Carbon Footprint Reduction through Modern Supply-Chain Measures

Subjects: Green & Sustainable Science & Technology
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The worldwide Sustainable Development Goals (SDGs) for smart cities and communities focus significant attention on air quality and climate change. Technology and management can reduce fossil fuel dependence in smart cities' energy supply chains (SC). A sustainable smart city and reduced carbon emissions require coordinated technology and management with appropriate infrastructure.

Sustainable Development Goals carbon footprint climate change greenhouse gas

1. Introduction

In today's cities, populations are growing due to uncontrolled migration, causing several problems. To address this issue, it is necessary to progress toward sustainability by reducing greenhouse gas (GHG) emissions and mitigating climate change by the United Nations' 2030 and 2050 targets [1].

In addition, the increasing number of people moving to cities has led to growth of urban areas, which has harmful consequences such as higher energy consumption, deforestation, and the extinction of plants and animals. In essence, cities are becoming a threat to planet because they consume many natural resources [2].

2. Greenhouse Emissions and Carbon Footprint

One of the elements for the quick increase in global temperature is the "Enhanced Greenhouse Effect", or the greenhouse effect that nature has contributed to because of human-caused GHG emissions into the atmosphere. This influence may speed up negative results like climate change. Although not all GHGs have the same capacity to warm the atmosphere, this capacity depends on the radiative power they provide and how long, on average, their molecules stay in the atmosphere [3].

Any gas's "global warming potential" (GWP) refers to a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period relative to the emissions of 1 ton of carbon dioxide (CO_2). Consequently, one GWP unit equals one kilogram of carbon dioxide (CO_{2eq}) [4]. GHGs are an insulating blanket that warms the Earth by absorbing energy and limiting its escape into space. The warming of the Earth may be influenced in many ways by various GHGs. These gases vary from one another, primarily in terms of their capacity to absorb energy (known as "radiative efficiency") and the length of time they remain in the atmosphere (also known as their "lifetime") [5].

GWP was created to compare the effects of various gases on global warming. It calculates the energy that a ton of gas or regular CO_2 emissions will absorb over a certain period. The higher the GWP, the more gas warms the Earth than CO_2. By standardizing measurements, GWPs allow analysts to estimate gas emissions (e.g., to compile a national GHG inventor). They enable decision makers to evaluate emission-reduction prospects across industries and gases [6].

According to the US Environmental Protection Agency (US EPA), C.F measures all direct and indirect GHG emissions from an activity or product's life cycle [7]. This term covers goods, services, people, groups, governments, businesses, etc. All direct, internal, off-site, external, embodied, upstream, and downstream emissions must be included [8].

Governments and practitioners may use the C.F definition to answer research-related questions about smart cities. Although CO_2 is a part of GHGs, it is also essential to consider other compounds that contribute to greenhouse warming, such as SOx and NOx [7].

The most critical part of these air pollutants is C.F and, as studied by Lombardi et al., this is defined as "CO_2 and other GHG gases over the whole life cycle of a process or product", as follows, in Equation (1) [8]:

$$C.F = CO_2 + GHG \quad (1)$$

C.F is carbon footprint, CO_2 is carbon dioxide, and GHG is greenhouse gas.

3. Carbon Footprint Reduction in Smart Cities across the Supply Chain

Cities and residential places are significantly more digitally and technologically advanced nowadays. The performance of outdated equipment and infrastructure is currently being updated, driven by data analytics [9]. Therefore, complex sociocultural developments are the outcome of technological developments. On the other hand, countries are starting to battle climate change and carefully monitor its environmental effects, so there is a well-recognized need to lower the environmental and climatic footprint, particularly C.F, in order to offer cleaner energy sources or more efficient energy services [10].

Furthermore, digital SC management, which is defined as "A type of SC management system that uses advanced technology and automated data analysis methods to optimize the flow of goods and services from suppliers to consumers", is used in place of traditional SC management to mitigate smart cities C.F [11].

A report by "Carbon Trust" titled "Carbon Footprints in the SC, the Next Step for Business" states how contemporary carbon management must be used across the whole SC, starting with raw materials and ending with the use and disposal of the final product or service. That is, the adoption of automated analysis techniques evolving the traditional SC to smart or digital SCs.

Figure 2 from the abovementioned report contrasts traditional and modern emission management strategies in SC [12]. The following paragraphs describe the relationship between smart cities and sustainable and digital SCs.

