services and engage citizens is essential to Oslo's smart city strategy (Julsrud & Krogstad, 2020). This demonstrates how technology and public involvement are integrated into Oslo's sustainability efforts.

In addition, Oslo has made significant investments in electric vehicles (EVs) and bicycles, offering incentives like free parking and exemptions from road tolls (Ruggieri et al., 2021). Moreover, the city uses biogas for city transport, reducing reliance on fossil fuels (Nikolov, 2024). Consequently, the transition to a car-free city centre promotes walking and cycling, which improve air quality and reduce emissions. In addition, Oslo's strategic plan for Hovinbyen aims to transform the area into a self-sufficient urban space, balancing environmental sustainability with economic development (Senior et al., 2021).

However, while these strategies have shown success, challenges persist. This implies that there exist high costs and difficulties in implementing zero-emission construction practices are ongoing issues (Nikolov, 2024). Despite this, Oslo continues to be a leader in sustainability, demonstrating the effectiveness of its policies in driving environmental change.

Sustainability strategies in Copenhagen

In contrast to Zurich and Oslo, Copenhagen has set an ambitious goal of becoming the world's first carbon–neutral capital by 2025 (Alaverdyan et al., 2018). Notably, the city has developed an extensive cycling infrastructure, promoting cycling as a primary mode of transportation. Similarly, Copenhagen has implemented innovative solutions across sectors such as transport, waste management, and alternative energy sources. According to Ipsen et al. (2019), the city's focus on green roofs, smart energy grids, and waste collection systems shows its commitment to sustainable urban development.

It is evident in the existing literature that through the Gate21 project, Copenhagen has positioned itself as a greater leader in green transition, with a focus on energy-efficient innovations in the climate and energy sectors (Bjørner, 2021). Furthermore, public–private partnerships between the municipality and citizens have played a crucial role in the city's success, demonstrating how collaboration fosters effective sustainability initiatives (Cristea et al., 2018). In addition, Copenhagen's smart mobility initiatives, such as smart traffic management systems and pedestrian detection systems, further contribute to reducing emissions and improving traffic flow (Wolniak, 2023). However, high costs and the slow implementation of new technologies remain challenges for Copenhagen, limiting the speed of its green transition (Sørensen et al., 2023).

Environmental footprint impacts in smart cities

This section presents the findings on the impact of sustainability strategies on the environmental footprint in the smart cities of Zurich, Oslo, and Copenhagen, based on 18 extracted studies. The analysis focuses on the reduction of greenhouse gas emissions, improved urban sustainability, and how smart city initiatives have influenced resource consumption and environmental resilience.

Environmental footprint in Zurich

Zurich has made significant strides in managing its environmental footprint through a variety of sustainability strategies. In a study conducted by Schrotter and Hürzeler (2020), it was emphasised that the use of urban planning tools like the digital twin to manage land use and urban growth sustainably. This approach seeks to mitigate both the positive and negative effects of population increases on the city's environmental footprint. Duygan et al. (2021) also highlight Zurich's integration of information and communication technology (ICT), which has reduced resource consumption and improved service efficiency. This demonstrates that the city's smart city framework is not only focused on technological growth but also on minimising environmental harm.

Moreover, Zurich's transportation strategies have proven effective in reducing the environmental footprint. Menendez and Ambühl (2022) show that greenhouse gas emissions from transportation, which account for 40 % of total emissions, have decreased significantly between 1990 and 2020. The city serves as a model in mobility-related emission reductions, reflecting Zurich's commitment to environmental sustainability. Additionally, green urban spaces have contributed positively to Zurich's footprint. Perić et al. (2023) emphasise how the presence of diverse green spaces promotes biodiversity and supports ecosystem services, both of which play a key role in reducing the environmental footprint. These strategies demonstrate the link between urban green spaces and environmental sustainability.

However, emerging challenges related to energy consumption remain critical. David et al. (2024) stress that while AI technologies have immense potential for improving sustainability, their energy consumption and the reliance of data centres on non-renewable energy sources pose a growing concern. This emphasises the need for Zurich to incorporate energy-efficient AI systems into its sustainability strategies to balance technological innovation with environmental preservation. AI-driven solutions, such as predictive energy optimization and emissions monitoring, could further reduce the city's carbon footprint while supporting its sustainability goals. However, some strategies remain more qualitative than quantitative. Toh (2022) discusses Zurich's efforts in waste management and climate change response, but specific metrics on environmental footprint reduction are not provided. Nevertheless, these strategies indicate the city's broad focus on sustainability.

Environmental footprint in Oslo

In comparison to Zurich, Oslo has adopted comprehensive strategies aimed at reducing its environmental footprint. Hofsta and Torfing (2017) describe Oslo's climate and energy plan, which promotes renewable energy and sustainable urban development to significantly reduce emissions. Consequently, these strategies have positively influenced the city's environmental sustainability. Oslo's smart city transformation has also resulted in notable emission reductions. Nikolov (2024) reports that the city's sustainability initiatives have decreased greenhouse gas emissions by 4,500 metric tonnes per year. Furthermore, Oslo's goal of 50 % emission reduction by 2020 and carbon neutrality by 2050 highlights the city's forward-looking approach to environmental sustainability (ruggieri et al., 2021).the city's forward-looking approach to environmental sustainability (Ruggieri et al., 2021).

The city's focus on electric vehicles (EVs) is another critical factor in reducing its environmental footprint. Ruggieri et al. (2021) discuss how Oslo was recognised as the world capital of electric cars in 2018, reflecting the successful adoption of EVs and a positive impact on the city's emissions profile. Similarly, Senior et al. (2021) point to Oslo's plan to create climate-smart urban areas, which further aligns with its broader goal of footprint reduction.

On the other hand, some challenges exist in translating theory into practice. Andersen and Skrede (2017) discuss how Oslo's sustainability ideals face challenges in implementation, which could indirectly affect its ability to reduce its environmental footprint. Despite this, Oslo's overall progress shows a strong commitment to environmental resilience.

Environmental footprint in Copenhagen

Copenhagen has also focused on reducing its environmental footprint through a range of smart city solutions. Firstly, the city's ambitious goal to become the world's first carbon–neutral capital by 2025 drives much of its environmental agenda (Alaverdyan et al., 2018). An evident initiative developed was to reduce water consumption from 100 L per person per day to 90 L by 2025 and demonstrate the city's efforts to lower resource usage.

