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Municipal Waste Management in Polish Cities—Is It Really Smart?

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Abstract: Efficient municipal waste management is one of the key aspects of smart cities. In the literature, modern technological solutions are mainly analyzed in this context on the example of specific case studies. However, the author of this article attempts a more fundamental, holistic and comparative assessment of waste management in cities, recognized as smart and aspiring to this title. The objective of this attempt is to answer the following question: What results do the designated cities achieve in terms of waste volume reduction, waste segregation and collection costs? The research was carried out on 16 Polish provincial cities used as examples, including two (Warsaw and Wrocław) classified as smart cities in ranking of the *Cities in Motion Index 2020*. The analysis period covers 2019–2021, and during the research, in addition to the parameters listed above, a multi-criteria analysis was used to allow a collective assessment of the effectiveness of municipal management in the surveyed cities. The results obtained allow the conclusion that the volume of waste per capita in most of the analyzed cities is steadily increasing. The cost of waste management is also growing significantly. These unfavorable phenomena are particularly acute for smart cities, which in the holistic assessment were ranked among the three least effective units in terms of waste management (Lublin, Warsaw, Wrocław).

Keywords: municipal waste management; smart city assessment; quality of life in smart cities

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1. Introduction

Waste management is currently a highly analyzed and discussed topic [1–5]. This is because economic, civilizational and social development generates not only better living conditions, but also many adverse side effects. One of them is the increasing volume of municipal and industrial waste. This is a very serious environmental problem that poses a threat to the entire ecosystem [6,7].

Unsustainable consumption and production are primarily blamed for the rise in waste problems [8], and their solution is seen in the propagation of sustainable development, including primarily the implementation of a closed-loop economy [9,10].

The Smart City (SC) concept, which has been heavily humanized and greened in recent years [11–14] to better meet the needs of the modern world and foster improvements in the quality of life for all urban stakeholders [15–17], is also part of this trend of consideration, research and action. Cities created and improved under this concept are no longer exclusively smart, but also sustainable and humane [18]. Nevertheless, it remains an open question whether it succeeds in practice to build and transform cities in this way.

For these reasons, this article attempts to assess the effectiveness of waste management in 16 Polish cities that are, or aspire to be, Smart Cities. This assessment was carried out from the perspective of the basic elements related to municipal waste, i.e., its generation, segregation and collection efficiency. In this context, answers are sought to the following questions:

- How much waste is there, and at what rate do smart city residents generate it?
- How much of the municipal waste generated is segregated?
- How much does it cost to collect and process municipal waste?

Questions posed in this way make it possible to assess the actual state of waste management, since they address it in a holistic, dynamic and comparative way, rather than in a fragmented way concerning mainly technological, smart city solutions for municipal management. Obtaining answers to the above questions also allows the assessment of the approach of residents to sustainable consumption, and of city authorities to the issue of waste segregation and the formation of waste collection costs.

Empirical studies in the above area are very rarely conducted [19–21], even though they make it possible to assess the actual effects of cities in key areas of their development. They also allow us to confront the assumptions postulated in the literature and in city strategies about being "sustainable and humane" with the reality of urban life. This is necessary and required in order to holistically and continuously monitor the quality of life in cities that are and want to be smart.

An additional rationale for this consideration and research is also the low representation of cities from emerging and developing economies in smart city ranking [22–24]. This creates an impression of exclusivity reserved only for cities located in highly developed economies and adds to the arguments against the development of smart city structures.

From a theoretical perspective, the research conducted provides a methodological framework for the dynamic assessment of municipal waste management in the context of the sustainable development of smart cities. They also enhance the existing knowledge on the functioning of smart cities, with a diagnosis of the state of municipal waste collection, processing and collection efficiency in cities that are smart or aspire to that title in developing economies.

In summary, the contribution of the analyses conducted in the article to the development of the Smart City concept includes:

- Confronting the theoretical assumptions of the SC concept of waste sustainability with the reality of smart cities;
- Complementing the ecological stream of SC considerations with research conclusions on development trends in the size and efficiency of municipal management in smart cities;
- Subjective expansion of previous analyses related to municipal management in SC to include cities operating in developing economies;
- Creating a methodological framework for assessing the quality of urban life in the context of municipal management that takes into account the basic criteria for such assessment and their changes over time;
- Verifying the arguments cited by the critical school of thought on smart cities regarding their consumerism and work against sustainability.

The following part of the article presents a literature study covering the theme of the development and scope of the Smart City concept, as well as considerations to identify current areas of analysis of waste management in smart cities. This made it possible to specify the research gap and formulate research intentions. Next, the research methodology is described, taking into account the selection of instruments for assessing the effectiveness of waste management and the characteristics of the research sample. The results are presented in accordance with the principle of content hierarchy, starting with detailed and individual analyses and ending with a holistic multi-criteria analysis. Conclusions and research insights are contrasted with the existing state of analysis and evaluation presented in the literature studies. The conclusion also includes recommendations, research limitations and directions for further scientific inquiry.

2. Literature Overview

This chapter presents a literature study that forms a basis for identifying the research gap and defining the thematic scope of the research conducted. Two main themes are presented: (1) The Smart City concept and (2) Current areas of analysis of waste management in smart cities.