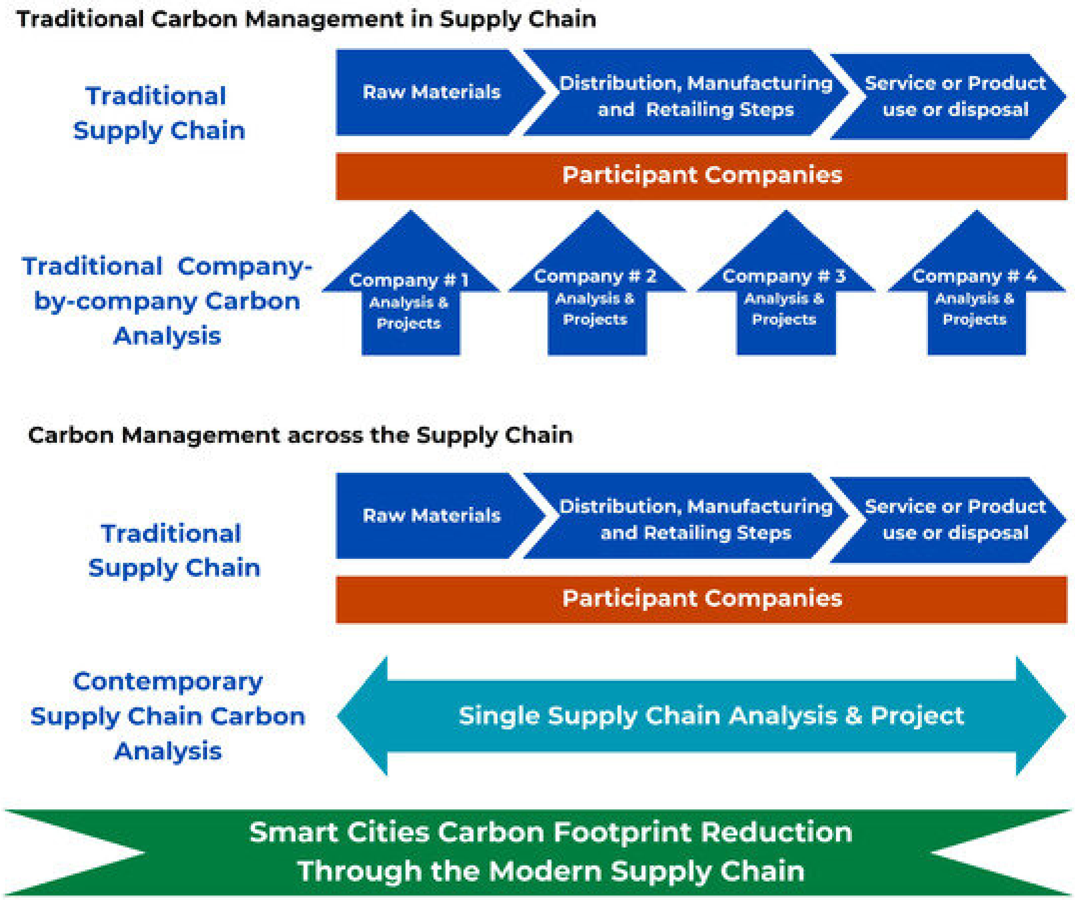

Figure 2. The comparison of traditional and contemporary methods of managing emissions across SC, based on [12].

Modern SC management and emission mitigation have particular applications in the era of mass customization and new technologies, as well as new structures such as last-mile delivery and other forms of smart logistics. Both smart city and modern SC management use inelegancy, innovative technology, and data-driven insights to improve efficiency and sustainability.

Furthermore, cutting-edge technologies, such as the Internet of Things (IoT), cloud computing, and artificial intelligence (AI), help smart cities collect and evaluate real-time data from traffic, energy, and waste management systems. This data allow SC managers to choose transportation routes, manage inventory, and predict demand. Traffic congestion data help SC managers optimize delivery routes and timetables, lowering transportation costs and emissions [9].

Consequently, technology integration in smart cities improves SC coordination and communication. Real-time product monitoring utilizing radio-frequency identification (RFID) or Global Positioning System (GPS) technology allows SC management to identify and fix delivery issues quickly. Smart cities enable smart warehouses that use automation, robots, and predictive analytics to manage inventory better and fulfil orders.

By integrating these technologies, SC managers may improve responsiveness, accuracy, and traceability, delivering items on time, reducing waste, and improving customer satisfaction. As smart cities and modern SC management have several synergies to enhance SC efficiency, accuracy, and sustainability, it is necessary to assess smart city components and analyse their emission-reduction effects.

During the Conference on Climate Change 2014, the International Panel on Climate Change (IPCC) examined the subject of C.F in detail and discovered that 27 cities with a population of over 10 million produced around 12.6% of the total air pollution in the world [13]. This highlights the need to research strategies for lowering C.F in smart and big cities [14].

On the other hand, using the elements shown in **Figure 3**, global and digital SC may aid in C.F mitigation in smart cities, according to a study by Yuanchao Hu et al. [15].

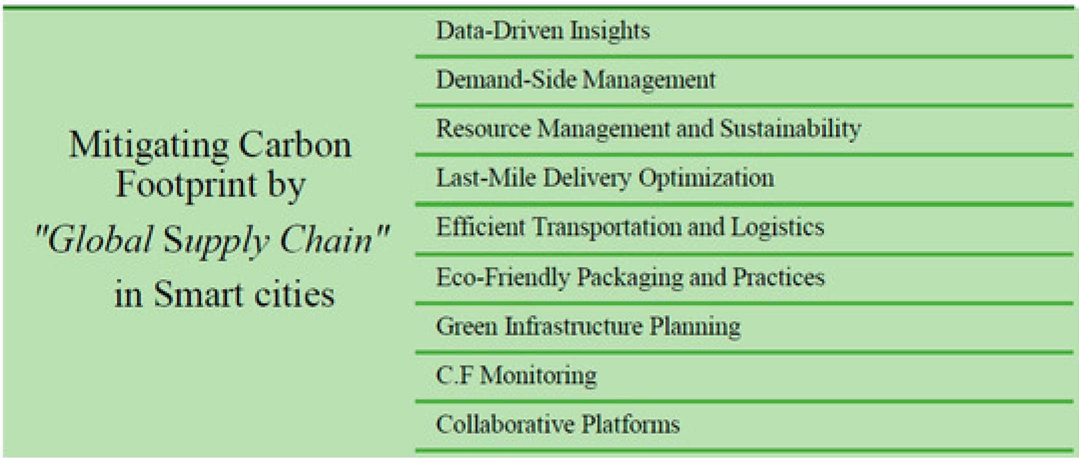

Figure 3. Global SC mitigation of C.F in smart cities, based on [15].

Utilizing all of the features shown in **Figure 3**, the most prevalent SC characteristics in smart cities might minimize the generation of C.F, aiding in the fight against climate change [15].

On the other hand, based on other studies, it was found that accurate estimation and analysis of C.F of cities could provide policymakers with more valuable information than the fundamental data of countries' C.F, which is presented in the dimensions of a country and can help them come up with better strategies [8].

4. Smart Cities' Components and Performance Contribution in Emission Reduction

A smart city comprises many different things, such as advanced technology in infrastructure, transportation, energy, healthcare, communication, and governance (see **Figure 4**). These components may interact to form new ones, but must rely on each other to perform optimally and wisely. Each high-tech part works with IoT, ICTs, and other network infrastructures to reduce pollution and aid smart cities in their fight against climate change [13].

