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Evaluating the Environmental Sustainability of Smart Cities in India: The Design and Application of the Indian Smart City Environmental Sustainability Index

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Abstract: There is a growing consensus that the initiatives taken under the Smart Cities Mission (SCM) in India should be used as an opportunity to prepare models for Environmentally Sustainable Smart Cities (ESSC). While developed countries have earlier worked towards Sustainable Cities and now are moving towards Smart Sustainable Cities, the conditions in developing countries are different. In their current form, SCM guidelines appear to emphasize more on social and economic development along with governance issues using modern tools of information and communication technology (ICT). To ensure environmental sustainability of such large-scale development planning, after a two-stage screening process, 24 environmental indicators have been finalized (including 11 from the existing guidelines), which can be used to monitor various environmentally sustainable elements of smart cities. Accordingly, in the present study; a tentative framework has been developed using these indicators to arrive at a Smart City Environmental Sustainability Index (SCESI) on a 0–100 increasing scale, and the city's environmental sustainability has been classified under five categories: Excellent; Good; Fair; Poor or Critically Low; based on decreasing SCESI. Using this framework, five Indian cities, which are currently being developed under SCM (Delhi; Patna; Allahabad; Varanasi; and Bhubaneswar), have been examined. The analyses indicate that while three of them (Delhi, Allahabad, and Bhubaneswar) are found in the Fair (SCESI = 40–60) category of environmental sustainability, two (Varanasi and Patna) are in the Poor (SCESI = 20–40) category. The SCESI developed may be used as a monitoring and diagnostic tool for planning and managing services connected with the environment surrounding human life.

Keywords: smart cities; Sustainable Smart Cities; Environmentally Sustainable Smart Cities (ESSC); Smart City Environmental Sustainability Index (SCSEI)

Citation: Shruti, S.; Singh, P.K.; Ohri, A. Evaluating the Environmental Sustainability of Smart Cities in India: The Design and Application of the Indian Smart City Environmental Sustainability Index. *Sustainability* **2021**, *13*, 327. https://doi.org/10.3390/su13010327

Received: 26 November 2020
Accepted: 11 December 2020
Published: 31 December 2020

1. Introduction

As per the census report 2001, there were 5161 classified towns and 384 urban agglomerations in India, which increased to 7935 classified towns and 475 urban agglomerations in 2011 [1]. The urban population is expected to increase up to 540 million, i.e., 40% of the total population. This massive growth will provide 70% of new employment and contribute to 70% of India's GDP by 2030 [2]. However, the population growth in the urban sector will also lead to environmental degradation, lack of resources, congestion, and destruction of habitats, etc. Consequently, the life of a city-dweller will become arduous unless the development of physical, institutional, social, and economic livelihood infrastructure is sustainable [3]. The concept of sustainability in developmental activities was introduced in 1987, which is comprised of three pillars: Social, environmental, and economic [4]. In European countries, the concepts of sustainability and sustainable development have been applied to urban planning and design since the 1990s. Visions for Green Cities [5], Compact City [6–8], Eco-cities [9–11], and Sustainable Cities [12–15] were formed based on such considerations. With sustainability awareness engrained, urban growth using technological development subsequently resulted in the thinking of Smart Sustainable Cities [16–19]. The notion of a smart city is established from the combination of the knowledge society and digital city [20]. The development of Information and Communication Technology (ICT) has given new ways of addressing urban challenges and problems, which have resulted in an opportunity to rethink the way we plan cities in a new urban form called "Smart Cities" [21,22]. Smart Cities Mission (SCM) in India was introduced in June 2015 by the Ministry of Urban Development (MoUD), Government of India (GOI), with an idea to develop 100 smart cities in the country [23]. It has been developed for setting in motion a virtuous cycle of growth and development for improving the quality of life and attracting ventures for the city. Thus, while in developed countries, the cities are being planned as 'Smart Sustainable Cities' after working on sustainable cities over several decades, in India, the smart cities mission (SCM) is perhaps the first program of its kind to interject scientific tools and techniques in urban life. In long-term visions, developmental initiatives taken under this mission may be used as stepping stones and an opportunity to develop 'Sustainable Smart Cities' (SSC). Accordingly, the programs and projects must be monitored using indicators of sustainability from the initial phases to ensure long-term benefits. However, as observed by Yadav et al., environmental protection finds very low priority amongst the 'enablers' of sustainability, and within the three pillars (social, economic, and environmental), the first two appear to outweigh the third [24]. Hence there appears a definite need to emphasize Environmentally Sustainable Smart Cities (ESSC) in India. In its current form, the SCM guidelines of India appear to have barely explored the collaboration between smartness and environmental sustainability [25].

In order to move towards planning and development of Environmentally Sustainable Smart Cities (ESSC), the objectives of the present study have been set as (i) to develop a framework for evaluating the environmental sustainability of a smart city, (ii) to use the tool in the classification of Smart Cities based on environmental sustainability, and (iii) suggest the priority areas for attention and action. Thus, in the present study, a vision of "Environmentally Sustainable Smart Cities (ESSC)" has been proposed, and a framework has been developed to calculate "Smart City Environmental Sustainability Index (SCESI)" on a 0–100 increasing scale using selected indicators to classify the existing environmental conditions of cities. The SCESI may serve as a tool to measure, monitor, and maneuver the infrastructural development initiatives based on existing and planned environmental indicators.

2. Literature Review

From the perspectives of Indian and similar developing countries, the process of future urban planning may take place in three phases: First from cities to 'Smart Cities', then from 'Smart Cities' to 'Sustainable Smart Cities' [26], and finally, towards "Environmentally Sustainable Smart Cities (ESSC)' which is yet to be explored.

2.1. From 'Cities' to 'Smart Cities'

The concept of Smart Cities was introduced in 1994 as cybernetically planned cities [27]. Thus, Smart Cities rely on ICT for providing services and improving the quality of life [19]. In other words, a smart city is a city that can provide and maintain modern infrastructure for roads, power plants, water treatment plants, sewerage and sewage treatment systems, etc. [28]. Since this built environment lasts a long time, getting the right infrastructure in place shapes a city for decades to come. Planning a city with the right infrastructure, learning from the mistakes of the past, and making them sustainable for the long term remains the objective. In the process, the promise of "smart cities" is their ability to collect, analyze, and use the data in order to make better decisions at the municipal level through the greater use of technology. In the next section, the paradigm shift of Smart Cities to Sustainable Smart City is discussed.