2.1. Smart City Concept and Areas of Smart City Analysis

The development of the smart city concept can be observed since the middle of the last century in connection with increasing urbanization and the associated need to improve the lives of urban communities [24–27]. The assumption was that this improvement would come about through the technicization and computerization of urban infrastructure [28–31]. Thus, cities were introducing modern IT, communication and transportation solutions so that urban life would be more comfortable, faster and more efficient.

This approach, however, has come under criticism over time due to a variety of circumstances. The first of these was undoubtedly the overlooking of the needs of urban communities in the decision-making process for the development and improvement of smart cities [32,33]. This is because cities were very often treated merely as an attractive market for suppliers of information technology (IT) and information and communication technology (ICT). In turn, city governments used modern technological solutions mainly to improve the image of cities [34–39].

With regard to the original concept of the Smart City—in addition to overlooking the urban community—there has also been criticism of the elitism and exclusivity of smart cities [40], which can lead to multidimensional exclusion that includes:

- Seniors, finding it harder to adopt modern technological solutions [41];
- People with disabilities, with limited ability to use universal smart city solutions [42];
- Less affluent residents who cannot afford to purchase and/or pay for devices and/or services typical of smart cities [43];
- Less developed areas lying outside cities (towns, villages), which cannot offer such attractive living conditions as Smart Cities [44];
- Cities in underdeveloped, emerging and developing economies that face a lack of resources for urban infrastructure development.

Issues related to the protection of residents' personal data and systems for safeguarding the cities' IT infrastructure from failure or cyber attacks have also become the subject of harsh criticism from SC [45].

Furthermore, it has also begun to be noted that the development of smart cities may adversely affect the environment due to the high urbanization and excessive consumerism that characterize these social structures [46–49]. Among the negative side effects of smart cities have been pointed out: air pollution associated with high industrialization and transportation intensity; high water consumption and pollution; and the generation of above-average amounts of municipal and industrial waste.

The premises indicated above have brought the SC concept many adversaries. Academics and practitioners opposed to the Smart City concept are now forming a current known as the critical school of thought. However, it should be added that criticism of smart city development has also initiated a process of reorientation and refinement of the concept [50–53]. Thus, it had tangible cognitive and utilitarian effects.

There was a systematic move away from bilateral city-business relations to multilateral contacts involving representatives of science, the urban community and environmentalists. This was a direct reference to the successive economic helixes: triple, quadruple and quintuple. As a result, in addition to the word "smart", adjectives such as "sustainable," "humane" or "green." As a result, the concept of SC has become more humanized and less technocentric [54,55].

2.2. Dimensions of Defining Smart Cities

The real dimension of expanding and refining the idea of SC was undoubtedly the European Commission's 2014 report, entitled *Mapping Smart Cities in the EU*, which highlighted 6 key areas that characterize a Smart City [56]:

(1) Smart people: referring to city residents who have access to and are able to use smart city solutions, and are also actively participating in their creation [57,58];

(2) Smart economy: encompassing efforts to increase urban competitiveness and innovation resulting in increased productivity, efficiency and internationalization [59–61];
(3) Smart mobility: involving the movement of people and goods in a safe, fast, efficient, hassle-free and environmentally friendly manner [62];
(4) Smart environment: concerning sustainable resource management, use of renewable energy sources and attention to environmental quality, and environmental education of the urban community [63–65];
(5) Smart governance: offering high quality public services, attractive development strategies, public efficiency and public participation;
(6) Smart living, including: universal access to public services, educational, cultural, health and social infrastructure [66–68].

The evolution of the SC concept described above is right and desirable, especially in the context of the improved quality of life that modern smart cities are supposed to offer. Nevertheless, in the author's opinion, it requires verification in practice. This is because the above assumptions are attractive, but in practice their implementation requires concretized actions and considerable human and financial effort. For these reasons, this article attempts to confront them with the realities of the operation of smart cities in developing economies. The area of analysis conducted is narrowed down to smart environment and municipal waste management. At the same time, it gets away from the typical technicized approach referring to innovative technological solutions, which is strongly exposed in the literature, and which refers to the original understanding of the SC concept. The author perversely analyzes the basic aspects of municipal waste management, so as to confront the obtained conclusions with both positive and negative perceptions of smart cities, and to obtain an answer to the question: Are the studied cities really smart in the ecological dimension of waste management?

2.3. Waste Management in Smart Cities in Light of Past Research and Experience

The literature on waste management in smart cities mainly addresses technological issues. Most of it concerns innovative solutions for municipal waste planning and collection using information and communication technologies. As pointed out by Heidari et al. [69], the Internet of Things (IoT), Internet of Drones (IoD), and Internet of Vehicles (IoV) are most often used for this purpose. Among waste data analysis methods, the most popular are Machine Learning (ML), Federated Learning (FL) and Deep Learning (DL) [70–72].

A very popular solution from this area is smart trash garbage cans [73,74]. For example, Karthnik et al. [75] describe a sensor system for public trash garbage cans that informs when they are overflowing and need to be picked up. They use the Internet of Things (IoT) to do this, as do other researchers analyzing these solutions [76]. Radio frequency identification (RFID) systems are also very common in smart trash garbage can design technology [77]. Solutions based on fuzzy logic or multi-agent approaches allowing real-time access to data are also proposed [78]. Systems for identifying trash containers using surveillance and video cameras are also being used, as proposed by Morale et al. [79]. Ijemaru et al. [80], on the other hand, present the use of Internet of Vehicles (IoV) in the process of collecting information about the status of waste in trash containers. The system they designed not only collects data, but also aggregates and processes it to optimize transportation routes.