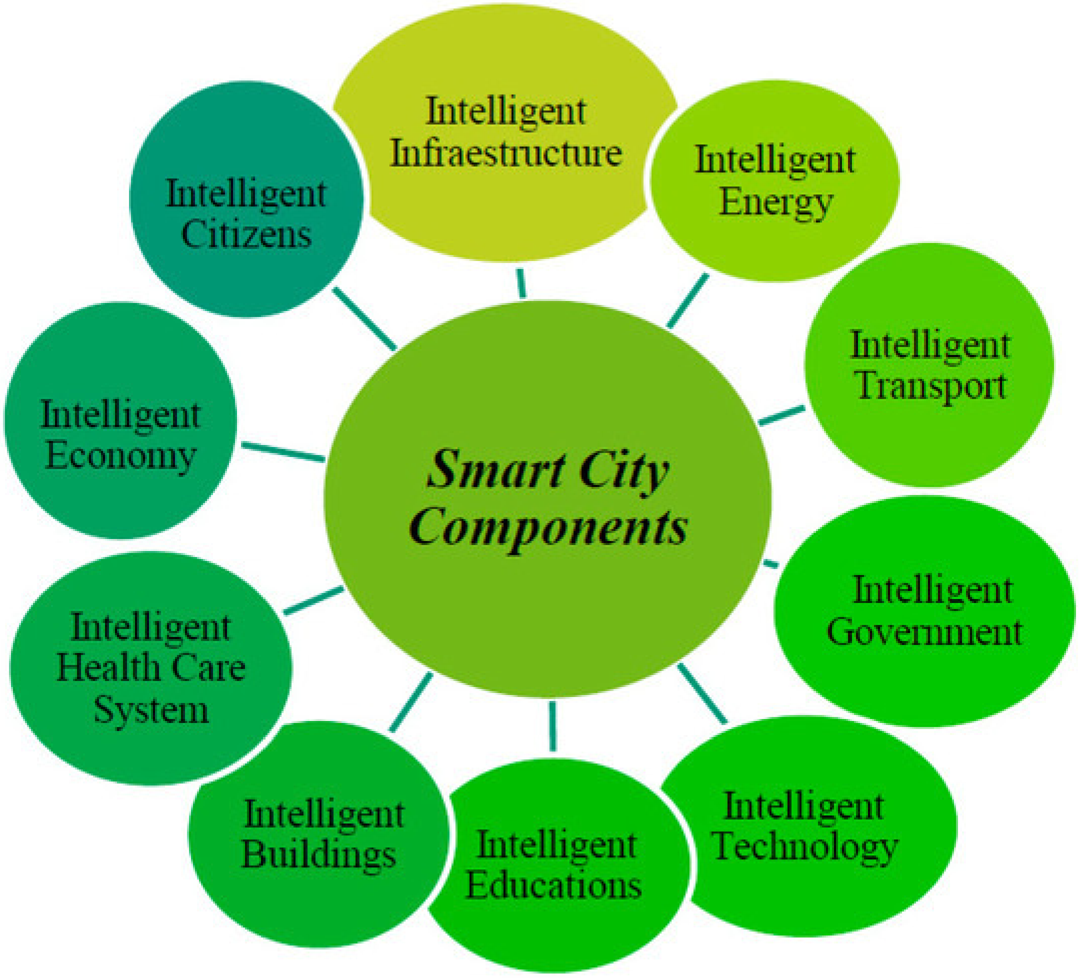

Figure 4. Components of smart cities, based on [13].

In addition, there are three distinct types of smart city criteria:

- Attributes (such as sustainability, quality of life, urbanization, and smartness);
- Themes (such as society, economics, environment, and governance);
- Infrastructures (such as physical infrastructure and transport) [13].

The novelty of issues in the UN's Sustainable Development Goals, the conclusions of the climate change review, and the evaluation of the article by Yigitcanlar et al. led to the conclusion that more innovation and creativity must be used in the development of new technologies and in the search for methods to reduce CO_2 emissions [16].

Naturally, it should be kept in mind that each city should act in line with its distinctive traits, such as its climate, infrastructure, restrictions, and features, and that solutions should be appropriate for that city's and region's environment [17].

In contrast, the contributions proving that a smart city might reduce C.F rates are listed numerically in **Figure 5** [18][19].

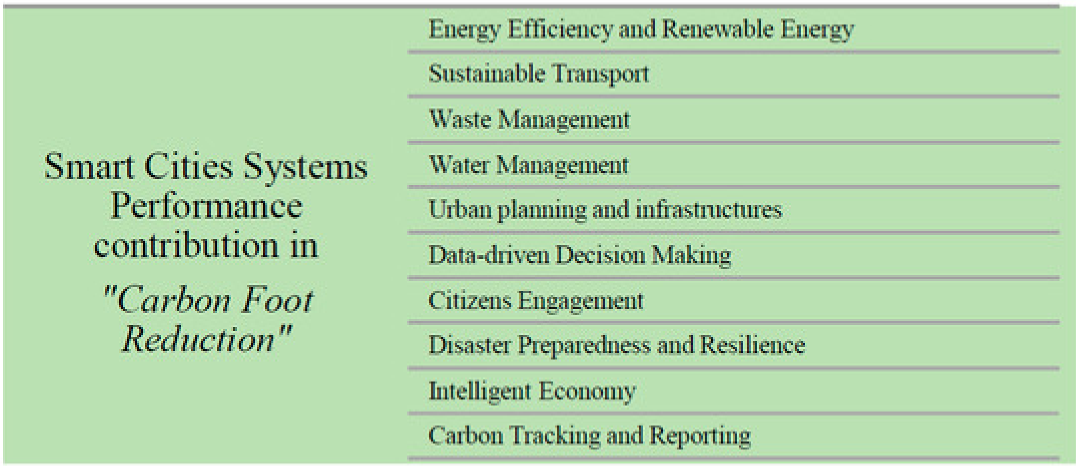

Figure 5. Smart cities' system performance when reducing C.F, based on [18][19].

As a result, there may be some extra categories and issues associated with each consequence of smart cities and their contribution to C.F reduction; each contribution has been briefly explored in the following sections with the assistance of some limited valuable examples.

5. Energy Efficiency and Renewable Energy

Smart cities may lower their C.F by using efficient and renewable energy, as shown by the components in **Figure 6**.

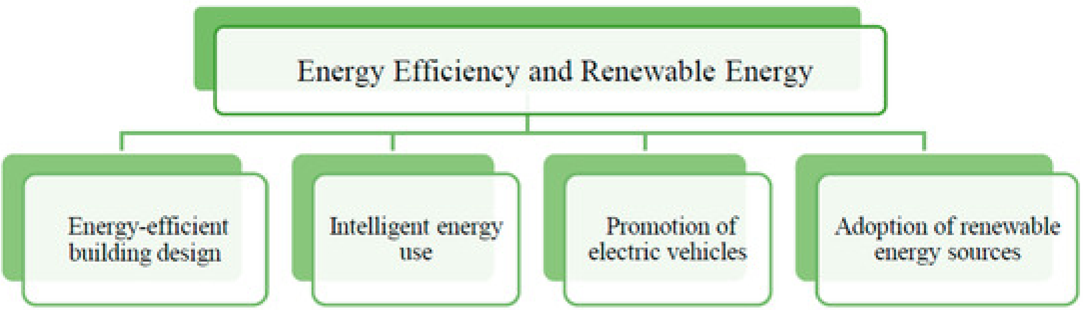

Figure 6. Components of energy efficiency and renewable energy to mitigate C.F in smart cities, based on [20].

These four elements could cooperate with other groups that impact pollution reduction, in addition to acting alone. By implementing "energy-efficient practices", smart cities can lower their energy usage. To maximize "intelligent energy use", energy management systems, smart meters, and smart grids are used. For "renewable energies", solar, wind, geothermal, and other energy sources can assist smart cities in lowering their dependency on fossil fuels to produce electricity. In smart cities, "electric vehicles (EVs)" contribute to a decrease in pollution emissions caused by transportation.