Copenhagen has also made significant advances in transportation and air quality. In a study conducted by Wolniak (2023), it was revealed that the city's reduction in car dependency and smart mobility initiatives have contributed to improved air quality. This shift away from car use and toward more sustainable modes of transport has directly influenced Copenhagen's environmental footprint. However, not all Smart City Solutions (SCSs) have had a positive environmental impact. Ipsen et al. (2019) show that some SCSs, such as pneumatic waste collection systems, have actually increased the city's environmental burden. Nevertheless, Copenhagen's overall sustainability performance remains above average, suggesting that the positive effects of other solutions outweigh these negative impacts (Cristea et al., 2018).

In contrast to Zurich and Oslo, Copenhagen also benefits from strong public–private partnerships. Cristea et al. (2018) note that collaboration between the municipality and citizens has enabled the city to achieve higher levels of environmental performance. Subsequently, these partnerships have played a key role in supporting the city's transition to a low-carbon economy. The evidence presented in this section shows that the integration of smart technologies, green spaces, and sustainable transportation systems has significantly influenced the environmental sustainability of these cities.

Energy impact in smart cities

This review also explored the impact of sustainability strategies on energy consumption and efficiency in the smart cities of Zurich, Oslo, and Copenhagen. The analysis focuses on how smart technologies, renewable energy sources, and mobility solutions contribute to reducing energy usage and enhancing energy efficiency.

Energy impact in Zurich

Research has shown that Zurich has a clear commitment to improving energy efficiency through the adoption of smart technologies. Duygan et al. (2021) emphasise that Zurich's smart city strategies have increased energy efficiency, leveraging technological advancements to optimise resource use. This demonstrates the link between smart city infrastructure and reduced energy consumption. According to Menendez and Ambühl (2022), Zurich has set ambitious energy goals through its 2000-watt Society strategy, which aims to reduce energy consumption to 2000 W per person per year and CO_2 emissions to one tonne per person per year. This strategy highlights Zurich's determination to reduce mobility-related energy consumption, which accounts for 18 % of the city's total energy use and 37 % of its CO_2 emissions. Consequently, these initiatives contribute significantly to improving the city's energy sustainability.

Moreover, Zurich's integration of green spaces into urban planning supports energy efficiency. Perić et al. (2023) note that these spaces contribute to natural cooling and improved air quality, reducing the need for artificial cooling and ventilation. In addition, Peric Momcilovic et al. (2022) suggest that sustainable urban design strategies in Zurich improve energy efficiency through thoughtful urban planning. However, some studies, like Toh (2022), discuss Zurich's focus on green energy without providing specific data on the city's energy consumption impacts. Nevertheless, the city's high ranking in smart city indices implies effective energy management practices.

Energy impact in Oslo

In comparison, Oslo has prioritised renewable energy sources as part of its energy strategy. Hofsta and Torfing (2017) explain that the city's climate strategy emphasises the transition to renewable energy, which is essential for reducing reliance on fossil fuels and lowering energy consumption. This demonstrates Oslo's focus on mitigating climate change through energy transformation. Moreover, Oslo has made significant strides in electric mobility. Ruggieri et al. (2021) highlight how the city's focus on electric vehicles (EVs) improves energy efficiency by reducing the need for fossil fuels. This shift aligns with the city's broader goal of increasing the supply of renewable energy, which accounts for 60 % of Oslo's total energy consumption, primarily from hydropower (Nikolov, 2024).

Thus, Oslo's emphasis on renewable energy and electric mobility contributes to its energy sustainability goals.

Likewise, the city promotes alternative modes of transportation, such as walking, cycling, and public transit, as part of its strategy to reduce energy consumption (Senior et al., 2021). As a result, these initiatives have led to lower carbon emissions and reduced energy use in urban mobility. On the other hand, Andersen and Skrede (2017) discuss the challenges in turning urban theory into practice in Oslo, indicating that while the city's energy goals are ambitious, some barriers to implementation remain.

Energy impact in Copenhagen

In contrast to Zurich and Oslo, Copenhagen has also demonstrated a strong commitment to energy efficiency, particularly through the development of smart energy grids. Ipsen et al. (2019) show that the Smart Energy Grid solution in Copenhagen has improved the city's environmental performance, particularly with a 10 % reduction in the global warming potential (GWP). Nevertheless, the overall impact of Smart City Solutions (SCSs) on energy consumption has been mixed, with some solutions not significantly reducing energy use.

Copenhagen also prioritizes reducing energy consumption by utilizing alternative energy sources (Alaverdyan et al., 2018). The city's strategies reflect its efforts to promote energy-efficient innovations, aiming to create a society free of fossil fuels (Bjrner, 2021).

As a result, Copenhagen's transition towards renewable energy plays a crucial role in its broader sustainability goals. Besides, Copenhagen's smart mobility initiatives, as discussed by Wolniak (2023), contribute to energy savings by reducing car dependency and promoting more energy-efficient forms of transport. This demonstrates the city's focus on combining mobility solutions with energy efficiency strategies. However, Madsen (2018) notes the challenges in translating ideal smart city concepts into practice, implying that while Copenhagen's energy initiatives are promising, there may be difficulties in fully realising the expected energy savings.

Waste management in smart cities

The review also examined how smart city initiatives have improved waste management practices, recycling efforts, and overall waste-handling efficiency in these urban environments.

Waste management in Zurich

Zurich has improved waste management by integrating smart technologies and urban planning strategies. In a study conducted by Duygan et al. (2021), it was found that Zurich has improved its waste management practices and recycling initiatives, leading to more efficient handling of waste in the city. The integration of smart city infrastructure has helped Zurich optimise waste collection processes, improving overall efficiency. In addition, Toh (2022) emphasises that waste management is a key component of Zurich's broader sustainability strategy. While the paper does not provide specific data, it suggests that waste management is integral to the city's efforts to reduce its environmental footprint. This aligns with Zurich's focus on sustainable urban planning, which implicitly includes managing waste more effectively.

Also, the emphasis on cooperative planning and community participation in Zurich, as discussed by Peric Momcilovic et al. (2022), indicates that waste management could be improved through collaborative efforts between citizens and authorities. Consequently, the city's approach to dense and green urban development may lead to better waste handling, although the study does not provide direct evidence of this impact. However, Perić et al. (2023) note that their study does not explicitly address waste management strategies, focussing more on the green urban agenda in Zurich. Nevertheless, the city's integration of green spaces and sustainability practices may indirectly support more efficient waste management systems.

Waste management in Oslo

In comparison to Zurich, Oslo has adopted several smart city initiatives aimed at improving its waste management systems. Julsrud and Krogstad (2020) explain that Oslo leverages big data for urban planning, which can improve the efficiency of waste management systems. With the use of data-driven insights, Oslo can better monitor and optimise waste collection processes, contributing to a cleaner and more sustainable city. Additionally, Nikolov (2024) highlights that Oslo has made significant strides in improving the efficiency of its waste management practices. Thus, smart technologies have been applied to optimise waste collection, reducing the environmental impact and increasing overall efficiency in waste handling. Moreover, Oslo's broader focus on becoming a climate-resilient city indirectly supports its waste management strategies. Hofsta and Torfing (2017) describe how Oslo's commitment to sustainable urban development and climate change mitigation includes improved management of waste to reduce emissions and environmental harm. Therefore, Oslo's smart city strategy emphasises a holistic approach to sustainability, where waste management plays a critical role.