2.2. From 'Smart Cities' to 'Sustainable Smart City'

The concept of a Sustainable Smart City emerged due to the interlinked convergence of global trends: Urbanization, development of sustainability, and rise in ICT [19]. At present, the concept of 'Sustainable Smart Cities (SSC)' is just emerging, and 'Environmentally Sustainable Smart Cities (ESSC)' is yet to follow. In this section, the relevant literature related to sustainable and smart cities is discussed to show that environmental dimensions are barely explored in the realm of Smart Cities. Sustainable Cities International studied the "Indicators of Sustainability" to understand how cities are monitoring and evaluating their success [29]. The summary enlisted 32 indicators divided into social (7), economic (12), and environmental (13) dimensions of sustainability. It emphasized that environmental sustainability is one among the eight goals of Millennium Development Goals (MDG) and grouped 13 environmental indicators under six headings: i. Green Spaces, ii. Reduce Green House Gases/ Energy Efficiency, iii. Mobility, iv. Water Quality and availability, v. Air Quality, and vi. Waste/ Reuse/Recycle. Around the same time, the Economist Intelligence Unit (EIU), in cooperation with Siemens, commissioned the Green City Index series, which covers 120 cities across five continents of the world [30]. The methodology used a set of 30 indicators divided into eight categories: i. CO_2; ii. Energy; iii. Buildings; iv. Transport; v. Water; vi. Waste and land use; vii. Air quality; and viii. Environmental governance. It was observed that half of the indicators were quantitative in each Index and usually based on data from official/public sources. The remainder indicators were qualitative, which measures the city's environmental policies [30]. For Smart cities, Sureshchandra et al. identified and ranked nine factors (Mobility, Physical, Innovation and learning, Political, Information, Communication and Technological, Environmental, Operational and Managerial, Social, and Economical) involving 66 indicators using Questionnaire survey and Significance Index Method. Within the Environmental factor, eight indicators (Availability of natural resources, Greenhouse gas emission, Consumption of energy from renewable sources, Quality of resources, Environmental protection, sustainable resource management, Biodiversity and Recycling of used resources) were considered [31]. In addition, Water supply, Sanitation, Stormwater management, and Solid waste management were indicators grouped under Physical Factors. While Environmental factors ranked sixth among nine factors considered, recycling of used resources, sustainable resource management, and environment protection were found as the three top-ranking indicators in this group. Water supply, Sanitation, and solid waste management were found as the priority ranking indicators in Physical factors. Joshi et al. considered that smart cities are an endeavor to make cities more efficient, sustainable, and liveable. To bridge the gap regarding the concept of smart cities and its implementation, a framework using six significant pillars—Social, Management, Economic, Legal, Technology, and Sustainability (SMELTS)—was developed to get better insights about the idea of the smart city [28]. It was observed that smart city initiatives in the areas of Technology, Legal, and Economy have an influence on Social, Management, and Sustainability aspects. Ahvenniemi et al. reported the differences between sustainable and smart cities [32]. They analyzed 16 sets of assessment frameworks, which comprised 958 indicators. Thereafter, they divided the indicators into 3 impact categories and 12 sectors. The result revealed that modern technologies have a stronger focus on smart city frameworks than urban sustainability. The smart city framework highlights the social and economic aspects while ignoring the environmental aspects. Thus, it can be concluded from the study that in the 21st century, a shift from sustainability assessment to smart city goals is observed. The frameworks developed for Smart Cities are not sufficient to attain environmental sustainability. Moreover, environmental indicators selected in the Smart Cities framework are remarkably less compared to other domains: Social, economy, and governance. Basically, a general goal of smart cities is to improve social, economic, and governance-related sustainability with the help of technologies.

Randhawa and Kumar compared the number of indicators included under various headings of sustainable development and Smart Cities Mission and felt that the Smart Cities Mission of India lacks the concern towards the natural environment, which is an important dimension of sustainable development [25]. Yadav et al. enlisted 33 'enablers' of 'sustainable smart city (SSC)' and divided them into six major categories: (i) Energy, and Environmental, (ii) Infrastructural, (iii) Strategy and Policy-oriented, (iv) Social and Personal, (v) Informational and Technological, and (vi) Mobility enablers. Based on expert opinion, the authors dropped two enablers: 'Solid Waste Management' (considering it as a part of 'Sustainable Resource Management') and 'Effective Infrastructural Facilities' (as a part of 'Affordable Housing Facilities' and of 'Development of Smart Buildings') [26]. Then, weights of 31 enablers were computed, and three low-intensity enablers—Environmental Protection, Planning for disaster management, and Uplifting literacy rate—were also dropped in favour of high- and moderate-intensity enablers. Finally, 28 enablers were used in developing a framework. The framework revealed that the adoption of innovative construction techniques, supportive government policies, and advanced information and communication technology act as a foundation for the successful execution of the SSC project. The main output enablers are sustainable resource management, development of smart buildings, advanced research and development system, and intelligent transportation system. Focus on the renewable energy system, strong infrastructure development, strong informational and technological database, and strong mobility (transportation) is found as the broad aspects involved in strengthening the SSC projects.

2.3. Towards 'Environmentally Sustainable Smart Cities (ESSC)'

It is recognized that sustainability is an essential condition of planning for Smart Cities. However, even in the Sustainable Smart Cities approach, out of the three pillars of sustainability, many times, social and economic dimensions overweigh the environmental concerns of holistic planning. Huovila et al. criticized the concept of Smart Cities due to a lack of environmental awareness and being techno-centric where the sustainability was outdated because of the need for a digitized city [33]. Such conditions demand planning for 'Environmentally Sustainable Smart Cities (ESSC)' with an understanding that social and economic objectives are well engrained as part of being 'smart'.

3. Research Methodology

The methodology adopted in the present study follows the sequence as detailed below. Firstly, a framework is developed to calculate the Smart Cities Environmental Sustainability Index (SCESI) on a 0–100 increasing scale. This is broadly a four-step process, as given in Section 3.1. Then, a classification system for smart cities based on SCESI is adopted to categorize them based on existing environmental conditions. Finally, the priority areas of action are identified to improve the conditions and overall environmental sustainability.

3.1. Developing a Framework for Evaluating the Environmental Sustainability of Smart Cities

Here the purpose is to develop a method for calculating Smart Cities Environmental Sustainability Index (SCESI) on a 0–100 increasing scale. The process has been done in four steps: i. Selection of Indicators for Environmentally Sustainable Smart Cities, ii. Assigning weights for the indicators, iii. Benchmarking of selected indicators, and iv. Calculation of Smart City Environmental Sustainability Index (SCESI).