In turn, Marques et al. [81] focus on maximizing the efficiency of smart garbage costs and design a holistic system to manage their operation for the entire city. In their view, this is essential in the context of rapidly increasing urbanization and urban population density. Bharadwaj et al. [82] go a bit further and design a system to further optimize waste collection routes depending on signaling the fullness of waste containers. Similar research is conducted by Salehi-Amiri et al. [83], looking for the so-called threshold waste level (TWL), which will determine the optimal length of the waste transport route and at the same time ensure maximum efficiency in the use of the transport fleet.

An extension of the described issue is undoubtedly the use of renewable energy to power smart trash cans. Such a solution is described by Ashwin et al. [84]. In their proposal, smart public waste collection includes both waste selection into wet and dry fractions, as well as information about the garbage can being full. The entire process is carried out using solar energy obtained from a photovoltaic panel placed on the lid of the trash garbage can.

It is worth adding that smart waste separation and collection systems are also of interest in emerging and developing economies. Nevertheless, there they are the result of imitation and are most often prototype rather than implementation in nature, as pointed out by Fatimah et al. [85] using the Indonesian economy as an example.

In turn, Cheela et al. [86] focus on improving waste management in India. At the outset of their research they signal that the Indian government is interested in the idea of the Smart City, and one of its areas of particular concern in this regard is precisely the problem of municipal waste management in connection with the increasing urbanization of cities. Based on a case study of six cities, the authors propose an integrated solid waste management system including: waste characterization; identification of funding sources for waste collection; data processing technologies; and benchmarking of urban waste collection and management services. The research areas referred to herein indicate interest in, and attempts to implement, smart city solutions in emerging economies as well.

The research part is not limited to the problem of municipal waste collection, also analyzing the possibilities of waste segregation and recycling. Thus, Chen [87] proposes to use the Internet of Things and machine learning (ML) to gather information on collected waste and determine the possibility of segregating and recycling it. This approach promotes the greening of smart cities.

The literature also devotes considerable attention to management issues relating to planning, organizing and controlling municipal waste management. At the same time, developed in the theoretical version, they very often become the basis for the creation and implementation of computer systems to support their operation. This area also includes publications on municipal waste recycling technology [88].

Management recommendations to city governments also propose solutions of a financial nature. For example, Roy et al. [89] propose financial penalties for waste collection companies in situations of overflowing costs for garbage. At the same time, to minimize the oppressiveness of such a solution, they propose an intelligent variable neighborhood search with ant colony optimization method (VNS-ACO). It is designed to speed up and aggregate the process of centrally reporting the status of overflowing garbage cans.

In the area of waste management, there are also publications focused on raising the awareness of urban residents [90] in terms of possible reduction in the amount of generated waste. Thus, Cappelletti et al., for example, [91] propose the use of smart refrigerators that monitor food levels and consumption in households aimed at rationalizing consumption and reducing food waste, which in the European Union amounts to more than half of the trash generated by residents.

From the above review of the contemporary literature on the subject, it is clear that waste management issues are analyzed primarily in a technological context, which is complemented to a fairly small extent by optimization economic or ecological threads. This approach strongly relates to the original concept of the Smart City, treating the quality of life of residents and their needs as a certain background to the research and considerations carried out. In addition, waste management is treated in a fragmentary way, and mainly garbage collection and collection systems are analyzed. Far fewer studies deal with educational, social or recycling issues. Moreover, in the analyzed publications, we will not find an answer to the question: How residents interact with the level of waste generated in smart cities? For these reasons, this article focuses on a holistic, dynamic view of the process of waste generation in cities in an attempt to fill the existing research gap described above.

Before starting the considerations, it is worth adding that intelligent waste management in the Smart City concept is understood as technological improvement of waste management, including, above all, reverse logistics. Its aim is, of course, to improve the quality of life in the city. A side effect may be cost reduction or environmental protection, but these goals are not a priority.

In contrast to such an approach, the article proposes a look at the effectiveness of smart waste management assessed from the perspective of costs and environmental effects. Therefore, the author does not think about what the input is, but what the output is.

3. Materials and Methods

The research methodology is described in the next two subsections, including the research intentions and the indicators and research tools used. The characteristics of the studied cities are also presented within this section.

3.1. Research Intentions, Data, and Methods

From the literature studies conducted, direct research premises follow, which include:

- The lack of studies on evaluating the effectiveness of urban waste management, while it is the basic behavior of residents in terms of sustainable consumption and the choices and decisions of municipal authorities that determine the final outcome of waste management;
- Lack of analysis showing the level and variation in cost-effectiveness of municipal waste collection;
- Lack of dynamic statistical analysis illustrating trends and changes in urban garbage generation to assess the actual greenness and sustainability of smart city infrastructure;
- The need to conduct holistic, empirical research on urban waste management issues;
- The need to analyze waste management in emerging and developing economies, which have received far less attention in the literature than the best practices in this area that illustrate the functioning of smart cities in developed countries.

In the context of the rationale thus defined for the need for this research, its main objective is to evaluate the effectiveness of waste management in smart cities conducted from a dynamic and holistic perspective, considering the following: (1) the volume; and (2) the rate of municipal waste collection; (3) the extent of its segregation; and (4) the cost of collection by municipal management companies.