Waste management in Copenhagen

In contrast to Zurich and Oslo, Copenhagen has taken a more structured approach to waste management, with both successes and challenges. Ipsen et al. (2019) discuss the pneumatic waste collection system and greywater recycling solutions implemented in Copenhagen and revealed that while these systems were intended to improve efficiency, the study notes that they had minor negative performance effects on the city's global warming potential (GWP), indicating that some challenges remain in improving waste management outcomes. Nevertheless, Copenhagen continues to explore innovative waste management solutions as part of its broader sustainability goals. Also, Copenhagen's smart city strategy includes managing data related to waste, as highlighted by Madsen (2018). This data-driven approach focuses on garbage sorting and the optimisation of waste collection processes. As a result, Copenhagen's use of data in waste management aligns with the city's goal of becoming more efficient and sustainable.

In addition, Alaverdyan et al. (2018) emphasise that Copenhagen's smart city concept aims to reduce waste through alternative energy sources and more sustainable practices. Alaverdyan et al. (2018), also revealed that the city integrates waste management strategies into its broader urban planning initiatives, contributing to the reduction of waste and environmental impact. Considering these factors, it can be concluded that smart technologies and data-driven approaches are key to advancing waste management in smart cities, though challenges such as technological performance and public participation remain.

Air quality in smart cities

The review also explored how smart city initiatives, transportation policies, and green strategies contribute to improving air quality in these urban areas.

Air quality in Zurich

Zurich has seen improvements in air quality through the implementation of smart technologies and sustainable urban strategies. Duygan et al. (2021) note that the integration of smart city technologies in Zurich has contributed to better air quality by optimising urban systems and reducing emissions. In addition, Menendez and Ambühl (2022) highlight that Zurich's emphasis on reducing car dependency and promoting sustainable transport modes is expected to improve air quality. While specific data is not provided, the shift towards alternative transportation suggests a positive impact on urban air quality.

Besides, Perić et al. (2023) discuss the benefits of having natural environments close to urban areas, which improve air quality through the cooling effects of greenery and the reduction of airborne pollutants. Similarly, Peric Momcilovic et al. (2022) emphasise that Zurich's focus on creating healthy urban environments through green strategies likely contributes to cleaner air, aligning with the city's broader goals of improving public health and environmental sustainability. Also, Toh (2022) emphasises that improved governance and the use of technology in smart cities like Zurich can lead to improved environmental outcomes, including air quality improvements. Therefore, Zurich's comprehensive approach to urban planning and sustainability has a positive effect on its air quality, driven by both technological advancements and green infrastructure.

Air quality in Oslo

In comparison, Oslo has made substantial progress in improving air quality through its sustainable transport and emission-reduction initiatives. Hofsta and Torfing (2017) highlight Oslo's focus on reducing emissions through the promotion of sustainable transport, which includes reducing reliance on fossil fuels and encouraging public transport. These initiatives are expected to have a positive impact on air quality by decreasing the pollutants released into the atmosphere. Likewise, Oslo's push towards electric transport has played a crucial role in reducing vehicle emissions, which in turn improves air quality. Nikolov (2024) points out that Oslo's smart city initiatives, such as the reduction of car usage and the promotion of electric vehicles (EVs), directly contribute to lowering emissions, and enhancing the overall air quality in the city. Furthermore, Ruggieri et al. (2021) provide specific data showing a 22 % decrease in PM 2.5 and NO 2 emissions since 2016, indicating significant improvements in air quality due to the city's electric mobility initiatives.

Additionally, Senior et al. (2021) support these findings by emphasising that Oslo's promotion of sustainable transport options and the decrease in car reliance have led to cleaner air in the city. As a result, Oslo's approach to integrating smart technologies and promoting green transport modes has had a measurable positive impact on air quality, further supported by consistent monitoring data (Ruggieri et al., 2021).

Air quality in Copenhagen

In contrast, Copenhagen has similarly prioritised improving air quality through its smart mobility initiatives and emission-reduction strategies. Alaverdyan et al. (2018) explained that reducing emissions is a key goal of Copenhagen's smart city concept, contributing directly to the improvement of air quality. The city's focus on alternative energy sources and sustainable transport modes aligns with its broader objectives of reducing air pollution and enhancing environmental quality. Besides, Wolniak (2023) points out that Copenhagen's efforts to reduce car dependency through smart mobility solutions have led to improved air quality. Thus, through the promotion of cycling, walking, and public transportation, Copenhagen reduces the number of cars on the road, thereby decreasing the number of harmful pollutants in the atmosphere. This demonstrates the effectiveness of smart mobility in supporting cleaner urban environments.

As well, Copenhagen has taken steps to monitor and manage air quality as part of its broader sustainability agenda. Madsen (2018) states that the city tracks air pollution levels using data-driven solutions like sensor networks, enabling more targeted interventions to improve air quality. Hence, Copenhagen's smart city initiatives not only aim to reduce emissions but also use technology to maintain real-time monitoring and proactive management of air quality.

Achieved sustainability goals in the smart cities

This section's analysis examines the progress made in implementing sustainability initiatives, meeting environmental targets, and the overall effectiveness of smart city strategies in these cities.

Achieved sustainability goals in Zurich

Zurich has made consistent progress in achieving its sustainability goals. Zurich's smart city projects and initiatives have contributed to its high ranking in global sustainability indices, indicating progress toward its long-term goals (Duygan et al., 2021). The city's continued focus on smart technologies and green initiatives plays a key role in maintaining this momentum. Menendez and Ambühl (2022) also reveal that Zurich has successfully shifted the modal share in transportation, increasing the use of public transport and reducing reliance on private cars. This shift supports Zurich's sustainability targets, demonstrating that the city has achieved progress in reducing emissions and promoting sustainable mobility.

Urban planning initiatives such as the integration of green corridors and short distances have contributed positively to Zurich's sustainability efforts. Perić et al. (2023) emphasise the successful implementation of these principles, which are essential for achieving urban sustainability goals. Additionally, the Koch Areal redevelopment project, noted by Peric Momcilovic et al. (2022), demonstrates that Zurich's approach to public participation and urban planning is helping the city meet its sustainability objectives. Toh (2022) also suggests that Zurich's consistently high ranking in various global indices is a reflection of its progress toward sustainability goals. Thus, it can be concluded that Zurich has made significant strides in achieving its sustainability targets, particularly in areas such as mobility, urban planning, and public participation.