3.1.1. Selection of Indicators of ESSC

The draft concept note on the smart city scheme [3] showed four infrastructural pillars of Smart Cities: Social, physical, institutional, and economic. The mission statement and guidelines for smart cities in India [23] included adequate water supply, sanitation, solid waste management, and sustainable environment as the core infrastructure element. Waste to energy and fuel, waste to compost, wastewater to be treated, recycling and reduction of construction and demolition waste (under waste management), and use of smart meters, leakage identification, and preventive maintenance and water quality monitoring (under-water management) were identified as the areas of application of smart solutions. BIS issued Smart Cities-Indicators, which enlisted 17 sectors and identified 46 'core indicators' and 47 'supporting indicators.' 'Environment,' 'Solid Waste,' 'Sewerage and Sanitation,' and 'Water Supply' are the four sectors out of a total of 17, in which 14 'core' and 14 'supporting indicators' related to environmental dimensions of the cities were enlisted [34]. Based on such considerations, Singh et al. reported selecting environmental indicators for sustainable smart cities' mission in India [35]. In the process, 14 environmental indicators included in Smart Cities Mission [23] and 20 additional indicators were screened from available literature on sustainable cities frameworks. The first set of 14 environmental indicators taken from Smart Cities Mission of India were evaluated for their appropriateness on six criteria (Direct relevance to objectives, Direct relevance to the target group, Clarity in design, Realistic collection or development costs, High quality and reliability, and Appropriate spatial and temporal scale) as suggested by World Bank Environment Department (WBED) for Indicators of Environment and Sustainable Development [36]. Based on this evaluation, 11 indicators were found fulfilling all the criteria and thus were selected while the remaining 3 (Waste to energy and fuel, Waste to compost, and Stormwater reuse) were dropped out, primarily as they do not meet two criteria (Clarity in design and Realistic collection or development costs). The second set of 20 indicators selected from the literature on sustainable cities was screened on two levels: One for appropriateness based on six criteria of WBED, and the second on eight criteria (Relevance, Completeness, Availability, Measurability, Reliability, Familiarity, Non-Redundancy, and Independence) suggested as CITYKeys Indicators for Smart Cities [37]. In this process, 16 indicators were found appropriate in the first screening, out of which only 13 could get through the second screening. Indicators such as Street Sweeping [38–41], Availability of collection bin at the appropriate place in commercial and residential areas [40,41], Availability of roadmap for waste transportation of MSW as per Swachh city plan [41], and Incidence of waterlogging [42] were found inadequately defined in first stage and Household Coverage of SWM [38,41,42], Coverage of water supply connections [42], and Coverage of sewerage [34,43] were found overlapping with others. Overall, the process resulted in the finalization of 24 environmental indicators (Figure 1). Finally, for the purpose of the present study, in line with the sector approach of BIS, the selected indicators were grouped in four Environmental Domains (EDs): i. Solid Waste Management (SWM), ii. Water Supply Management (WSM), iii. Sewerage, Sanitation, and Stormwater (SSS) management, and iv. Ambient Environmental Conditions (AEC) [34]. With such divisions, there are 7 indicators under SWM, 7 for WSM, 7 for SSS, and 3 for AEC domains. Table 1 summarises the selected indicators, their broad environmental domain, weights under domain, and benchmarking.

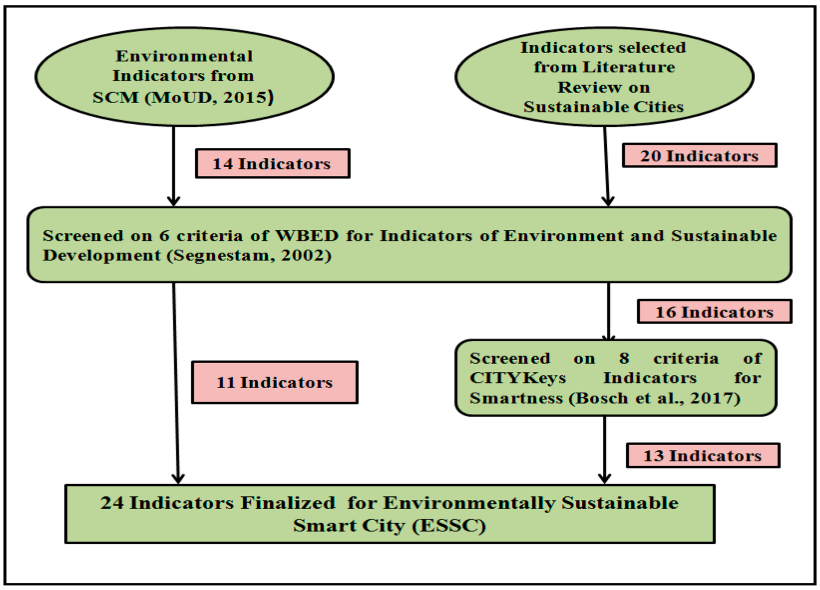

Figure 1. Process of indicators selection for Environmentally Sustainable Smart Cities (ESSC).

Table 1. Selected indicators, weights, and their benchmarking.

Indicators	Allocated Weights	Method of Benchmarking (x_k) (%)	Best level of Performance for Benchmarking	Classification based on Benchmarked Indicator Value (BIV) (x_k) (%)			
				Excellent	Good	Average	Poor
(A) Solid Waste Management (SWM)							
1. Efficiency in collection of MSW [41,42]	0.155	Amount of MSW collected/Total amount of MSW generated	100% of MSW generated should be collected.	>90	70–90	50–70	<50
2. Degree of Segregation [41,42]	0.171	Amount of waste segregated/Total solid waste collected	100% of collected solid waste should be segregated.	>50	25–50	0–25	0
3. Extent of Solid Waste recovered [42]	0.163	Amount of waste recycled/Amount of MSW collected	80% of collected solid waste should be recovered.	>50	25–50	0–25	0
4. Degree of Scientific disposal of MSW [42]	0.165	Amount of MSW disposed in sanitary landfills/Total MSW disposed	100% MSW disposed should go to sanitary landfills.	>50	25–50	0–25	0
5. Recycling and reduction of construction and demolition waste [23]	0.133	Availability of separate system for Construction & Demolition waste (Y or N)	Recycling and reduction of C&D waste should have been started.	100			0
6. Extent of cost recovery in Solid Waste Management [42]	0.130	Total revenues earned from MSWM/Total expenses on MSWM	100% of expenses incurred on MSWM should be recovered as revenue.	>60	30–60	0–30	0
7. SWM programs carried in the city during last 3 years [23]	0.083	SWM programs carried in the city during 3 years (Y or N)	SWMP should have been started within last three years.	100			0
Total	**1.000**						
(B) Water Supply Management (WSM)							
8. Adequacy of water supply [23]	0.151	Water supplied (lpcd)/135	135 lpcd.	>75	50–75	25–50	0–25
9. Smart meters and Management [23]	0.145	Number of metered connections/Total water supply connections	100% of water supplied connections should be metered.	>75	50–75	25–50	0–25
10. Leakage Identification [23]	0.138	Volume of productive water/Total volume of water supply	80% volume of water supply should be productive.	>80	70–80	70–50	<50
11. Continuity of water supplied in terms of average no of hours per day [42]	0.127	Hours of water supply hours/24	24 h × 7 days	>80	40–80	20–40	0–20