At the same time, efficiency—in accordance with the assumptions of praxeology—is understood in this case as the degree to which waste management goals are achieved, which can include minimizing the volume and rate of waste generated and maximizing the volume of segregated waste, while minimizing the cost of collection and processing (maximizing public efficiency).

To achieve such a goal, the research and subsequent description of its results are divided into two stages. The first relates to a detailed analysis of the performance of urban waste management, and the second involves an aggregate assessment of the effectiveness of urban waste management carried out through multi-criteria analysis. The research period covers 2019–2021, which allows for an assessment of effectiveness in a dynamic perspective. The analysis involved 16 Polish cities, the characteristics of which are included in the next subsection. The source research material comes from the Local Data Bank—a database maintained by the Statistics Poland [92].

The following indicators were used in the detailed analysis:

(a) The volume of municipal waste generated by one resident, expressed in kg per year:

$$MW = \frac{T_{MW}}{P} \tag{1}$$

where:

T_{MW}—the volume of annual total municipal waste in the city;
P_w—city population.

(b) The average annual rate of change in the volume of waste in the city expressed as %:

$$R_{ch} = \sqrt[n-1]{\frac{MW_n}{MW_0}} \tag{2}$$

where:

MW_n—the volume of municipal waste in the city per capita in the last analysis period;
MW_0—the volume of municipal waste in the city per capita in the first analysis period;
n—the number of periods subject to analysis.

(c) Share of mixed waste in total waste expressed in % and illustrating the scale of garbage segregation in the city:

$$S_{mixed} = \frac{W_{mixed}}{T_{MW}} \tag{3}$$

where:

W_{mixed}—the volume of annual mixed waste;
T_{MW}—the volume of annual total municipal waste in the city.

(d) Cost-to-effectiveness ratio calculated as the ratio of the cost of operation of the municipal waste collection system (including the costs of collection, transportation, gathering, recovery and disposal of municipal waste, establishment and maintenance of selective municipal waste collection points and administrative service of the system) per 1 ton of collected waste expressed in PLN/ton:

$$C_{ef} = \frac{C_t}{T_{MW}} \tag{4}$$

where:

C_t—costs of operating the municipal waste collection system;
T_{MW}—the volume of annual total municipal waste in the city.

A holistic assessment of the effectiveness of municipal waste management used a multi-criteria analysis that allows aggregating the indicators listed above, summarizing them and developing a ranking of the cities under analysis. Multi-criteria analysis allows combining the analyzed criteria within a single objective function, which in this article is the efficiency of municipal waste management in the studied cities. This is done according to the following formula.

$$F_w = \sum_{i=1}^{m} w_i \times f_i(x) \tag{5}$$

where:

$w_i \epsilon [0;1]$ i $\sum_{i=1}^{m} w_i = 1$—the weight of each criterion;
$f_i\ (x)$—functions describing each criterion.

In multi-criteria analysis, the analyzed variables are divided into stimulants, destimulants and nominants. In the process of variables normalization the method of zero unitization was used, which is characterized by assuming a fixed point of reference, which is the stretch of a given normalized variable. The article assumes that each of 5 analyzed criteria has the same weight of 1. The list of individual criteria finally used in the assessment of the effectiveness of energy policy is presented below:

- The volume of waste per capita in 2021 in kg (destimulant)—the more waste 1 inhabitant produces, the lower the effectiveness of waste management in the context of sustainable consumption and development;
- Average annual rate of change in waste volume per capita in % (destimulant)—the higher the rate of increase in waste volume per capita, the less effective is waste management from the point of view of environmental awareness of the urban community;
- Average share of mixed waste in total waste in % (destimulant)—the higher the share of mixed waste in total waste, the lower the effectiveness of waste management in the context of circular economy and waste recycling;

- Cost efficiency in 2021 in PLN/ton (destimulant)—the higher the cost of waste collection, the lower the efficiency of the public sphere (a parameter important for assessing the economy of the city government);
- Change in cost efficiency relative to 2019 in % (destimulant)—the faster the rate of deterioration of cost efficiency, the worse the city government's efficiency in waste management.

Accordingly, in the course of the conducted analyses, not only variables in static terms (referring to a single period) were taken into account, but also the rate/level of their changes allowing the assessment of the effectiveness of waste management in dynamic terms, which is an empirical distinctive of the conducted research.

3.2. Research Sample Characteristics

As already mentioned, 16 Polish cities were selected for the study. These are provincial capitals, and therefore units with high development potential that are centers of regions. Their locations on the map of Poland are shown in Figure 1.