Achieved sustainability goals in Oslo

In comparison, Oslo has also made considerable progress in achieving its sustainability goals, particularly through its climate and energy initiatives. Hofsta and Torfing (2017) highlight that Oslo has established 76 new initiatives across multiple sectors, aiming to reduce emissions and promote a green shift in the city. However, the authors note that the full realisation of ambitious climate goals is still in progress, reflecting ongoing efforts toward Oslo's long-term sustainability objectives.

Substantively, Oslo has achieved significant milestones in greenhouse gas reduction and renewable energy usage. In tandem with this, Nikolov (2024) notes that Oslo has successfully reduced greenhouse gas emissions and increased its use of renewable energy, positioning the city as a leader in climate action. Similarly, Oslo's recognition as the "European Green Capital" in 2019 and its dominance in the battery electric vehicle (BEV) market demonstrate substantial progress toward achieving environmental sustainability (Ruggieri et al., 2021).

In essence, while Oslo has progressed in some areas, challenges remain in addressing social sustainability. Andersen and Skrede (2017) point out that despite Oslo's efforts, issues of social segregation persist, indicating that the city's social sustainability goals are not fully realized. Nevertheless, the overall achievements in climate action and renewable energy place Oslo among the top cities for sustainability progress.

Achieved sustainability goals in Copenhagen

In contrast, Copenhagen has made significant progress toward its sustainability goals, particularly in its ambition to become CO2-neutral by 2025. Copenhagen's focus on smart mobility and sustainable transportation has positioned the city as a global leader in climate action (Wolniak, 2023). Hence, the increase in the percentage of commuters cycling to work from 35 % in 2011 to a target of 50 % by 2050 demonstrates progress in achieving mobility-related sustainability goals (Alaverdyan et al., 2018).

Another achieved sustainability goal is that the quality of life in Copenhagen has improved as a result of its smart city initiatives. Cristea et al. (2018) highlight that citizen involvement in decision-making processes has been a key factor in the city's progress. Additionally, Copenhagen has set ambitious goals for fossil-fuel reduction and renewable energy usage, although Ipsen et al. (2019) suggest that some Smart City Solutions (SCSs) have had limited impacts on environmental sustainability. However, Copenhagen continues to face challenges in fully realising its sustainability targets. Ipsen et al. (2019) note that while the city aims to become CO2-neutral by 2025, some of the technologies and initiatives have not yet produced the desired environmental results. Nevertheless, Copenhagen remains a leader in sustainable transportation and climate action, reflecting its progress toward achieving sustainability goals.

CHALLENGES HINDERING PROGRESS IN SMART CITIES

The section of the review focuses on political, social, technological, and economic barriers that affect the cities' ability to fully achieve their sustainability goals.

Challenges hindering progress in Zurich

Zurich faces several challenges that impede its progress in achieving sustainability goals. According to Schrotter and Hürzeler (2020), the city struggles with competition for land use, noise, and usage conflicts. These issues arise from urban densification pressures, which limit the effectiveness of urban planning strategies. Duygan et al. (2021) also revealed that political organisation and funding constraints are significant barriers to Zurich's smart city development. The limited political alignment and insufficient financial resources slow down the implementation of key sustainability projects. Similarly, Menendez and Ambühl (2022) argue that Zurich needs integrative solutions to balance transportation efficiency with ecological concerns, suggesting that the city's sustainability efforts face ongoing challenges in managing the spatial footprint of its transport systems. Peric Momcilovic et al. (2022) also point out that despite the cooperative planning norms in Zurich, the level of public involvement remains insufficient, and conflicting stakeholder interests further complicate progress. In addition, Perić et al. (2023) highlight the lack of promotion of cultural diversity in green spaces, which hinders broader community engagement in sustainability efforts.

Furthermore, the reliance on multiple sustainability indexes and rankings can create confusion for cities like Zurich, making it difficult to measure progress consistently and effectively (Toh, 2022). These challenges demonstrate the complexity of balancing urban development with the pursuit of sustainability.

Challenges hindering progress in Oslo

Oslo also faces several key challenges in its sustainability journey. These challenges stem from public scepticism and distrust toward data-driven initiatives, which are major obstacles to the successful implementation of smart city projects (Julsrud & Krogstad, 2020). Public trust is essential for initiatives that rely heavily on technology and data collection. Other challenges stem from governance and policy continuity, which present additional barriers in Oslo. Reierating this Hofsta and Torfing (2017) highlight the need for continuous policy updates, internal capacity building, and improvements in governance structures to foster collaboration with external stakeholders. Without these updates, Oslo's sustainability efforts risk stagnating.

In the same vein, social sustainability remains a challenge in Oslo, as Andersen and Skrede (2017) emphasise the issues of residential segregation and divergent interests among urban planners. These challenges hinder the city's ability to achieve a holistic approach to sustainability, particularly in social equity. Thus, while Oslo has made notable progress in electric mobility and emission reduction, the complexity of managing urban air quality and the continuous need for improvement suggest ongoing challenges (Ruggieri et al., 2021). Senior et al. (2021) also argue that empowering citizens in smart city projects, particularly in new development areas, remains a difficult task, which can delay or hinder progress.

Challenges hindering progress in Copenhagen

Copenhagen also faces a range of challenges, particularly in terms of regulatory barriers and stakeholder engagement. Bjørner (2021) notes that siloed government structures and fragmented collaboration between municipalities hinder progress in the city's smart city initiatives. Moreover, Cristea et al. (2018) explained the lack of strong public–private partnerships, which is crucial for the successful implementation of smart city solutions.

Undoubtedly, funding limitations and the high cost of implementation are major barriers in Copenhagen. Wolniak (2023) emphasises that the limited space for infrastructure expansion, resistance from residents and businesses, and ongoing maintenance needs add to the complexity and cost of smart city projects. Similarly, Ipsen et al. (2019) argue that policymakers often overlook the embedded impacts of Smart City Solutions (SCSs), which limits their positive environmental outcomes. Additionally, Copenhagen's transition from idealised concepts to practical implementation faces challenges in data management. Madsen (2018) discusses the difficulty of aligning technological frames with city planning goals, which can complicate the translation of smart city ideas into actionable results. This implies that overcoming these barriers is essential for these cities to fully realise their sustainability and smart city objectives.

Discussion

The findings from this study reveal that Zurich, Oslo, and Copenhagen have embraced innovative sustainability strategies to tackle urban environmental challenges. These cities employ a mix of advanced technologies, urban planning innovations, and policy measures to reduce their environmental footprint, improve energy efficiency, and improve waste management and air quality. Each city's approach reflects its unique context, but they collectively illustrate how smart cities can lead the global shift toward sustainable urban development.