Table 1. *Cont.*

Indicators	Allocated Weights	Method of Benchmarking (x_k) (%)	Best level of Performance for Benchmarking	Classification based on Benchmarked Indicator Value (BIV) (x_k) (%)			
				Excellent	Good	Average	Poor
12. Water quality monitoring [23]	0.167	Total volume of water supplied meeting water quality standards for drinking/Total water supplied	100% of water supplied should meet drinking quality standards.	>90	70–90	40–70	0–40
13. Water sources and extent of exploitation of ground water [39]	0.163	Ground Water Table increasing or decreasing (Y or N)	Ground Water Table should be almost constant.	100			0
14. Extent of cost recovery in water supply services [23]	0.109	Revenue earned from water bills/Total Cost in public water supply	100% of cost of public water supply should be recovered through water bills.	>75	50–75	25–50	0–25
Total	**1.000**						
(C) Sewerage, Sanitation and Storm water (SSS) management							
15. Collection efficiency of sewage network [42]	0.156	Volume of wastewater collected/Volume of total wastewater generated per day	100% of waste water volume should be collected.	>70	40–70	0–40	0
16. Adequacy of sewage treatment capacity [42]	0.149	Wastewater given secondary treatment/Total volume of wastewater generation per day	100% of domestic sewage should be given treatment up to secondary level.	>70	40–70	0–40	0
17. Quality of treated sewage [42]	0.152	No of treated wastewater samples which abide by the standards/Total number of samples collected.	100% of samples should meet secondary treatment effluent standards.	>90	80–90	40–80	0–40
18. Wastewater recycling [23]	0.148	Volume of recycling and reuse of wastewater/Volume of treated waste water recovered per day	More than 20% of total treated waste water should be recycled in the city.	>20	10–20	0–10	0
19.Extent of cost recovery [23]	0.101	Cost recovered from sewage management/Total cost involved.	100% of total cost incurred on sewage management should be targeted to be recovered.	>60	30–60	0–30	0
20. Coverage of toilets [23]	0.160	Urban population having access to toilets/Total urban population	100% of urban population should have access to toilets.	>90	70–90	35–70	0–35

Table 1. *Cont.*

Indicators	Allocated Weights	Method of Benchmarking (x_k) (%)	Best level of Performance for Benchmarking	Classification based on Benchmarked Indicator Value (BIV) (x_k) (%)			
				Excellent	Good	Average	Poor
21. Coverage of storm water drainage [42]	0.134	Length covered by the storm water drainage/Total road length	100% of roads should be covered with storm water drainage.	>60	10–60	30–60	0–30
Total	**1.000**						
(D) Ambient Environmental Condition (AEC)							
22. Ambient Air Quality [23]	0.376	(500-Air Quality Index)/500	Air Quality Index should be less than 500.	>75	50–75	25–50	0–25
23. Ambient Sound Level [34]	0.325	Number of samples abiding the standards of Noise Pollution Regulation Act, 2000 to the total number of samples surveyed.	Industrial areas: L < 75 dB (day), <70 dB (night). Commercial areas: L < 65 dB (day), <55 dB night), Residential areas: L< 55 dB (day) <45 dB (night) Silence zone: L < 50 dB (day) and <40 dB (night)	>75	50–75	25–50	0–25
24. Ambient Surface Water Quality [34]	0.299	Number of surface water samples abiding the standards of bathing to the total number of samples collected	Surface water bodies should meet criteria for bathing purpose: 1. Total Coliform Organism MPN/100 mL = 500 or less 2. pH between 6.5 and 8.5 3. Dissolved Oxygen = 5 mg/L or more 4. Biochemical Oxygen Demand 5 days 20 °C = 3 mg/L or less	>75	50–75	25–50	0–25
Total	**1.000**						

(Benchmarking as per MoUD, 2012 guidelines) [42].

3.1.2. Assigning Weights for the Indicators

Several methods of assigning the weights to the indicators have been reported in the literature. Best Worst Method (BWM) is used when a large number of input variables are present [44], and if the structural hierarchy is required, Interpretive Structural Modelling (ISM) is used [45]. Analytical Hierarchy Process (AHP) is a commonly used method for the decision-making process, which involves pairwise comparison [46]. It may become a tedious task to handle if a large number of input variables are involved [47]. Ameen and Mourshed used AHP [48], but Anand et al. used the Fuzzy Analytic Hierarchy Process (FAHP) [49] to determine the importance of sustainability factors. Multi-criteria decision making (MCDM) approaches are useful to solve problems where a large number of factors is involved. The output required and nature of the problem decides the selection of an appropriate MCDM approach [24]. To start with, in the present work, the weight to each indicator has been allocated using Delphi Method (DM). It is a structured communication technique for systematic and interactive forecasting based on the views of a panel of experts using a questionnaire. Several researchers, including Núñez, Musa et al., and Ogbeifun et al. have used DM for assigning weights to selected indicators [50–52]. Accordingly, for the present study, a Delphi questionnaire was prepared and communicated to a group of 50 environmental panelists comprising of academicians, environmental engineers, and policy-makers. The questionnaire was communicated to different regions so that a generic analysis can be achieved. Thirty experts responded to the questionnaire. The weights were assigned according to the relative importance of the indicators on a scale of 1 (worst) to 5 (best) by the experts. For the analysis of expert opinion, arithmetic mean and median is carried out to exploit the potential of each indicator. The arithmetic mean is intuitive for the expert panel; hence simultaneously, the median is carried out for rigorous statistical analysis of data. The calculated weight based on the significance levels for each of the indicator is given in Table 1. While all the four domains have been given equal weight, individual indicators within a domain have varying weights determined through the Delphi technique. The results reveal that Degree of Segregation (w = 0.171) possesses the highest influence on SWM followed by Degree of scientific disposal of MSW (w = 0.165) and Extent of solid waste recovered (w = 0.163). In the WSM domain, the precedence indicators are Water Quality Monitoring (w = 0.167), Exploitation of underground water (w = 0.163), and Adequacy of Water Supply (w = 0.151). Coverage of toilets (w = 0.160), Collection efficiency of sewage network (w = 0.156), and Quality of treated sewage (w = 0.152) are the key indicators for SSS. The order of indicators according to their strongest influence on AEC is Ambient air quality (w = 0.376), Ambient Sound Level (w = 0.325), and Ambient Surface water quality (w = 0.299). Cities should be encouraged to improve performance in high-weight areas to get better results on environmental sustainability.