Their environmental benefits are increased by installing charging infrastructure powered by renewable energy. Building with "energy-efficient design and materials, insulation, and ventilation" may significantly reduce the built environment's C.F Utilizing occupancy sensors, smart lighting, and temperature control, buildings can use less energy. Furthermore, recycling, composting, and other environmentally sound waste management practices reduce GHG emissions from landfills. This involves encouraging recycling, enhanced waste processing, and sustainable waste disposal [21].

According to research by Guangwu Chen et al. in Australia, the country's five largest smart cities, including Brisbane, Adelaide, Sydney, Melbourne, and Perth alone, release more than half of the country's total carbon dioxide output [22].

This main results state the importance of C.F mitigation in industrial and smart cities. However, the vital point is the "city carbon map" method; the life cycle approach (LCA) has also been used to estimate all CO_2 emissions. In this way, C.F in a smart city can be expressed using Equation (2), as follows:

$$C.F = RTE + EEI + EEE \quad (2)$$

where RTE is the remaining territorial emission (all emissions inside the territory of a city), EEI is emission embodied import (all emissions due to activities in the city's hinterland resulting from globalization), and EEE is emission embodied export (all products and services exported from cities, leading to emissions).

According to another research work by Castro et al., lighting consumes 19% of global power and produces 6% of GHGs. Smart cities that use IoT may help to prevent climate change by running lighter cities and buildings with fewer resources.

The Internet Protocol for Smart Objects (IPSO) alliance application may control smart city lights by employing chronological and astronomical scheduling, environmental and human behavior, concrete events programming, alarm conditions, and complex program logic or intelligent inference [23].

Intelligent control of a lighting management system contributes to sustainable architecture and lighting system designs, such as green energy environments, by allowing for remote monitoring and operation of the entire system to achieve an efficient operating mode, while preserving appropriate behavior based on physical-world interactions and reducing energy consumption.

6. Sustainable Transport

A smart city's second way to reduce C.F is by providing shrewd and environmentally friendly mobility and transport. This group may reduce emissions by carrying out the actions shown in **Figure 7** [24]:

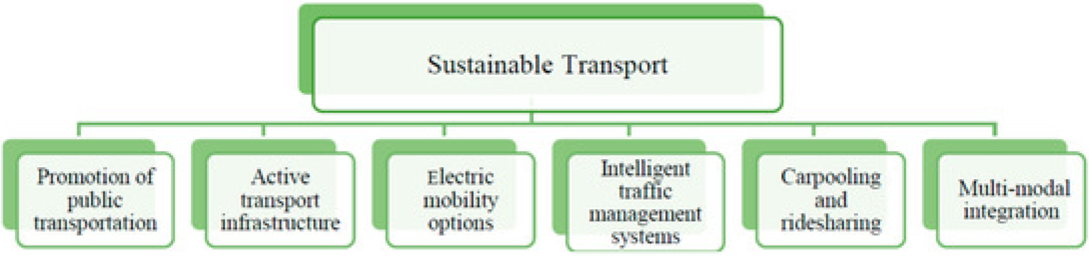

Figure 7. Sustainable transport components to reduce C.F in smart cities, based on [24].

"Public transportation" use declined as it increased. Carbon emissions from "electric vehicles (EVs)" were drastically reduced. "Active transport infrastructure" was promoted in smart cities with a convenient and safe walking and cycling infrastructure. "Carpooling and ridesharing" increase vehicle occupancy, while reducing emissions.

Travel time and pollution decrease when traffic flow is optimized utilizing effective "intelligent traffic management technologies". Sustainable mobility is promoted through easing integration and communication across "multi-model integration of transportation". This comprehensive plan provides locals access to simple, environmentally friendly car options [25].

In the research, the University of South Florida and the Islamia University of Bahawalpur examined how well intelligent transportation and intelligent governance performed in concert [26]. It proposes a new technique for gathering data utilizing wireless sensor networks (WSNs), which comprise tiny, inexpensive, and autonomous nodes that can be monitored from fixed nodes across the city.

The structure of wireless sensor networks is shown in **Figure 8**. The workings of a WSN system are shown in the following:

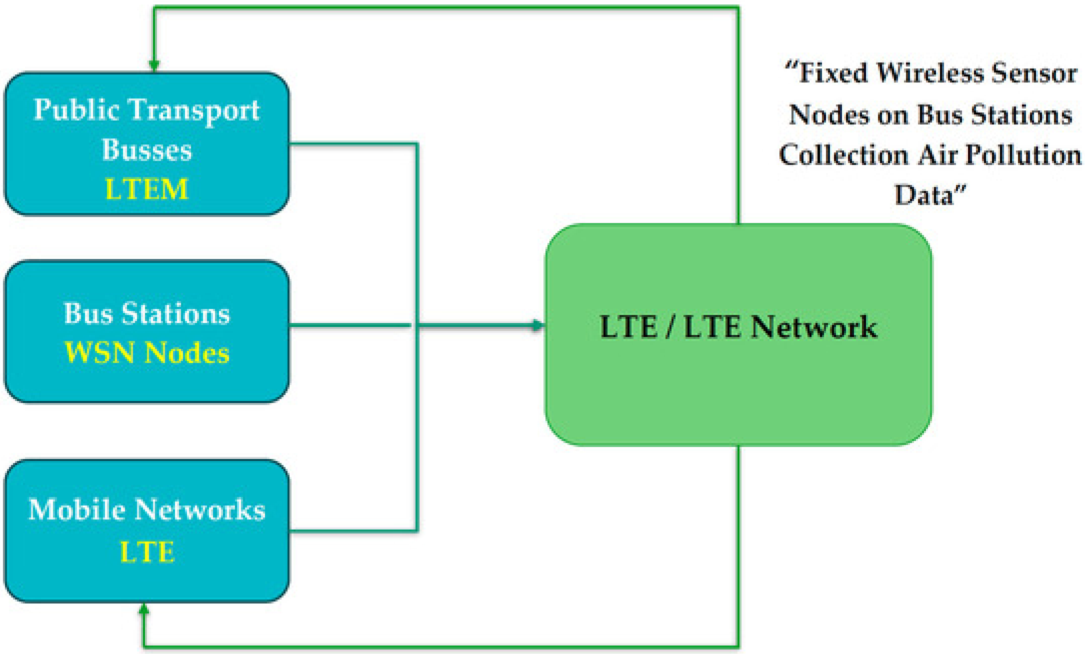

Figure 8. WSN working method, based on [26].

(A)Communication part;

(B)Memory region;

(C)Sensor node.

All of the steps were taken from the same work study.