Zurich has made significant progress by integrating digital twin technologies to improve urban planning and infrastructure management. These tools allow city planners to simulate urban scenarios, optimise land use, and identify potential inefficiencies that lead to reduced resource consumption and emissions (Cantuarias-Villessuzanne et al., 2021). Substantively, Zurich's 2000-Watt Society strategy targets a 50 % reduction in energy consumption and greenhouse gas (GHG) emissions per capita by 2030. This strategy combines renewable energy adoption, energy-efficient building practices, and public transportation improvements to achieve ambitious sustainability goals (Schrotter & Hürzeler, 2020).

Zurich's transportation sector also plays a key role in its sustainability efforts. Public transportation and cycling infrastructure have significantly reduced car dependency, lowering emissions and improving air quality. The city's investment in green spaces, such as urban parks and tree-lined streets, promotes biodiversity while improving residents' quality of life (Perić et al., 2023). However, challenges remain, including the high costs of implementing advanced technologies and achieving political alignment to sustain long-term initiatives.

Oslo has prioritised electric mobility and renewable energy integration as part of its Climate and Energy Strategy, which aims to achieve carbon neutrality by 2050. The city's electrification of public transportation and widespread adoption of electric vehicles (EVs) have significantly reduced transportation-related emissions (Nikolov, 2024). Furthermore, Oslo uses biogas produced from organic waste as a renewable energy source to further diversify its clean energy portfolio (Duygan et al., 2021).

The Hovinbyen project, a large-scale urban development initiative, integrates smart energy systems and green infrastructure to create climate-resilient urban areas. Additionally, Oslo has embraced data-driven technologies to optimise traffic flow, manage energy distribution, and engage citizens in decision-making processes. While these efforts have positioned Oslo as a leader in sustainable urban development, the city faces challenges in ensuring equitable access to these green innovations, particularly for lower-income communities (Andersen & Skrede, 2017).

Copenhagen has garnered global recognition for its ambitious goal of becoming the world's first carbon–neutral capital by 2025. Extensive cycling infrastructure, smart mobility systems, and waste-to-energy programs support this objective by converting waste into usable energy and reducing landfill reliance (Bibri et al., 2023). The city's smart energy grids further optimise energy use by integrating renewable sources, such as wind and solar, into the urban energy system.

Strong public–private partnerships, which have driven innovation and funding for its sustainability initiatives, are the foundation of Copenhagen's success. For instance, its real-time traffic management systems use sensor networks and AI to reduce congestion and emissions. However, achieving such ambitious goals has not been without challenges. High implementation costs and slow technology adoption have occasionally hindered progress, highlighting the need for more scalable and affordable solutions (Ipsen et al., 2019).

While these cities are making significant strides, there is a need to address emerging challenges associated with advanced technologies. David et al. (2024) highlight that the growing adoption of artificial intelligence (AI) and Internet of Things (IoT) solutions in smart cities is driving up energy demands, particularly in data centres that rely heavily on nonrenewable energy sources. By 2030, AI technologies could account for up to 20 % of global electricity demand, contributing to a significant carbon footprint unless mitigated through energy-efficient algorithms and renewable-powered infrastructures.

The integration of AI in transportation, energy optimisation, and emission monitoring offers immense potential but requires careful consideration of its environmental trade-offs. Bibri et al. (2023) suggest that AI-driven predictive analytics and climate modelling can improve decision-making processes in urban planning, but their computational intensity poses challenges for sustainability.

Succinctly, the sustainability strategies of Zurich, Oslo, and Copenhagen provide valuable insights into how smart cities can address climate change and urban environmental challenges. Their use of advanced technologies, innovative policies, and stakeholder collaborations showcases the potential of sustainable urban development. However, addressing challenges such as high implementation costs, equitable access, and the environmental impact of emerging technologies will be critical to sustaining their progress. Future efforts should focus on integrating advanced technologies, like AI and IoT, in ways that minimize their ecological footprints while ensuring inclusivity and scalability.

Conclusion and recommendation

This study has examined the sustainability strategies adopted by Zurich, Oslo, and Copenhagen in their efforts to reduce environmental footprints, improve energy efficiency, manage waste, and improve air quality. The findings reveal that these smart cities have made significant strides in balancing economic growth, environmental protection, and social sustainability, as framed by the Triple Bottom Line (TBL) Theory. Zurich's focus on urban densification, green spaces, and public transport, Oslo's investment in electric vehicles, biogas, and renewable energy, and Copenhagen's ambitious goal of becoming carbon–neutral by 2025 demonstrate their leadership in global sustainability efforts. However, challenges such as high implementation costs, slow technological adoption, and social sustainability issues persist, highlighting the complexity of achieving long-term sustainability in urban development.

Despite significant progress, socio-economic barriers such as public participation and funding constraints continue to hinder the full realisation of these sustainability strategies. Additionally, technological limitations and the lack of quantitative data in certain areas, such as waste management and energy consumption, hinder a comprehensive understanding of the cities' long-term environmental impacts. Despite these challenges, the integration of smart technologies, green infrastructure, and collaborative planning has had a notable positive impact on the environmental and social landscapes of these cities.

To further strengthen future studies, it is essential to explore innovative solutions that address funding constraints and improve public engagement in sustainability initiatives. Researchers could also focus on the quantitative analysis of waste management efficiency and energy consumption patterns to provide a more holistic evaluation of sustainability outcomes. Additionally, longitudinal studies that monitor the long-term impacts of these strategies could offer invaluable insights into their effectiveness and scalability. Further investigation into the socio-economic dimensions of sustainability, such as equitable resource distribution and community inclusion, is recommended to ensure that smart city frameworks holistically address diverse urban challenges.

Drawing from the foregoing conclusions, this study proposes the following recommendations for countries across the globe to build on and improve the successes of their sustainability initiatives:

1 **Increase public participation and stakeholder engagement:** Cities should adopt more inclusive approaches to urban planning that engage a wider range of stakeholders, including residents, businesses, and community organizations. Enhancing public participation will help address social equity issues and ensure that sustainability initiatives reflect the needs of all citizens. Cities should consider hosting public forums and using digital platforms to encourage feedback on ongoing projects.