3.1.3. Benchmarking of Selected Indictors

Venkatesh, who wrote a critique of the European Green Index, opined that while adopting such performance evaluation methodologies, it is important to set targets and goals [53]. Benchmarking is a popular tool to judge the performance of the services provided to consumers [54]. Most of the indices developed by the agencies, such as Green City Index [30], ISB Index [55], etc., do not provide benchmarking of indicators and hence judge the performance by simply comparing data of different cities. However, a minimum set of a standard must be defined and ensured while monitoring the service delivery. The urbanization challenge can be addressed by identifying the gaps and introducing the best practices for improving the city's performance. In the present research, benchmarking has been done for each indicator on a 0–100 scale based on the best-suggested condition for different domains applicable under Indian conditions based on Handbook of Service Level Benchmark [42]. Here, 0 indicates 'Poor' condition and 100 indicate 'Excellent' level. Some of the indicators are scored on the logical basis i.e., if the indicator satisfies the condition, then it is allocated 100, representing the Excellent category, and if the indicator does not satisfy the condition, it scores 0, signifying the Poor category. The indicators based on the logical conditions include Solid Waste Management Programs carried in the city during last three years, Recycling and reduction of construction and demolition waste under SWM, and Exploitation of underground water in WSM (Table 1).

3.1.4. Calculation of Smart City Environmental Sustainability Index (SCESI)

The proposed framework produces an index, called Smart City Environmental Sustainability Index (SCESI), based on four domain indices (DIs): Solid Waste Management Index (SWMI), Water Supply Management Index (WSMI), Sewerage, Sanitation, and Stormwater Management Index (SSSI) and Ambient Environment Condition Index (AECI). Data for indicators of SWM, WSM, and SSS have mostly been taken from the City Development-Plan (CDP) and Swachh Sarvechhan Report (SSR) from the Swachh Bharat Mission (SBM) program. Central Pollution Control Board (CPCB) and ENVIS website data for respective cities have been used for AEC domain indicators.

The general expression for the Smart City Environmental Sustainability Index (SCESI) is given by:

$$\text{SCESI} = \left(\sum_{i=1}^{m} \text{vi DIi}\right)/\text{m} \tag{1}$$

where i is the serial number of the domain considered, m is a total number of domains; v_i is the weight of ith domain, and DI_i is the respective Domain Index.

Domain Indices (DIs) are the summation of individual Indicator Scores (ISs), given by:

$$\text{DI} = \sum_{j=1}^{n} \text{ISj} \tag{2}$$

where j is the serial number of Indicator, n is the number of indicators in the chosen domain, and IS_j is Indicator Score of jth indicator

Indicator Score (IS) is obtained using the weight of the indicator (w_k) and the benchmarked indicator value (x_k), given by:

$$IS_k = (w_k.\ x_k) \tag{3}$$

where k is the identification number of a chosen indicator.

Figure 2 presents the skeletal structure for calculating SCESI.

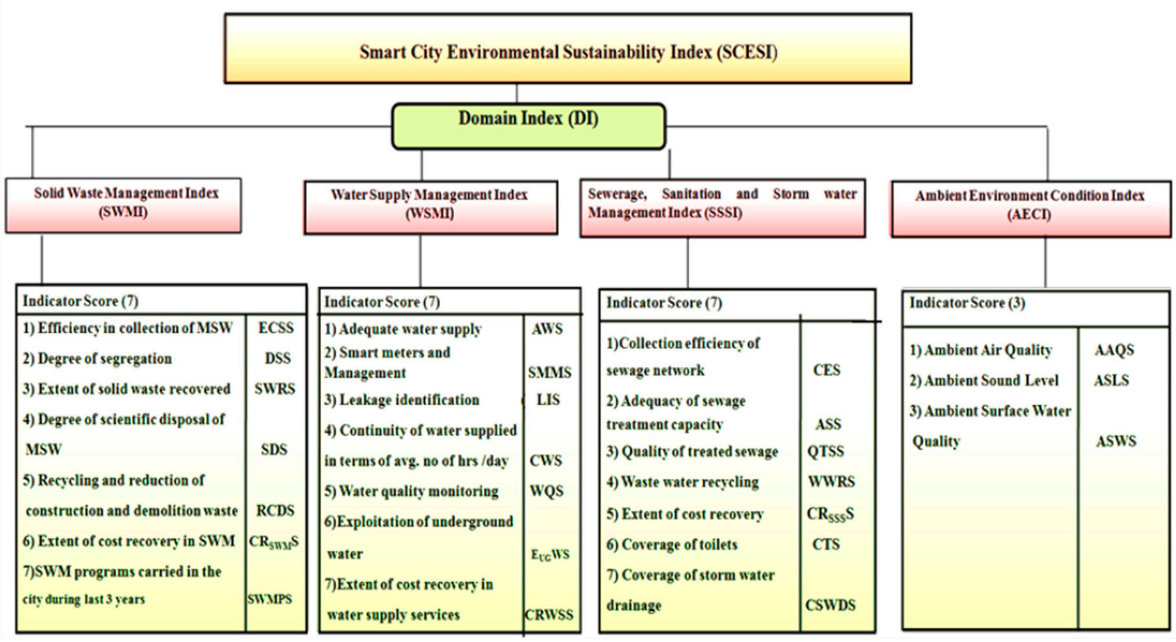

Figure 2. Skeletal structure for Smart Cities Environmental Sustainability Index (SCESI).