The proposal incorporates IoT and long-term evolution mobile (LTE-M) modules, which are practical, cost-efficient solutions for machine-to-machine (M2M) devices. It is possible to monitor air quality throughout a smart city using both fixed and mobile nodes to comprehend the concept of air pollution and develop a strategy to reduce C.F. This example can help understand the role of sustainable and intelligent transportation infrastructure in smart cities and its role in reducing emissions and, as a result, C.F [26].

7. Waste Management

Waste management is one of the most crucial functions of smart cities, and studies have argued that it might significantly reduce the quantity of C.F in such cities. According to **Figure 9**, the following variables are impacted by waste management [27]:

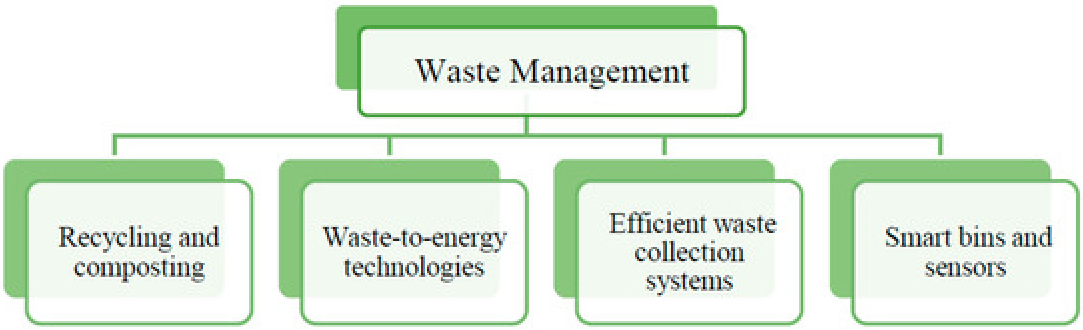

Figure 9. Waste management components to reduce C.F in smart cities, based on [27].

Additionally, several other elements, such as intelligent economies, public awareness, and education, may be included under this heading; however, the writers attempted to place them in other headings owing to the interconnectedness of the categories.

A viable “composting and recycling system” has the potential to reduce garbage and pollution. Cities may minimize their GHG emissions, mainly methane, by composting organic waste and using “waste-to-energy systems”. An effective garbage collection system may include sensors, Global Positioning System (GPS) monitoring, and other similar technologies to optimize trash collection routes and guarantee that trucks use the most direct routes. “Smart bins and sensors” can track garbage to better schedule pick-ups [28].

In research by Marques et al. on the use of IoT-based garbage cans, indoor and outdoor scenarios were specified, and the case of the study was utterly dependent on four layers [17]:

- Physical objects;
- Communication;
- Cloud platform;
- Services.

The premise was entirely dependent on internet-based technologies; at the same time, the end outcome of IoT-based smart cities’ infrastructure architecture could manage up to 3902 garbage bins simultaneously as urbanization increases (in the research case study), correctly separating organic and recyclable waste in both indoor and outdoor scenarios, with low response times, and providing a good user experience. This results in a Social Satisfaction Indicator, an environmentally friendly system, and air pollution mitigation consequences, and can be a helpful example for literature on intelligent and sustainable waste management in smart cities [29].

8. Water Management

Another element that might affect C.F mitigation in smart cities is water management. The following implications of water management on C.F mitigation in a smart city are shown in **Figure 10** [30]:

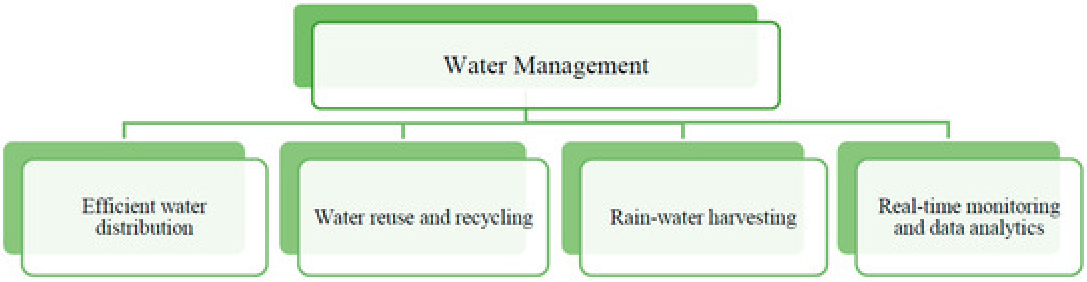

Figure 10. Water management components to reduce C.F in smart cities, based on [30].

Utilizing intelligent "efficient water distribution" systems may decrease water leaks and losses, save energy needed to pump water, and, hence, lower C.F. Implementing wastewater treatment systems through "water reuse and recycling" may lessen the requirement for freshwater extraction, as well as minimize energy use and emissions. Encouragement of "rainwater collecting" and storage will decrease the need for treated water.

Water networks that use intelligent sensors and "real-time monitoring systems" may provide information on water use, leakage, and quality. With this knowledge, proactive efforts may be made to reduce energy use, water waste, and related carbon emissions [31].

Molinos-Senante et al. conducted research on lowering CO_2 emissions from drinking-water treatment plants. Based on the research, determining the CO_2 "shadow price" is essential for addressing environmental policy issues. Given that the shadow price is considered the marginal abatement cost, it may be used to determine the initial market price for CO_2 emissions and the carbon tax rates.

From a policy perspective, the economic value of the negative externalities related energy consumption may be seen in the shadow price of CO_2 emissions from DWTPs. The water regulator should incentivize water businesses to promote energy-saving measures to achieve this goal.

9. Urban Planning and Infrastructure

Urban planning and infrastructure are crucial for reducing C.F in smart cities, and in this section, **Figure 11** shows a numerical representation of those factors [24]:

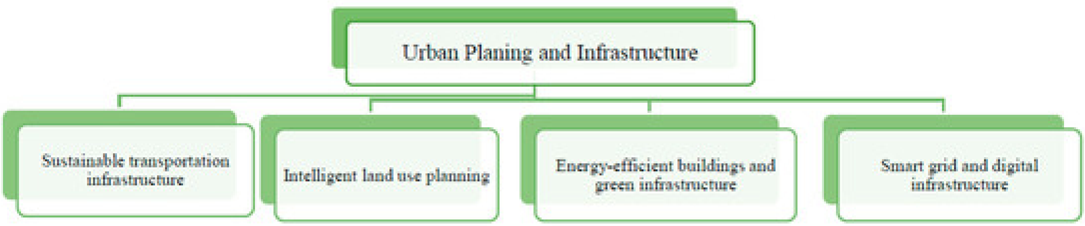

Figure 11. Urban planning and infrastructure components to reduce C.F in smart cities, based on [24].