2 **Invest in Comprehensive Data Collection and Monitoring:** There is a need for more quantitative research on the impacts of sustainability strategies, particularly in areas like waste management and energy efficiency. Cities should invest in data collection technologies such as sensor networks and big data analytics to monitor real-time environmental impacts and adjust strategies accordingly. This will provide valuable insights into the long-term benefits and challenges of smart city initiatives.
3 **Strengthen Policy and Funding Frameworks for Sustainability Projects:** To address the challenges identified in Zurich, Oslo, and Copenhagen, it is crucial to improve policy frameworks that support sustainable urban initiatives. Governments and municipalities should prioritize funding mechanisms specifically tailored to sustainable transportation systems, renewable energy projects, and waste management infrastructure. Practically, Zurich could benefit from additional investments in its digital twin technologies to expand their application across all urban sectors, while Oslo's focus on electric mobility could be bolstered through subsidies or incentives for low-income residents to access electric vehicles.
4 **Improve Public Engagement and Social Equity:** The cities analyzed in this study have demonstrated significant environmental and economic progress; however, social sustainability remains a key challenge. Increasing public participation in decision-making processes and ensuring equitable access to sustainability benefits are vital. Copenhagen could focus on creating inclusive platforms to involve marginalized communities in planning its carbon–neutral initiatives. Similarly, Oslo should develop targeted programs to ensure that renewable energy benefits reach all socioeconomic groups.
5 **Promote Cross-City Collaboration and Knowledge Sharing:** Given the comparative nature of this study, fostering collaboration among smart cities globally is essential to accelerate progress. Zurich, Oslo, and Copenhagen should share their experiences, particularly in reducing environmental footprints and improving energy efficiency, through international networks like the C40 Cities Climate Leadership Group. Such collaborations could provide insights into scaling successful models, such as Zurich's 2000-Watt Society strategy or Copenhagen's waste-to-energy programs, in other urban contexts.
6 **Address Emerging Challenges of Technological Advancements:** The increasing reliance on AI and IoT in sustainability strategies presents significant energy consumption challenges. It is recommended that cities adopt energy-efficient AI algorithms and renewable-powered data centres to mitigate their environmental impacts. Oslo's integration of AI in transportation could include predictive analytics systems optimized for low energy use, while Zurich could explore renewable energy-powered data centres to support its digital twin initiatives.
7 **Develop Metrics for Monitoring and Evaluating Sustainability Outcomes:** To ensure accountability and track progress, cities should establish standardized metrics for monitoring and evaluating the impacts of their sustainability strategies. Zurich, Oslo, and Copenhagen could implement comprehensive reporting systems to quantify reductions in GHG emissions, energy savings, and improvements in air quality. These metrics should be integrated into annual sustainability reports to provide transparency and foster continuous improvement.

Study limitations

While the findings reveal several positive outcomes, there are notable limitations that affect the depth and scope of this analysis. One major limitation is the unavailability of detailed quantitative data on the impacts of sustainability strategies, particularly in areas such as waste management and energy consumption. While Zurich and Oslo have demonstrated significant progress in reducing emissions, detailed and standardized metrics on waste reduction and the long-term energy impacts of smart technologies, such as AI and IoT, are lacking, making it difficult to assess the broader environmental implications (Madsen, 2018; Toh, 2022).

Another limitation relates to the qualitative elements of the reviewed literature, where potential biases may have influenced the selection and interpretation of studies. The reliance on English-language peer-reviewed studies may have excluded valuable insights from non-English sources or grey literature, leading to a potentially skewed representation of smart city strategies and their outcomes. Additionally, the selection process may reflect a publication bias, as studies reporting positive impacts of sustainability initiatives are often more likely to be published, potentially downplaying challenges or failures in implementation.

Social sustainability issues, such as public participation and equity, also present limitations. These factors are inherently complex and challenging to quantify, and their measurement often relies on subjective assessments or case-specific narratives (Andersen & Skrede, 2017). This reliance on qualitative data, without consistent frameworks for measurement, may limit the ability to draw generalizable conclusions about the social dimensions of sustainability strategies. These limitations emphasize the need for more comprehensive and systematic data collection methods to address gaps in both quantitative and qualitative evidence. Future research should prioritize the inclusion of diverse data sources, standardized metrics for environmental and social impacts, and strategies to minimize biases in literature selection and interpretation. Such efforts will improve the reliability and applicability of findings, providing a more nuanced understanding of the long-term impacts of smart city initiatives.

CRediT authorship contribution statement

Oluwadamilola A. Oyadeyi: Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Olajide O. Oyadeyi:** Writing – original draft, Project administration, Validation, Supervision, Writing – review & editing.

Declaration of competing interest

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

Appendix

Study ID	Author)	((((s ((	Year	Title	City	Sustainabilit y Strategies	Impact on Environmental Footprint	Impact on Energy	Impact on Waste Management	Impact on Air Quality	Achieved Sustainabili ty Goals	Challenges Hindering Progress	Quality Assessment
1	Schrott and Hürzele	er r	2020	The digital twin of the city of Zurich for urban planning.	Zurich	The strategies for Zurich 2035 focus on urban densification, preserving identity, and minimising conflicts.	The goal is to manage land use and urban growth sustainably, addressing both positive and negative effects of increased population.					Significant challenges include increased competition for land use, noise, and usage conflicts.	Medium
2	Duygan et al.		2021	Where do Smart Cities grow? The spatial and socioeconomic configurations of smart city development	Zurich	Integration of Information and Communicati on Technology (ICT) High urban density Presence of research institutions Focus on the service sector	Reduction in resource consumption Improved service efficiency	Increased energy efficiency through smart technologies	Improved waste management practices Improved recycling initiatives	Improved air quality through smart city technologies	Progress in smart city projects and initiatives	Limited by political organisation Funding constraints	High
3	Menenz and Ambühl	de	2022	Implementing Design and Operational Measures for Sustainable Mobility: Lessons from Zurich.	Zurich	The paper discusses various integrated measures aimed at reducing dependency on private cars and promoting alternative modes of transport, such as public transport and cycling. Strategies include discouraging private motorized transport, encouraging public transport, and promoting humanpowered mobility.	Transportatio n accounts for around 40 % of total greenhouse gas emissions in Zurich, but emissions in this sector have decreased from 1990 to 2020, indicating a positive impact on environmental sustainability The city serves as a model for reducing mobilityrelated greenhouse gas emissions compared to the national trend	The city aims to reduce energy consumptio n to 2000 W per person per year and CO_2 emissions to one tonne per person per year as part of its 2000Watt Society strategy Mobility accounts for 18 % of energy consumed and 37 % of CO_2 emissions in Zurich		The reduction in car depen dency and promotion of sustainable transport modes is expected to improve air quality, although specific data is not provided in the contexts.	Zurich has consistently ranked high in various sustainability and smart city indices, indicating successful implementati on of its strategies. The modal share of public transport has increased at the expense of private cars over the past 20 years.	The paper highlights the need for integrative solutions to reduce ecological and spatial footprints while maintaining transportation efficiency, suggesting ongoing challenges in achieving these goals.	High
4	Toh		2022	IET Smart Cities.	Zurich	Zurich is recognized for its consistent ranking among the top cities, indicating that it likely employs various sustainability strategies, although specific strategies are not detailed in the contexts provided. The paper emphasizes the importance of governance,	The paper discusses sustainability in terms of environmental footprint but does not provide specific metrics for Zurich. It mentions that cities like Zurich are involved in handling waste management and responding to climate change, which would contribute positively to	While the paper highlights the importance of green energy and sustainable practices, it does not provide specific data on Zurich's impact on energy. However, it can be inferred that Zurich's high ranking suggests effective energy	The paper indicates that waste management is a critical component of sustainabilit y strategies in smart cities, including Zurich.	The paper found that improved governance and technology can lead to better environmental outcomes, which would include air quality improvemen ts.	The paper suggests that Zurich has consistently ranked high among cities, which may indicate that it has achieved certain sustainability goals.	The paper notes that the existence of multiple indexes and rankings can create confusion, which may hinder progress for cities like Zurich. Additionally, past performance affecting current rankings could be a challenge for cities that have made recent improvements.	High