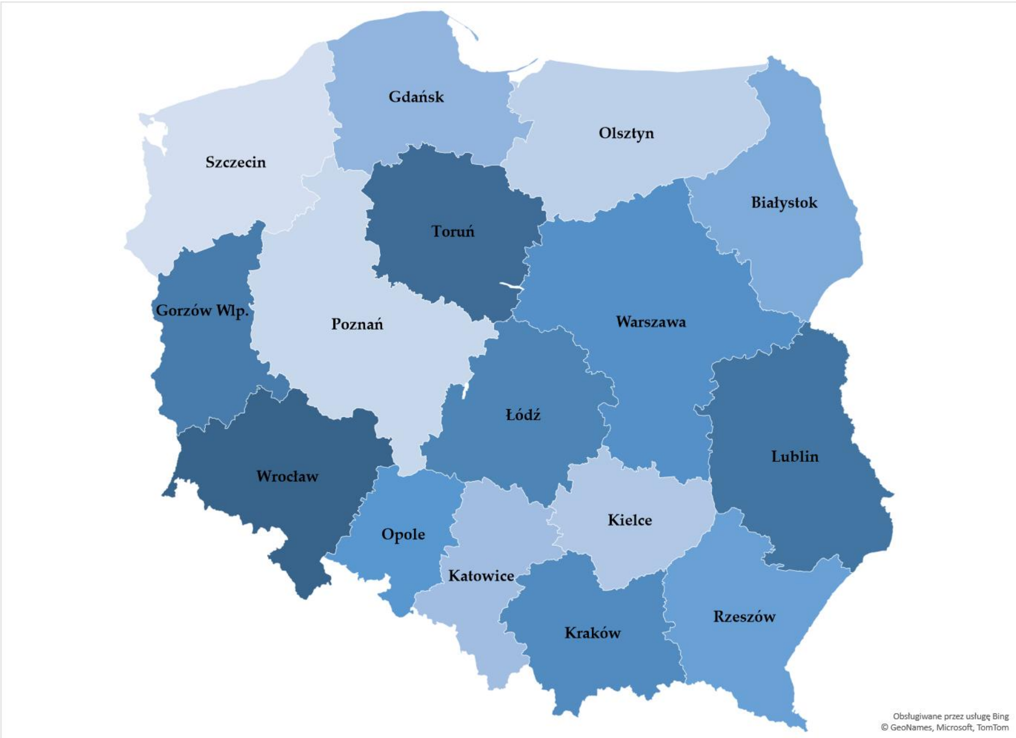

Figure 1. Location of the surveyed cities.

Basic characteristics of the analyzed cities are shown in Table 1.

All analyzed cities have a population of more than 120,000. The largest in this respect are Cracow, Łódź and Wrocław (above 600,000 inhabitants), with the smallest being Gorzów Wlk., Opole and Toruń. The area of the cities also varies, ranging from 83 km^2 (Olsztyn) to 517 km^2 (Warsaw) and population density ranging from 858 persons/km^2 (Opole) to 3466 persons/km^2 (Warsaw).

The analyzed cities are implementing, and are interested in obtaining, the Smart City designation, which is associated not only with prestige but also with the popularization of the city's image worldwide. It was therefore assumed that they aspire to be smart or already have such status. The latter applies to Warsaw and Wrocław, which in 2019 were the only Polish cities to be included in the *IESE Cities in Motion Index 2019* (Warsaw ranked 69, and Wrocław ranked 95) [93]. The listed entities can therefore be theoretically treated as exemplary, representing a set of good practices in various aspects of urban quality of life.

Table 1. Characteristics of the surveyed cities.

City	Inhabitants	Surface	Population Density
Białystok	296,000	102 km^2	2902 persons/km^2
Gorzów Wlk.	120,087	86 km^2	1400 persons/km^2
Gdańsk	471,000	263 km^2	1787 persons/km^2
Katowice	292,000	165 km^2	1756 persons/km^2
Kielce	192,500	110 km^2	1686 persons/km^2
Kraków	782,000	327 km^2	2450 persons/km^2
Lublin	338,000	147 km^2	2270 persons/km^2
Łódź	670,642	293 km^2	2287 persons/km^2
Olsztyn	170,622	83 km^2	1932 persons/km^2
Opole	127,839	149 km^2	858 persons/km^2
Poznań	532,000	262 km^2	2031 persons/km^2
Rzeszów	198,609	129 km^2	1539 persons/km^2
Szczecin	396,472	301 km^2	1319 persons/km^2
Toruń	197,812	116 km^2	1511 persons/km^2
Warsaw	517,000	517 km^2	3466 persons/km^2
Wrocław	643,000	293 km^2	2298 persons/km^2

At this point, it is worth adding that in the aforementioned ranking the environment is one of the key areas of assessment, but waste management is only one of the 101 assessed criteria. As part of the environmental conditions 11 elements are assessed, including the total amount of solid waste per capita. It should also be emphasized that the overall environmental assessment of Polish cities in this ranking is not the best, which additionally emphasizes the difficulty of shaping the quality of the environment.

4. Results

This section presents the results of the research conducted with data on the volume of waste generated and cost effectiveness. This was followed by an evaluation of waste management in the aspects mentioned above using multi-criteria analysis.

4.1. Quantitative and Efficiency Analysis of Municipal Waste Generation

In the first stage of the analysis, reference was made to the amount of municipal waste per capita. These values for the studied cities are listed in Table 2.

The data in Table 2 show that the volume of waste per capita, by geography, varied quite significantly. It ranged from 351.0 kg/inhabitant (Kielce in 2020) to 570.9 kg/inhabitant (Wrocław in 2021). Over time, the average value for all cities ranged from 404.0 in 2020 to 419.7 kg/inhabitant in 2021. The slightly lower values in 2020 were most likely due to the COVID-19 pandemic, which reduced consumption and thus the amount of garbage generated.

The lowest values of the studied parameter (below 400 kg/inhabitant) were recorded in such cities as Białystok, Kielce and Olsztyn. These are less urbanized cities, which may have a positive effect on the volume of waste generated. Nevertheless, it is worth adding that in the first two, which are dynamically developing regional centers, the rate of growth of waste per capita was very high, which may mean that these cities will lose their environmental advantage over the other units in the near future.