For demonstration purpose in the present study, all the four environmental domains: Solid Waste Management (SWM), Water Supply Management (WSM), Sewerage, Sanitation and Storm water (SSS) management, and Ambient Environment Condition (AEC) have been given equal weightage (i.e., $v_1 = v_2 = v_3 = v_4 = 1$). As m = 4 in this case, Equation (1) simplifies to:

$$\text{SCESI} = (\text{SWMI} + \text{WSMI} + \text{SSSI} + \text{AECI})/4 \tag{4}$$

DIs: SWMI, WSMI, SSSI, and AECI are calculated by summing the indicator scores (ISs) under the respective domain. The IS is a reflection of performance of the city for a given indicator with respect to a standard benchmark value decided for the purpose and relative weight assigned to it. The indicators have been benchmarked on a 0–100 scale with respect to the intended standard values, and the summation of the weight of indicators in a given domain is 1.

The effectiveness of solid waste management may be measured by calculating the Solid Waste Management Index (SWMI), using seven selected indicator scores (ISs), and maybe written as:

$$\text{SWMI} = (\Sigma\ \text{IS}) = (\text{ECS} + \text{DSS} + \text{SWRS} + \text{SDS} + \text{RCDS} + \text{CR}_{\text{SWM}}\text{S} + \text{SWMPS}) \quad (5)$$

where ECS, DSS, SWRS, SDS, SWMPS, RCDS and $\text{CR}_{\text{SWM}}\text{S}$ are the indicator scores (ISs) obtained through the respective BIV (x_k) and weight (w_k) using Equation (3).

The Water Supply Management Index (WSMI) may be calculated using its seven selected indicator scores (ISs):

$$\text{WSMI} = \Sigma\ (\text{IS}) = (\text{AWS} + \text{SMMS} + \text{LIS} + \text{WQS} + \text{CWS} + \text{E}_{\text{UG}}\text{WS} + \text{CR}_{\text{WS}}\text{S}) \quad (6)$$

For benchmarking in water supply, adequacy is calculated with reference to 135 lpcd (Benchmark set by MoUD, GoI). The continuity of water is calculated in terms of an average number of hours of water supply, which has a benchmark of 24h. For calculation of exploitation of underground water, the groundwater table (GWT) data of five years for dug wells in pre-monsoon, monsoon, and post-monsoon periods are collected (e.g., from Central Groundwater Board sources). If GWT shows almost a constant level within limits, BIV = 100, and if there is a significant declining trend, then it is taken as 0.

The Sewerage, Sanitation, and Stormwater Management Index (SSSI) is calculated using the seven selected indicator scores (ISs) as:

$$\text{SSSI} = (\Sigma\ \text{IS}) = (\text{CES} + \text{ASS} + \text{QTSS} + \text{WWRS} + \text{CTS} + \text{CR}_{\text{SSS}}\text{S} + \text{CSWDS}) \quad (7)$$

The Ambient Environment Condition Index (AECI) is calculated using three selected Indicator Scores (ISs) and given by:

$$\text{AECI} = \Sigma\ (\text{IS}) = (\text{AAQS} + \text{ASLS} + \text{ASWS}) \quad (8)$$

where AAQS, ASLS, and ASWS are related indicator scores for air, noise, and surface water bodies, respectively. The condition of ambient air quality (AAQ) is found using the Air Quality Index (AQI), which is a tool developed by the Central Pollution Control Board (CPCB) foreffective communication of air quality status of the city. AQI transforms complex air quality data of various pollutants into a single number and the lower is the AQI of a city, the better is the air environment. Its highest value is 500. In order to make it an incremental value index, we calculate the Ambient Air Quality Score (AAQS) given by:

$$\text{AAQS} = [(500 - \text{AQI})/500] \times 100 \quad (9)$$

For ambient sound level score (ASLS), the data are collected from residential, commercial, industrial and silence zones of the city and compared with the standards given by Noise Pollution (Regulation and Control) Rules, 2000 [56]. Noise pollution is calculated by mapping the noise level L (day-evening-night) likely to cause annoyance as given in ISO 1996-2:1987 [34]. The result shall be expressed as the percentage of the population affected by noise pollution.

For the ambient surface water quality score (ASWS), sampled water quality are compared with the standards for bathing. The number of samples meeting the standards to the total number of samples collected gives the quality of ambient surface water quality.

3.2. Classification of Environmental Sustainability Status of Smart Cities Based on SCESI Score

Based on the SCESI score on 0–100 scale, the smart cities may be classified in five categories, as given in Table 2.

Table 2. Classification of environmental sustainability status of smart cities based on SCESI.

SCESI Score	Environmental Sustainability Category of the City
>80	Excellent
60–80	Good
40–60	Fair
20–40	Poor
<20	Critically Low

4. Application of SCESI: Case Study of Five Cities under SCM of India for Environmental Sustainability

SCESI is the arithmetic mean of four DIs: SWMI, WSMI, SSSI, and AECI. In order to check the applicability of SCESI, five cities, namely Delhi, Patna, Varanasi, Allahabad, and Bhubaneswar, which are enlisted for development under Smart Cities Mission in India, have been selected (Figure 3). Delhi has been selected as it is the capital city of India and grapples with numerous challenges like rapid population growth, urbanization, environmental degradation due to heavy pollution, and offering a poor quality of life to many of the populace. Patna, Varanasi, and Allahabad are situated on the bank of river Ganga, the longest river of India that is significantly important for its economic, environmental, and cultural values. Rapid population growth, industrialization, haphazard urbanization, and discharge of untreated sewage in the river have degraded the quality of river Ganga. Hence, the framework is applied to these cities to understand the prevailing situation and challenges lying in the water environment and sanitation facility management. Bhubaneswar is selected because it has been shortlisted at the top rank in the first round of Smart Cities Mission among 100 cities [57]. Hence, these cities are the perfect epitome for the study and validation of the framework.