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					technology, and environmenta l practices as part of smart city initiatives.	their environment al footprint.	manageme nt practices.					
5	Perić et al.	2023	Green Cities: Utopia or Reality? Evidence from Zurich, Switzerland.	Zurich	The study examines the integration of the 'green urban agenda' within various Swiss policies, particularly in district 9, which includes neighbourhoods like Altstetten and Albisrieden. This agenda aims to improve green spaces despite urban densification.	The presence of diverse green spaces contributes positively to the environmental footprint by promoting biodiversity and ecosystem services.	Green spaces are typically integrated into urban areas to support energy efficiency through natural cooling and improved air quality.	The contexts do not explicitly address waste management strategies or their impacts in Zurich.	The proximity of natural environment s to urban areas is noted to improve air quality.	The study indicates a satisfactory implementati on of principles like'short distances' and 'green corridors,' which are essential for achieving sustainability goals in urban planning.	Challenges include the need for better acknowledgement of residential behaviours and visitors' needs, as well as improving the quality and connectivity among green spaces. Additionally, the limited promotion of cultural diversity in green spaces may hinder broader community engagement.	High
6	Peric Momcilov ic et al.	2022	Urban Strategies for Dense and Green Zurich: From Healthy Neighbourhoo ds towards Healthy Communities?	Zurich	The paper discusses urban strategies that focus on cooperative planning and stakeholder engagement in urban development, particularly in relation to the Koch Area redevelopme nt project.	The study reflects on the sociospatial complexity of urban health, indicating that cooperation among stakeholders is essential for addressing environmental challenges.	The emphasis on green urban strategies suggests a potential positive impact on energy efficiency through sustainable design and planning.	The emphasis on cooperative planning may imply improved waste management practices through community participatio n.	The overall goal of creating healthy urban environment s suggests that green strategies could lead to improvements in air quality.	The paper highlights the ongoing efforts in urban redevelopment and public participation, indicating progress towards sustainability goals, particularly in the Koch Areal project.	The paper identifies challenges such as insufficient public participation and social inclusion, despite the cooperative planning norm in Swiss urban policy. The paper also notes political pressures and conflicting interests among stakeholders as obstacles.	High
7	Julsrud and Krogstad	2020	Is there enough trust for the smart city? exploring acceptance for use of mobile phone data in oslo and Tallinn.	Oslo	Oslo has implemented various smart city initiatives that leverage mobility data to improve urban living. The city focusses on integrating technology to improve public services and citizen engagement, which is essential for effective sustainability strategies.		The general trend in smart cities is to improve energy efficiency through data-driven solutions. This aligns with Oslo's goals of becoming a smarter city.	The integration of big data in urban planning can lead to more efficient waste management systems, which is a common goal among smart cities.	The paper highlights that smart city initiatives often aim to improve air quality through better urban planning and data utilisation.		The study notes that scepticism and distrust among citizens can hinder the acceptance of data-driven initiatives. This challenge is relevant for Oslo, where public trust is essential for successful implementation.	Medium
8	Hofsta and Torfing	2017	Towards a climateresilient city: Collaborative innovation for a 'green shift'in Oslo.	Oslo	Oslo has implemented a comprehensi ve climate and energy plan aimed at becoming a low-carbon city. This includes establishing cross-cutting climate groups to improve collaboration across various administrativ e sectors.	The strategies are designed to significantly reduce the city's environmental footprint by promoting renewable energy and sustainable urban development.	The city government emphasises climate change mitigation, aiming to transition to renewable energy sources, which is a core component of their climate strategy.		The initiatives aimed at reducing emissions and promoting sustainable transport are expected to improve air quality in Oslo.	Oslo has made significant progress in establishing collaborative frameworks and initiatives, resulting in 76 new initiatives across 16 administrativ e sectors. However, the full realisation of ambitious climate goals is still in progress.	Challenges include the need for continuous updates to policies, internal capacity building, and the transition of governance structures to facilitate collaboration with external stakeholders.	High