Sustainable urban design that promotes “intelligent land-use planning” leads to improved accessibility, optimized commuting, and user-friendliness for disabled individuals. The problem of sustainable mobility in smart cities may also be related to the need to create a well-connected and “sustainable transportation infrastructure” and, consequently, less mobility and less emissions [32].

However, putting in place a “smart grid and digital infrastructure system” makes it possible to monitor energy production, distribution, supply, and consumption effectively. This, as well as using renewable energy sources, reduces energy waste and lower carbon dioxide emissions through “energy-efficient buildings and green infrastructure” [33].

In 2016, the National Research Foundation of Korea (NRF) and Balasubramaniam et al. released the Analysis of Intelligent Transportation Systems for a Sustainable Environment in Smart Cities. By stopping the carbon emissions caused by reducing traffic density, transportation officials may slow down climate change. “Intelligent” and “sustainable” have been the main topics of Internet of Vehicles (IoV) transportation research. The term “transportation system” has been replaced by the term “intelligent transportation system” due to substantial advancements in transportation technology (ITS) [2].

10. Data-Driven Decision Making

“Data-driven decision making” is another component that considerably lowers C.F in smart cities. Here are four elements that illustrate its effect [16]:

I. Real-time monitoring and analysis.

Real-time monitoring of the energy utilized by different smart city components is made feasible through data-driven decision making. By analysing this information, city authorities may receive more information about areas with high emissions and make informed decisions to reduce them [34].

II. Predictive modelling and optimization.

Data analytics may predict future energy use using predictive modelling techniques. This allows city planners to maximize resources and infrastructure effectively, decreasing emissions through less energy usage [34].

III. Interventions for behavioral change.

Data-driven decision making enables the identification of behavioral trends among city dwellers. By analysing these trends, city planners may create targeted interventions and campaigns to encourage sustainable behavior. These treatments may use green technologies, thus reducing their C.F [34].

IV. Smart infrastructure management.

Effective smart infrastructure management is facilitated by data-driven decision making. Reducing C.F may be achieved more effectively using data to manage and maintain infrastructure [34].

“Optimizing the Energy Use in Cities with a Smart Decision Support System (OPTIMUS)” is a project carried out in Europe and it is sponsored by the European Union Seventh Framework Program (FP7/2007–2013) [2].

The Smart City Energy Assessment Framework (SCEAF) sub-framework is implemented by this web-based tool, which provides energy managers a platform to evaluate the city’s performance as a whole or the performance of individual buildings in terms of energy optimization, CO_2 emissions reduction, and energy cost minimization. This system may be a fantastic illustration of “data-driven decision making” and may also be categorized under “urban planning and infrastructure”, “energy efficiency”, and other concepts [2].

The suggested technique is valuable as it combines management with energy efficiency by leveraging data from several disciplinary fields. The proposed framework has been used in some notable buildings, including (A) Savona’s “Colombo-Pertini School” in Italy (6092 m^2), (B) Sant Cugat’s “Sant Cugat Town Hall” in Spain (8593 m^2), (C) Sant Cugat’s “Sant Cugat Theatre” in Spain (4150 m^2), and (D) Zaanstad’s “Zaanstad Town Hall” in the Netherlands (18,531 m^2) [2].

A project undertaken in partnership with the Unitec Institute of Technology and the National Institute of Water and Atmospheric Research (NIWA) in New Zealand and conducted in the city of Rangiora examined the role of developing a database and an intelligent system to identify locations with high C.F. It demonstrated how collaboration between an intelligent government and intelligent citizens to monitor air quality could lead to preventing entering a high C.F area [2]. **Figure 12** depicts how this mechanism, called “Airtify”, works.

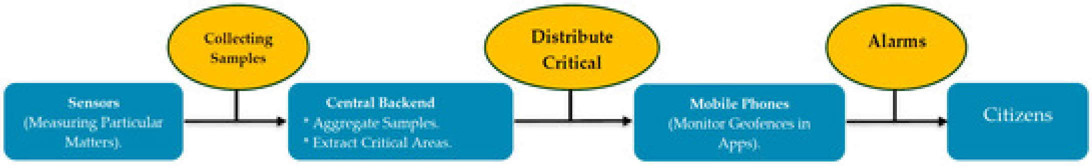

Figure 12. “Airtify” network processing chain and citizens’ feedback to provide controls for smart cities’ continuous improvement, based on [2].

Figure 12 depicts the four components’ access to the internet and an intranet network, which can transmit data about sensor emissions, as well as to the people, starting with the sensors and ending with the backend, mobile devices, and, finally, citizens. Finally, smart citizens can be alerted to minimize emissions by forecasts via “Airtify”. Customers may obtain this data online by utilizing relevant smartphone apps and fixed sensors in critical locations exposed to ambient particulate matter concentrations. Additionally, these clients reduce emissions by promoting a moral culture [2].

Airtify adapts to the grid size and updates its frequency based on the particulate matter sensor dispersion, density, and sampling frequency in metropolitan environments. Further research with different urban features is needed to improve the performance of this system and exceed the current limitations so that citizens are not only end users. Then, the government can use system information to force residents to reduce emissions. Airtify demonstrates the advantages of merging urban air quality sensors with citizen-centric location-based services for environmentally conscientious smart city residents [2].

In addition, one of the causes of the public sector's excessive CO_2 emissions is energy supply for streetlights; thus, utilizing sensors to enhance their working hours might be a vital step towards optimizing energy consumption and reducing pollution. R. Carli et al. in Bari (southern Italy) and Radulovic et al. in Rijeka (Croatia) conducted two more research works on optimization tools for energy-efficient control of street lighting systems in smart cities using the same premise and approach.

11. Citizens Engagements

In addition to technological solutions, intelligent residents may play a significant role in reducing the risk of C.F in smart cities. They can help smart cities reduce emissions through the factors listed in **Figure 13** [35]:

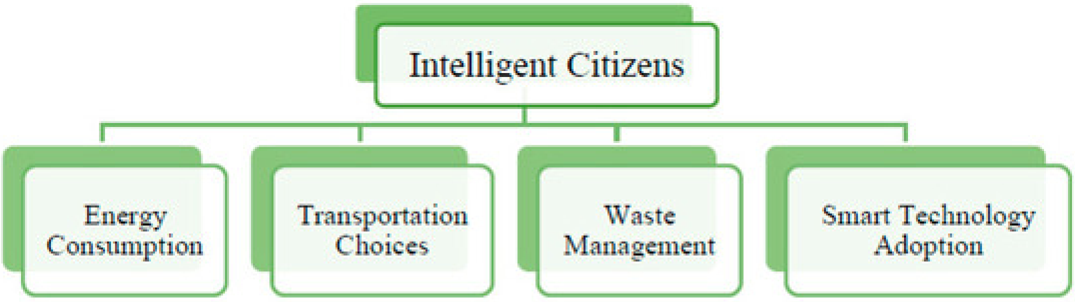

Figure 13. Intelligent citizens' main features to reduce C.F in smart cities, based on [35]. Citizens can embrace intelligent home technology such as intelligent thermostats, energy-efficient lighting, and automated systems that optimize energy use. The numbers in **Figure 14** pertain to energy use, transportation options, and trash management. These decrease C.F individually and contribute to the smart city infrastructure's overall carbon-reduction goals [20][28][33][36].