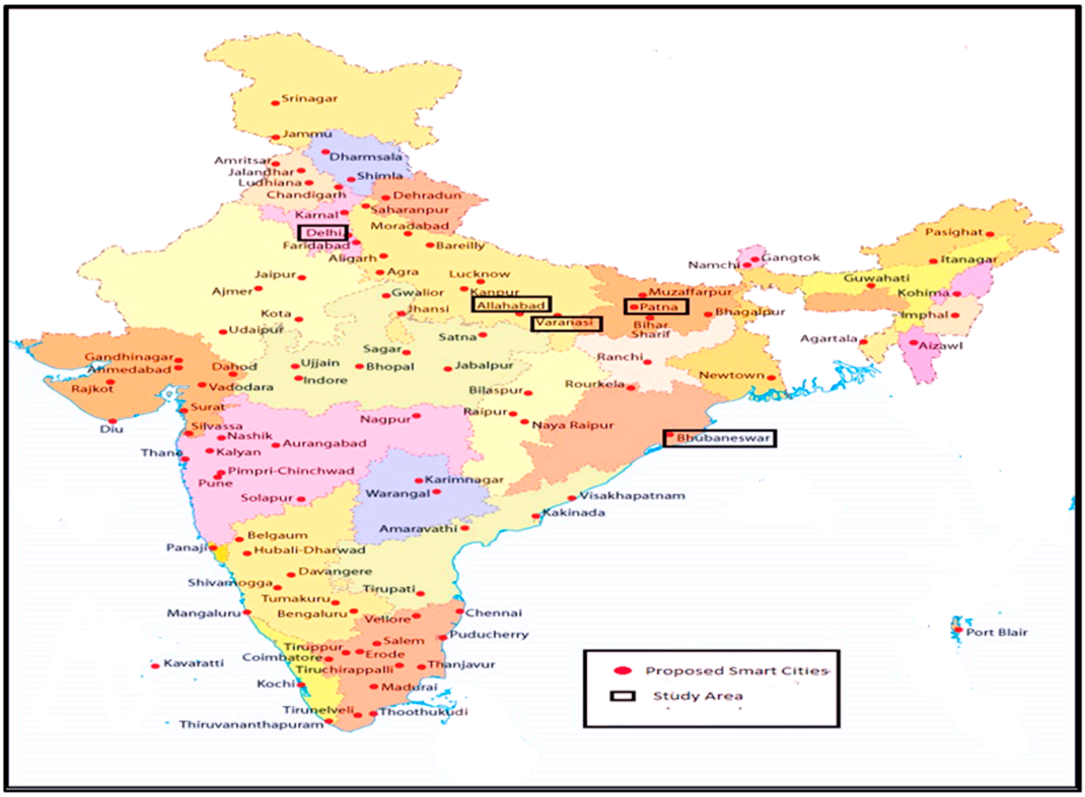

Figure 3. Proposed Smart cities of India and selected study area [58].

5. Result and Discussions

The 24 selected indicators are used for calculating the 'Smart City Environmental Sustainability Index (SCESI)'with secondary data for five Indian cities: Delhi, Patna, Allahabad, Varanasi, and Bhubaneswar. Based on the results obtained from the framework using available data in the public domain, while the environmental sustainability of Delhi, Allahabad, and Bhubaneswar fall in the Fair category (SCESI = 40–60), Varanasi and Patna are in the Poor category (SCESI < 40) (Table 3). With a current set of data, the environmental sustainability level of Allahabad appears the best, followed by Bhubaneswar and Delhi (Figure 4). While SWM is the most critical environmental domain to be attended to and addressed on a priority basis for Allahabad, it is SSS for Bhubaneswar and AEC for Delhi. Similarly, Varanasi needs to focus on improving its AEC, and SWM appears the most critical for Patna. The domains currently under Critically Low (SCESI < 20) and Poor (SCESI = 20–40) need to be prioritized, and those in the Fair category (SCESI > 40) also need to be worked for achieving Good status (SCESI > 60). Thus, comparing 4 DIs (SWMI, WSMI, SSSI, AECI) for each of the 5cities (Total 20), 2 are found in Good (SSSI and AECI for Allahabad), 11 in Fair (SWMI for Delhi and Bhubaneswar; WSMI for all the selected cities; SSSI for Delhi and Varanasi), 5 in Poor (SWMI for Patna, Varanasi, Allahabad; SSSI for Patna and Bhubaneswar), and 2 in Critically Low (AECI for Delhi and Varanasi) categories of environmental sustainability.

Table 3. Domain Indices (DIs), SCESI, and environmental sustainability category of five selected cities.

Index		Values with Environmental Sustainability Category				
		Delhi	**Patna**	**Varanasi**	**Allahabad**	**Bhubaneswar**
DIs	**SWMI**	44.83 (Fair)	25.80 (Poor)	20.70 (Poor)	20.70 (Poor)	48.28 (Fair)
	WSMI	52.20 (Fair)	40.56 (Fair)	48.76 (Fair)	52.28 (Fair)	41.56 (Fair)
	SSSI	58.72 (Fair)	39.52 (Poor)	50.44 (Fair)	60.04 (Good)	35.00 (Poor)
	AECI	11.40 (Critically Low)	47.48 (Fair)	12.40 (Critically Low)	63.88 (Good)	56.68 (Fair)
SCESI		**41.80 (Fair)**	**38.36 (Poor)**	**33.08 (Poor)**	**49.24 (Fair)**	**45.39 (Fair)**

(Environmental Sustainability Category:DI or SCESI > 80: Excellent; 60–80; Good; 40–60: Fair; 20–40: Poor and <20: Critically Low).

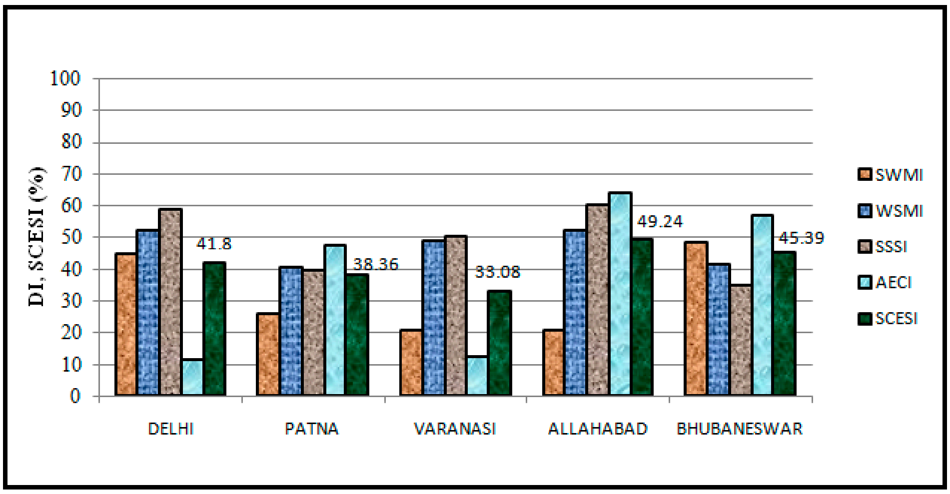

Figure 4. Domain Indices and SCESI of five selected cities under SCM [59–68].