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9	Senior et al.	2021	Empowering citizens in a smart city project one step at a time: A Norwegian case study.	Oslo	The strategic plan for Hovinbyen aims to transform the area into a self-sufficient urban space with shops, restaurants, and services, promoting a blue-green structure for sustainability.	The development plan emphasises the creation of a climatesmart urban area, suggesting a focus on reducing the environment al footprint.	The plan includes promoting walking, cycling, and public transport as the primary modes of travel, which can lead to reduced energy consumptio n and lower carbon emissions.		Promoting sustainable transport options and decreasing reliance on cars improves air quality.	The contexts indicate that the strategic plan has involved public participation and engagement, which is a step towards achieving sustainability goals, but specific goals achieved are not detailed.	The contexts mention that empowering citizens at all stages of the project can be challenging, particularly in new development areas, which may hinder progress in achieving sustainability goals.	High
10	Nikolov	2024	Smart cities as a tool for environmental sustainability: opportunities and challenges.	Oslo	Oslo has implemented several sustainability strategies, including: A car-free city centre to promote walking and cycling. Investment in electric transport and bicycles. Use of biogas for city transport and heavy-duty vehicles produced locally. Regulatory restrictions on construction without fossil fuels and the use of zero-emission machines.	The transformatio n into a smart city has led to a significant reduction in greenhouse gas emissions, with a decrease of 4,500 metric tons/year.	Approximat ely 60 % of Oslo's total energy consumptio n comes from renewable sources, primarily hydropower. The city encourages electric vehicle ownership through tax cuts and the creation of numerous charging stations.	Oslo has made strides in waste management efficiency.	The initiatives in Oslo, such as reducing car usage and promoting electric transport, contribute positively to air quality by lowering emissions from traditional vehicles.	Oslo has achieved notable sustainability goals, including a significant reduction in greenhouse gas emissions and a high percentage of renewable energy usage.	While specific challenges for Oslo were not detailed, common challenges in smart cities include the dependence on data management and the need for substantial investments in infrastructure and technology.	High
11	Ruggieri et al.	2021	Electric mobility in a smart city: European overview.	Oslo	Oslo has adopted a comprehensi ve energy strategy, "The Climate and Energy Strategy," which aims for a transition to an energy system powered entirely by renewable sources. The city has implemented various incentives for electric vehicles (EVs), such as exemptions from road tolls, VAT, and	The strategies have led to a significant reduction in greenhouse gas emissions, with goals of 50 % reduction by 2020 and carbon neutrality by 2050. Oslo was recognised as the world capital of electric cars in 2018, indicating a positive shift in the environmental footprint due to increased EV adoption.	The city aims to improve energy efficiency and increase the supply of renewable energy, which is crucial for achieving its sustainabilit y goals. The focus on electric mobility is expected to reduce reliance on fossil fuels, contributing to a cleaner energy landscape.		Monitoring data indicates a 22 % decrease in PM 2.5 and NO 2 emissions since 2016, showcasing improvements in air quality due to implemente d policies. The annual average of PM 10 was reported to be well below the WHO recommend ed threshold, further indicating improved air quality.	Oslo has made significant strides, such as earning the title of "European Green Capital" in 2019 and dominating the market for battery electric vehicles (BEVs).	The contexts do not explicitly mention obstacles to progress, but the complexity of urban air quality management and the need for continuous improvement suggest ongoing challenges.	High

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					registration taxes, as well as free parking.						
12	Andersen and Skrede	2017	Planning for a sustainable Oslo: the challenge of turning urban theory into practice.	Oslo	Oslo's municipal authorities have launched a master plan titled "Smart, safe and green: Oslo towards 2030″ to address population growth and promote sustainability	The paper discusses the challenges of turning sustainability ideals into practice, indicating that the official strategy may not effectively cater to social sustainability, which can indirectly affect the environmental footprint			The paper suggests that while there are goals for social sustainability, the reality shows a reproduction of segregation, indicating that these goals are not fully achieved	Key challenges include divergent interests among city makers, residential segregation, and the lack of a concise understanding of sustainability	Medium
13	Bjørner	2021	The advantages of and barriers to being smart in a smart city: The perceptions of project managers within a smart city cluster project in Greater Copenhagen	Copenhagen	The Gate21 project's vision aims to position Greater Copenhagen as a leader in green transition and growth, focusing on energy and resource-efficient innovations in the climate and energy sectors	The project managers perceive various needs and goals related to smart city innovations, which may positively influence the environmental footprint	The strategies involve developing and deploying new energy-efficient innovations, contributing to the goal of a fossilfuel-free society		The study indicates a focus on ambitious targets for a fossil-fuelfree society, but specific goals are not detailed	Major barriers include regulations, silos, and stakeholder issues, such as companies overpromising.	Medium
14	Ipsen et al.	2019	Environmenta l assessment of Smart City Solutions using a coupled urban metabolism—life cycle impact assessment approach.	Copenhagen	The study evaluates seven Smart City Solutions (SCSs) implemented in Copenhagen, including Green Roofs, Smart Windows, Pneumatic Waste Collection, Sensorized Waste Collection, Smart Water Meters, Greywater Recycling, and Smart Energy Grid.	Implementati on of SCSs generally has a negative influence on Copenhagen's environmental sustainability performance, with some solutions increasing the environment al burden.	The study indicates that the Smart Energy Grid solution shows a 10 % improvement in environmental performanc e concerning global warming potential (GWP). However, the overall influence of SCSs on energy consumption is not significantly positive.	The pneumatic waste collection and greywater recycling solutions have minor negative performance effects on GWP, indicating challenges in waste management improveme nt.	Copenhagen aims to become CO2 neutral by 2025, but the study suggests that the SCSs analysed have limited ability to positively alter the environmental sustainability performance of the urban system.	Policymakers often overlook the burden shifting from direct impacts to embedded impacts, which accounts for the limited positive influence from SCSs. Additionally, the focus of SCSs may not align with the major contributors to environmental burdens in Copenhagen.	High

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15	Madsen	2018	Data in the smart city: How incongruent frames challenge the transition from ideal to practice.	Copenhagen	The project "Copenhagen Connect" aimed to integrate ICT with urban planning, utilize sensor data for city understandin g, and promote crowdsourced data solutions.	The paper discusses the challenges of translating idealized smart city concepts into practice, implying potential improvements but not quantifying specific impacts.		The project included managing data related to waste (e.g., garbage sorting)			The existence of incongruent technological frames and the complexity of data interpretation are noted as significant challenges.	Medium
16	Alaverdy an et al.	2018	Implementatio n of the smart city concept in the eu: importance of cluster initiatives and best practice cases.	Copenhagen	Vision to become the world's first carbonneutral capital by 2025. Implementati on of innovative solutions in transport, waste, water, heating, and alternative energy sources. Extensive cycling infrastructure and promotion of cycling as a primary mode of transport.	Aims to reduce each citizen's water consumption from 100 L per day to 90 L by 2025. Initiatives to attract innovative companies to support a greener economy.	Focus on alternative energy sources and reducing energy consumption.		Reduction of emissions is a key goal, contributing to improved air quality.	Increase in the percentage of commuters cycling to work from 35 % in 2011 to a target of 50 % by 2050.		High
17	Cristea et al.	2018	Copenhagen as a smart city. In *Proceeding s of the International Management Conference*	Copenhagen	Collaboration between municipality and citizens, public–private partnerships, advanced egovernment competence.	Copenhagen surpasses the average in all sectors, indicating a positive impact.				High quality of life, citizen involvement in decisionmaking.	Fragmented government work, insufficient collaboration between municipalities, challenges in building publicprivate partnerships.	High
18	Wolniak	2023	Smart mobility in smart city–Copenhagen and Barcelona comparision.	Copenhagen	Promotion of sustainable transportation modes (cycling, walking, public transport), smart traffic management, pedestrian and cyclist detection systems.	Reduced car dependency and improved air quality.			Improved air quality due to reduced car dependency.	Positioned as a leader in sustainable transportatio n and climate action.	Limited space for infrastructure expansion, resistance from residents/ busines ses, high implementation costs, ongoing maintenance needs, and limited resources/funding.	High

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