The average annual rate of change in the volume of municipal waste per capita for all the provincial cities studied was 1.10%, which means that the problem of garbage generation is steadily increasing. Only in 5 out of 16 surveyed units the volume of municipal waste was decreasing (Katowice, Olsztyn, Szczecin, Łódź and Rzeszów), which was also due to the depopulation of these cities and the rapid rate of aging in urban communities [41]. It was therefore not directly related to improvements in municipal waste management.

The volume of garbage per capita is steadily increasing in cities classified as smart. Nevertheless, in Wrocław, the average annual rate of change was significantly lower than in Warsaw, which ranked first in this regard. It should be added, however, that the amount of garbage per capita was the highest in Wrocław during the entire period under research. This means that the smart cities studied generate a significant and increasing volume of municipal waste over time.

Table 2. Volume and average rate of change of municipal waste generated in the studied cities from 2019 to 2021 [in kg/inhabitant].

Cities	Years			
	2019	2020	2021	Average Rate of Changes [%]
Białystok	344.8	365.8	367.8	3.29%
Gdańsk	423.3	350.0	434.9	1.36%
Gorzów Wlk.	379.4	407.4	381.0	0.21%
Katowice	440.6	472.8	436.7	−0.44%
Kielce	353.3	351.0	388.1	4.81%
Kraków	430.9	451.3	464.0	3.77%
Lublin	377.0	385.0	405.0	3.69%
Łódź	437.6	389.9	395.0	−4.99%
Olsztyn	392.5	370.9	362.9	−3.85%
Opole	418.9	430.6	449.3	3.56%
Poznań	400.1	392.1	416.6	2.04%
Rzeszów	450.2	422.8	421.2	−3.27%
Szczecin	419.1	392,4	414.9	−0.50%
Toruń	388.0	405.4	391.9	0.51%
Warsaw	374.9	394.4	414.9	5.20%
Wrocław	545.8	481.5	570.9	2.27%
Arithmetic mean	411.0	404.0	419.7	1.10%
Coefficient of variation	11.6%	9.7%	11.7%	281.0%

Cities recognized as SC in *Cities in Motion Index 2019*.

In the following analysis, the share of mixed waste in total waste generated by one resident was determined. The results for 2019–2021 are shown in Table 3, and the average for this period is shown in Figure 2.

Table 3. Share of mixed waste in total waste per capita from 2019-2021 [in %].

Cities	Years			
	2019	2020	2021	Trend
Białystok	53.37%	50.82%	53.70%	increase/decrease
Gdańsk	63.48%	46.49%	54.56%	increase/decrease
Gorzów Wlk.	75.36%	65.95%	63.52%	falling
Katowice	72.08%	66.67%	69.11%	increase/decrease
Kielce	73.57%	68.86%	65.42%	falling
Kraków	65.98%	54.75%	53.02%	falling
Lublin	60.45%	56.59%	55.33%	falling
Łódź	65.57%	62.55%	61.24%	falling
Olsztyn	76.13%	71.56%	68.61%	falling
Opole	62.25%	58.85%	55.13%	falling
Poznań	67.30%	64.45%	60.25%	falling
Rzeszów	69.75%	51.30%	51.80%	increase/decrease
Szczecin	74.76%	70.46%	67.82%	falling
Toruń	76.58%	69.88%	66.83%	falling
Warsaw	80.69%	64.98%	66.64%	increase/decrease
Wrocław	68.28%	61.81%	63.46%	increase/decrease
Arithmetic mean	69.10%	61.62%	61.03%	63.92%
Coefficient of variation	10.35%	12.53%	10.17%	10.28%

Cities recognized as SC in *Cities in Motion Index 2019*.

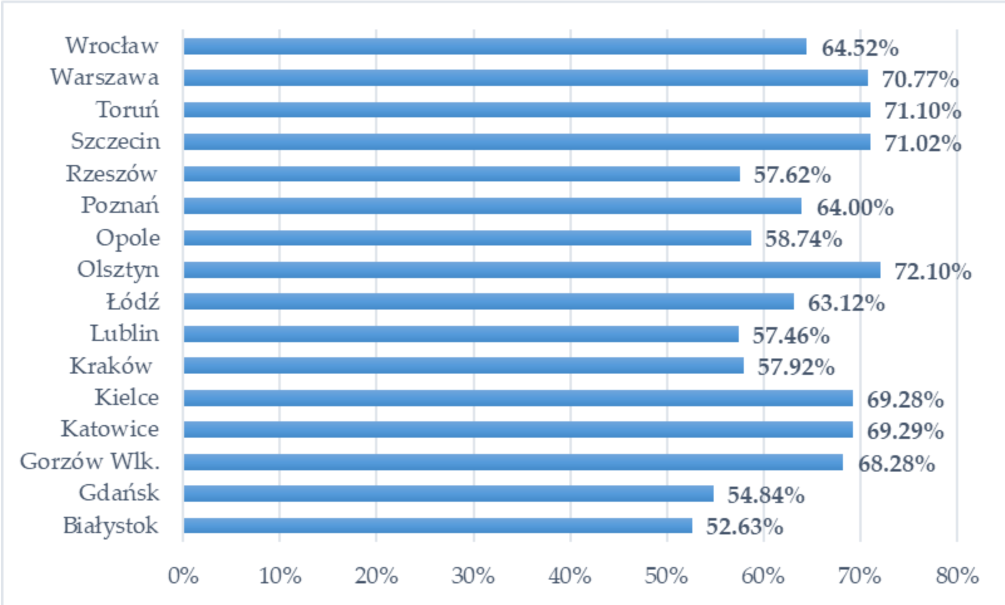

Figure 2. Share of mixed waste in total waste per capita from 2019–2021 [in %] in the analyzed cities.