Accordingly, a sequential prioritization has been done for these cities with an emphasis on improving the environmental domains under Critically Low and Poor conditions (Table 4). As can be seen, while the achieved level of services in domains with the Fair category and above (SCESI > 40) have to be maintained and improved, AEC falls under the Critically Low category and is indicated as the first priority for Delhi and Varanasi. Similarly, SWM is found under the Poor category for three cities (Allahabad, Varanasi, and Patna) with SSS for two cities (Patna and Bhubaneswar).

Table 4. Environmental domain(s) under 'Poor (P)' and 'Critically Low (CL)' categories of sustainability and priority Indicators.

Name of City	Sequential Priority of Environmental Domains for Fund Allocation	Environmental Domain(s) under 'Poor' or 'Critically Low' Categories	Priority Indicators		
			First	Second	Third
Delhi	AEC, SWM, WSM, SSS	AEC (CL) *	Ambient Sound Level	Ambient Surface Water Quality	Ambient Air Quality
Patna	SWM, SSS, WSM, AEC	SWM (P) *	Degree of scientific disposal of MSW	Extent of solid waste recovered	Recycling and reduction of construction and demolition waste
		SSS (P) *	Quality of treated sewage	Extent of cost recovery	Collection efficiency of sewage network
Varanasi	AEC, SWM, WSM, SSS	AEC (CL) *	Ambient Sound Level	Ambient Surface Water Quality	Ambient Air Quality
		SWM (P) *	Degree of Segregation	Degree of scientific disposal of MSW	Extent of solid waste recovered
Allahabad	SWM, WSM, SSS, AEC	SWM (P *)	Degree of Segregation	Degree of scientific disposal of MSW	Extent of solid waste recovered
Bhubaneswar	SSS, WSM, SWM, AEC	SSS (P) *	Waste water recycling	Collection efficiency of sewage network	Adequacy of sewage treatment capacity

* P = Poor; CL = Critically Low.

Figure 4 shows the current status of DIs and SCESI scores for five selected cities for the study.

Based on individual indicator scores (ISs) obtained using currently available data, it is observed that management of ambient sound level followed by quality of water bodies and ambient air quality (all under AEC domain) are the priority areas of action for in Delhi. In Patna, for improving solid waste management, the first three priority areas are (a) scientific disposal, (b) resource recovery, and (c) recycling and reduction of construction and demolition waste, along with (a) improvements in quality of treated sewage, (b) cost recovery from recycling and reuse, and (c) enhancing collection efficiency of sewerage network which constitute the three priority actions under SSS domain. For Varanasi, while the AEC domain improvement requirements are similar to Delhi, under the SWM domain, (a) increasing degree of segregation, (b) scientific disposal of MSW, and (c) recovery of resources from MSW are priority areas. Allahabad needs similar prioritized intervention in SWM as recommended for Varanasi. For improving SSS conditions in Bhubaneswar, (a) wastewater recycling, (b) enhancement of collection efficiency of sewage network, and (c) adequate sewage treatment capacity are found as priority action areas.

6. Conclusions

Experiences from the development of Smart Cities across the world have shown general weak connectivity between initiatives of 'smartness' and environmental sustainability.

At present, among various urban development programs, there are varying levels of emphasis on different sectors/domains of environmental infrastructure, e.g., according to AMRUT guidelines, Water Supply is the first priority, followed by Sewerage and Storm Water Drainage depending upon the availability of funds. The initiatives take under Smart Cities Mission (SCM) of India needs to ensure a benchmarked level of service delivery in each of the chosen sectors. Furthermore, the country needs to develop models for 'Sustainable Smart Cities' and further move to 'Environmentally Sustainable Smart Cities (ESSC)', in which all domains of environmental management, such as Solid Waste Management (SWM), Water Supply Management (WSM), Sewerage, Sanitation and Storm water (SSS) management, and Ambient Environmental Conditions (AEC) covering noise, air quality and water bodies have equal emphasis with a certain benchmarked level of service in indicator areas. The present study focussed on identifying a set of indicators that can be used to reflect the environmental sustainability of Smart Cities. The 24 selected indicators have been used in a framework to calculate a Smart City Environmental Sustainability Index (SCESI) on a 0–100 increasing scale. Each indicator is benchmarked with respect to a standard value on a 0–100 scale and converted into an Indicator Score (IS) using its weight. ISs are grouped to form Domain Index (DI) and DIs are used to give SCESI. While ISs reflect current achievement levels in a given specific area of environmental management with respect to the benchmarked standard, DIs reflect the performance in different environmental domains, such as solid waste management, water supply, etc. The SCESI gives an overall measure to understand and categorize the environmental sustainability of the city.

The approach has been tested using the available secondary data in the public domain for five cities of India, namely Delhi, Patna, Allahabad, Varanasi, and Bhubaneswar, which are currently being developed as part of SCM. Accordingly, for each city, there are 24 ISs, 4 DIs, and one SCESI. The analyses have been used to identify the domains under Poor (P) and Critically Low (CL) categories of environmental sustainability along with related three priority indicators that need urgent attention. Among the five cities examined, while three cities (Delhi, Allahabad, and Bhubaneswar) are in Fair category (SCESI = 40–60), two cities (Patna and Varanasi) are found in the Poor category (SCESI = 20–40). The application of the Smart Cities Environmental Sustainability Index (SCESI) seems to reflect justifiable results and hence may be used as a scientific tool to identify critical areas of intervention, investment, and improvement. The application of benchmarked indicator value to give indicator score (IS) may be quite handy for the cities to compare and judge its performance in specific environmental activity and direct the investment plan accordingly for better gains.

Limitations and Future Scope

The present research work focused on a framework for evaluating Environmentally Sustainable Smart Cities (ESSC) in the context of developing countries, such as India. The indicators have been finalized based on available monitoring parameters under SCM and other concurrent Government programs, keeping in mind the experiences reported in the literature concerning sustainable and smart cities across the world. The approach may be useful for other developing countries as well, but the indicators, their relative weights, and the importance of various environmental domains may vary. In addition, other dimensions of sustainability, such as social and economic, may also need to be suitably examined for cities under SCM.

Author Contributions: Formal analysis, A.O.; Investigation, P.K.S.; Methodology, S.S.; Supervision, P.K.S.; Writing—original draft, S.S.; Writing—review & editing, P.K.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgments: The authors would like to thanks Ramesh Singh, Visiting Faculty, Department of Civil Engineering, IIT (BHU) for providing valuable suggestions and other experts of the panel who helped in using Delphi Method for assigning weights to environmental indicators in the present study.

Conflicts of Interest: The authors declare no conflict of interest.

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