It should be noted, however, that the characteristics listed in **Figure 13** can only exist with the backing and development of intelligent and circular economies from shrewd governments. On the other hand, it has been determined that intelligence must begin with the most fundamental aspects of human life, such as employing intelligent devices in homes, relating IoT's function in smart cities, and evaluating the impact of utilizing technical resources that an intelligent government can assist with.

The 2020 US EPA report states that electricity manufacturing accounts for 28% of commercial and 12% of residential carbon emissions worldwide. As a result, intelligent citizens can significantly impact emissions, and their behavior is crucial for reducing C.F [29]. Although it has been reported that homes with an IoT system and sensors to keep their temperature at the ideal level emit 22.4% less carbon in managing the home's temperature than homes without this system, this difference is not statistically significant [37].

12. Disaster Preparedness and Resilience

One of the other essential requirements for a smart city is "disaster preparedness and resilience", which both aim for smartness and sustainability. This standard may help smart cities reduce C.F and reduce emissions in three different ways, as detailed below:

I. Efficient resource allocation.

Smart cities can deploy resources more efficiently by prioritizing disaster preparedness and resilience. Networks for better waste management, transportation, and energy distribution are included. When disasters occur, these well-organized systems are better equipped to handle disruptions, decreasing the need for energy-intensive recovery efforts and lowering emissions [38].

II. Renewable energy integration.

Building a resilient infrastructure often involves incorporating renewable energy sources like solar and wind power. These sources might provide dependable energy alternatives if regular power networks fail during disasters. Utilizing renewable energy more often reduces C.F, lowering reliance on fossil fuels and GHG emissions [39].

III. Integrated urban planning.

Integrated urban planning entails developing surroundings and infrastructure that can withstand shocks and natural disasters, which are highly valued in smart communities resilient to catastrophes. This approach may lead to more concentrated urban expansion, reducing the need for urban sprawl and lengthy commutes. As a result, residents travel reduced distances, lowering transportation emissions [40].

Another research work regarding the significance of disaster planning and resilience, by Sobrino et al. conducted at the Polytechnic University of Madrid (UPM), found that CO_2 emissions by attendants, employees, students, tourists, etc., could predict how effective the government is at lowering CO_2 emissions [41].

Another study, "Smart Energy Regions" in Europe, looked at construction rules for zero energy buildings (ZEBs), which are crucial to smart cities, and the relevance of ZEBs in intelligent energy regions. Intelligent governments provide these guidelines to reduce thoughtful building energy consumption and C.F [40].

Environmental design, building practices, renewable energy sources, technical building system labelling, and intelligent energy management in smart cities are all priorities for ZEBs. They improve energy efficiency, conservation, and renewable energy generation in smart cities [42].

This argues that intelligent cities need energy-efficient smart buildings. Reducing GHG emissions by following current and applicable regulations, such as the European Strategic Energy Technology Plan, which started in 2010 and is implemented via European Industrial Initiatives, or the zero energy standards in European countries, can be achieved as follows [42]:

- Wind initiative;
- Solar Europe is photovoltaic and concentrated solar electricity;
- Electricity Grid Initiative;
- CTS Initiative;
- Sustainable Nuclear Initiative;
- Industrial Bioenergy Initiative;
- The Smart Cities and Communities Initiative;
- JTI on fuel cells and hydrogen.

13. Intelligent Economy Systems

Another crucial aspect influencing C.F reduction in smart cities is the implementation of intelligent and circular economies, which may considerably impact emission reduction. This factor may play its part by using the components shown in **Figure 14** [40]:

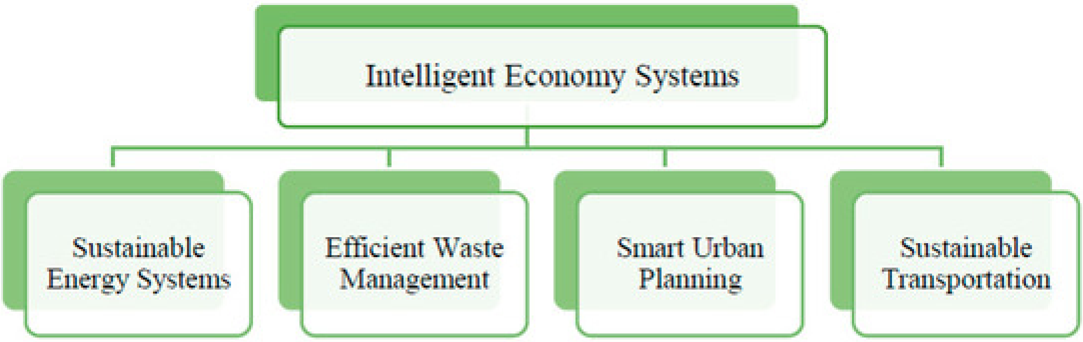

Figure 14. Intelligent economy components in smart cities affecting C.F reduction, based on [40].

Circular and intelligent economies prioritize using renewable energy sources, energy-efficient technologies, and smart grid systems to optimize energy production and consumption. They also strive to decrease waste while enhancing resource recovery by recycling and reuse [43].

What is more, circular and intelligent economies support the sustainable transportation methods already mentioned. Additionally, they emphasize the previously mentioned green and sustainable urban development practices, which may impact emissions reduction [44].

In research by Q. Guo et al. in 231 Chinese cities, the impact of smart city development on emission reduction, energy saving, and the interaction between them was examined. Moreover, in smart city construction, energy efficiency reduced the CO_2 emissions per person by 18.42 logarithmic percentage points. The benefits of smart city development, which lowers per capita CO_2 emissions by increasing energy efficiency, are most remarkable in cities with higher administrative levels, neutral technological growth and green innovation, and advanced industrial structures [45].