According to the data presented in Table 2, most of the waste generated by residents was not segregated. The average share of mixed waste in total waste for the entire group of surveyed cities ranged from 69.10% in 2019 to 61.03%. Nevertheless, it should be noted that this average systematically decreased over time, which is a favorable indication of the overall trend in ecological waste management.

Białystok and Gdańsk fared best in terms of waste segregation. In these cities, the average share of the mixed waste fraction was the smallest and did not exceed 55%. The largest amounts of unsegregated waste were generated by Olsztyn, Szczecin and Toruń. However, it is worth mentioning that in the indicated cities, throughout the entire period under research, systematic progress in waste segregation was recorded, manifested by a decrease in the share of mixed waste in total waste. This trend eventually extended to 10 of the 16 cities under analysis. There was also no clear upward trend in the described aspect in any of the analyzed entities. This confirms the efforts to green municipal waste management.

Warsaw and Wrocław, considered SC, were characterized by an above-average share of non-segregated waste in total waste (above the average of 63.92%). Unfortunately, Warsaw turned out to be a city with a very high share of mixed waste in total waste. Their average share exceeded 70%, which gave the capital the infamous fourth place in terms of unsegregated municipal waste. Moreover, both Wrocław and Warsaw showed no clear trend toward reducing the harmful fraction of municipal waste. Of course, both cities are very large entities with significant population densities, which can complicate the process of waste segregation and recycling. Nevertheless, as smart cities they should exemplify good practices, or at least be below the analyzed average.

In the third stage of the analysis, reference was made to total cost efficiency of collected municipal waste services. The value of this efficiency in unit terms is included in Table 4.

A general analysis of the data in Table 4 indicates that the level of variation in cost efficiency was very high (coefficients of variation for individual years about 40%). Record values were recorded in Warsaw—a maximum of 1776.41 PLN/t in 2020. The lowest were in Łódź—a minimum of 241.90 PLN/t. This means that the companies collecting municipal waste used very different rates, and in addition, due to their monopolistic nature, they were characterized by high bargaining power towards the city authorities.

In almost all cities analyzed, the cost of municipal waste collection increased significantly. In Lublin, the increase was more than 200%. In other cities, the level of increases in waste disposal costs grew from 28.59% (Gdańsk) to 96.71% (Szczecin). Łódź was the only one to reduce the cost effectiveness of total municipal waste collection services. The changes are mainly due to price increases caused by the COVID-19 pandemic. It is difficult to link them to an increase in the scope of services offered, since the earlier analysis shows that the volume of segregated waste, although slow, increased in most cities. Thus, from the identified trends, it appears that municipal waste collection was a significant and increasing burden on the budgets of the surveyed cities over time, which was further exacerbated by the increasing amount of total waste per capita noted in as many as 11 of the 16 surveyed units.

Table 4. Total cost-effectiveness of collected municipal waste services in the studied cities from 2019–2021 [in PLN/ton].

Cities	Years			
	2019	2020	2021	Change Compared to 2019 [in %]
Białystok	515.71	499.16	672.21	30.35%
Gdańsk	590.36	920.94	759.17	28.59%
Gorzów Wlk.	503.99	629.50	715.48	41.96%
Katowice	410.16	489.90	599.68	46.21%
Kielce	454.65	662.43	615.10	35.29%
Kraków	494.79	637.09	717.15	44.94%
Lublin	539.62	973.26	1635.45	203.07%
Łódź	286.90	243.90	241.90	−15.68%
Olsztyn	635.28	690.86	887.17	39.65%
Opole	479.26	701.74	748.72	56.22%
Poznań	486.39	1233.99	835.72	71.82%
Rzeszów	488.64	748.29	718.22	46.98%
Szczecin	435.36	717.60	856.38	96.71%
Toruń	275.09	265.61	383.85	39.54%
Warsaw	1220.53	1776.41	1297.17	6.28%
Wrocław	563.73	659.20	595.29	5.60%
Arithmetic mean	523.78	740.62	767.42	48.60%
Coefficient of variation	39.85%	49.76%	42.32%	100.37%

Cities recognized as SC in *Cities in Motion Index 2019*.

Comparing Wrocław and Warsaw in terms of cost efficiency, it can be said that these units were characterized by the lowest level of growth in this parameter (5.60% and 6.28%, respectively) in relation to 2019. However, in Warsaw, the level of efficiency was the highest in the entire analyzed period, while in Wrocław, except for 2019, it was below the average calculated for all the analyzed cities. This indicates a different range of possibilities and efforts in shaping the cost of municipal waste collection. Moreover, it makes Wrocław perform better than Warsaw in terms of efficiency.

Quite surprisingly, the analysis conducted above is also confronted with the conclusions drawn from nationwide studies, which indicate that cost efficiency is influenced by [94]:

- The degree of concentration of development (the more dispersed it is, the higher the cost);
- The structure of occupied properties (costs higher for single-family than multi-family developments).

In the cities under study, both of the above-mentioned determinants should have a favorable effect on the level of waste management costs; meanwhile, it is higher than the national average throughout the analyzed period, and in cities such as Poznań, Warsaw and Lublin it is record high.