14. Carbon Tracking and Reporting Systems

Finally, a smart city must include carbon monitoring and reporting systems, which could play a significant role in C.F mitigation. As illustrated in **Figure 15**, these systems can influence emissions reductions in the following ways [46]:

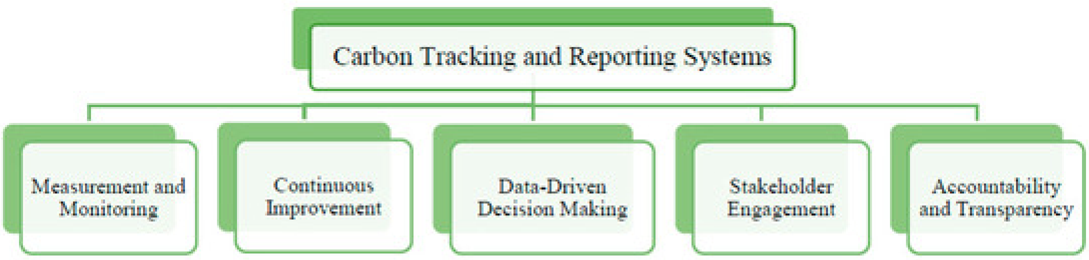

Figure 15. Carbon tracking and reporting systems components affecting C.F in smart cities, based on [46].

Systems for monitoring and reporting carbon emissions “detect and monitor” emissions from various sources. Cities may utilize C.F quantification to identify areas with high emissions and implement targeted reduction strategies as “data-driven decision making”. These procedures promote “transparency” and “accountability”, and cities may demonstrate their sustainability by accurately collecting and disclosing data on emissions [46].

By enticing individuals and organizations to adopt sustainable practices and reduce emissions, these systems track progress, analyze strategy effectiveness, and promote “continual improvement” and “stakeholder engagement” in emission-reduction programs [47].

Duangsuwan et al. researched the carbon tracking and monitoring systems in Bangkok, Thailand, using automobile sensors. By constructing an intelligent system consisting of automotive sensors and databases and coupling these systems to simple software in drivers’ smartphones, urban management agents can provide accurate data on CO_2 emissions for further action. This is called a low-power wide area network (LPWAN). It could be used to create an integrated database for managing and reducing C.F emissions [48].

Another study, by Shahid et al., discussed a model of an intelligent approach to identifying areas with a high volume of pollutant emissions, which is one of the new issues raised in using traffic information in the urban management system for the use of innovation in smart cities and following these innovations. This system can control and monitor traffic lights. The proposed technology can operate well in high-traffic regions and smart cities, lowering C.F. All of the regions with the most traffic congestion are designated high-potential CO_2 emission zones. It then directs traffic to other routes and strives to reduce traffic density significantly before attempting to cut transit time for cars in the city by managing traffic [2]. The research of Shahid et al. can serve as a valuable example of integrating various aspects and components of a smart city that collaborate to minimize C.F.

Figure 16 illustrates the link between smart city traffic management and sustainability. The figure proposes three factors interacting in the smart city, describing an ideal system focusing on reducing traffic and, as an effect, reducing C.F to achieve the basic principles of sustainability.

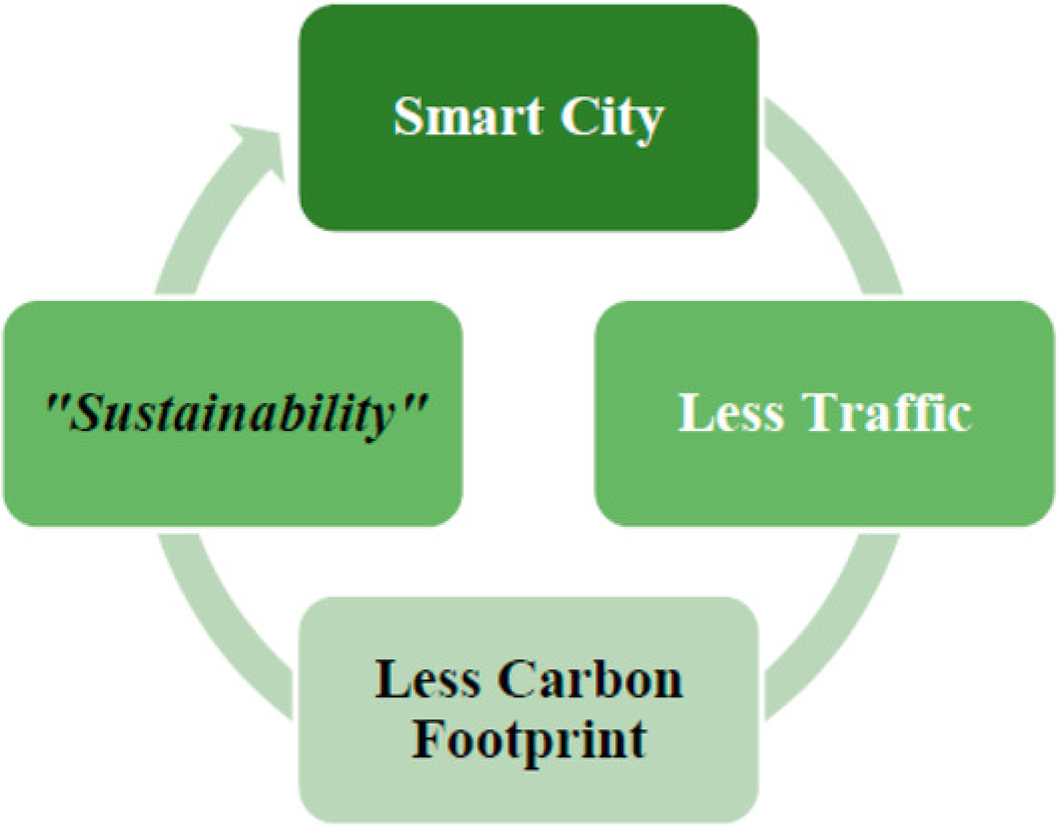

Figure 16. Sustainability loop through intelligent traffic management.

Finally, it can be stated that the following factors contribute to smart cities' contributions to reduce GHG emissions, which in turn helps to mitigate their C.F throughout the entire SC: "energy efficiency and renewable energy, sustainable transport, waste management, urban planning, and infrastructures, decision making driven by data, citizens' engagement, preparedness and resilience for disasters, intelligent economy, and carbon tracking and reporting". While each can be further subdivided, some have a critical impact on different categories due to their emerging and close contributions through SC to improve conditions for citizens and the governing city alongside the important issue of sustainability. For example, given the importance of mobility in today's world, the issue of intelligent and sustainable transportation can have a significant impact on all of the mentioned contributions, and the same issue can also be applied to citizens and the intelligent and circular economy.

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