Perhaps this was more intensely influenced by other factors identified in government analyses, such as:

- The structure of occupied properties (the costs are higher for single-family than multi-family developments);

- The structure of the inhabited property (the younger the population the more waste it generates);
- The cost of selective collection and collection of municipal waste (the more fractions of selectively collected waste, the higher the cost of waste management and disposal).

Nevertheless, the observed trend against the backdrop of the indicated and reasonable conclusions suggests some inadequacies in municipal management in cities with particularly high waste collection costs. These require deeper deterministic and comparative analyses.

4.2. Results of the Application of Multi-Criteria Analysis in the Evaluation of the Efficiency of the Municipal Management of the Analyzed Cities

The results of the research conducted above are summarized in the form of a multi-criteria analysis. The values of the variables adopted to conduct it are shown in Table 5, and its final results are shown in Table 6.

Table 5. Values of variables used in multi-criteria analysis of analyzed cities.

Cities	Variables				
	Waste Volume per Capita in 2021 in kg (Destimulant)	Average Annual Rate of Change in Waste Volume per Capita in % (Destimulant)	Average Share of Mixed Waste in Total Waste in % (Destimulant)	Cost Effectiveness in 2021 in PLN/t (Destimulant)	Change in Cost Efficiency Compared to 2019 in % (Destimulant)
Białystok	367.80	3.29%	52.63%	672.21	30.35%
Gdańsk	434.90	1.36%	54.84%	759.17	28.59%
Gorzów Wlk.	381.00	0.21%	68.28%	715.48	41.96%
Katowice	436.70	−0.44%	69.29%	599.68	46.21%
Kielce	388.10	4.81%	69.28%	615.10	35.29%
Kraków	464.00	3.77%	57.92%	717.15	44.94%
Lublin	405.00	3.69%	57.46%	1635.45	203.07%
Łódź	395.00	−4.99%	63.12%	241.90	−15.68%
Olsztyn	362.90	−3.85%	72.10%	887.17	39.65%
Opole	449.30	3.56%	58.74%	748.72	56.22%
Poznań	416.60	2.04%	64.00%	835.72	71.82%
Rzeszów	421.20	−3.27%	57.62%	718.22	46.98%
Szczecin	414.90	−0.50%	71.02%	856.38	96.71%
Toruń	391.90	0.51%	71.10%	383.85	39.54%
Warsaw	414.90	5.20%	70.77%	1297.17	6.28%
Wrocław	570.90	2.27%	64.52%	595.29	5.60%
maximum	570.90	5.20%	72.10%	1635.45	203.07%
Minimum	362.90	−4.99%	52.63%	241.90	−15.68%
Range	208.00	10.19%	19.47%	1393.55	218.76%

Cities recognized as SC in *Cities in Motion Index 2019*.

According to the results in Table 6, the lowest amount of total waste per capita was in Olsztyn, while the highest was recorded in Wrocław. The lowest rate of change in this parameter was found in Łódź (decrease) and the highest in Warsaw. As for the share of mixed waste in total waste, Olsztyn was the best and Białystok the worst. The highest cost efficiency distinguished Łódź and the lowest Lublin. The cost of waste disposal also grew slowest in Łódź, while it grew fastest in Lublin. In the context of these extreme assessments, it is worth noting Łódź, where the value of waste per capita was falling, and where cost efficiency was the best.

A summary evaluation of the multi-criteria analysis ranking the surveyed cities in terms of all parameters is presented in Figure 3. In the list presented there, the first place is held by the aforementioned Łódź. A score above 0.6 is also given to Rzeszów and Białystok. The aforementioned cities are distinguished by a relatively low level of waste per capita and good and slowly increasing cost efficiency of waste collection.

Table 6. The results of multi-criteria analysis for the analyzed cities.

Cities	Variables				
	Waste Volume per Capita in 2021 in kg (Destimulant)	Average Annual Rate of Change in Waste Volume per Capita in % (Destimulant)	Average Share of Mixed Waste in Total Waste in % (Destimulant)	Cost Effectiveness in 2021 in PLN/t (Destimulant)	Change in Cost Efficiency Compared to 2019 in % (Destimulant)
Białystok	0.9764	0.1874	1.0000	0.6912	0.7896
Gdańsk	0.6538	0.3768	0.8863	0.6288	0.7976
Gorzów Wlk.	0.9130	0.4897	0.1963	0.6602	0.7365
Katowice	0.6452	0.5535	0.1445	0.7433	0.7171
Kielce	0.8788	0.0383	0.1446	0.7322	0.7670
Kraków	0.5139	0.1403	0.7283	0.6590	0.7229
Lublin	0.7976	0.1482	0.7521	0.0000	0.0000
Łódź	0.8457	1.0000	0.4611	1.0000	1.0000
Olsztyn	1.0000	0.8881	0.0000	0.5370	0.7471
Opole	0.5846	0.1609	0.6859	0.6363	0.6713
Poznań	0.7418	0.3101	0.4159	0.5739	0.6000
Rzeszów	0.7197	0.8312	0.7437	0.6582	0.7135
Szczecin	0.7500	0.5594	0.0556	0.5591	0.4862
Toruń	0.8606	0.4603	0.0515	0.8981	0.7476
Warsaw	0.7500	0.0000	0.0681	0.2427	0.8996
Wrocław	0.0000	0.2875	0.3894	0.7464	0.9027

Cities recognized as SC in *Cities in Motion Index 2019*.

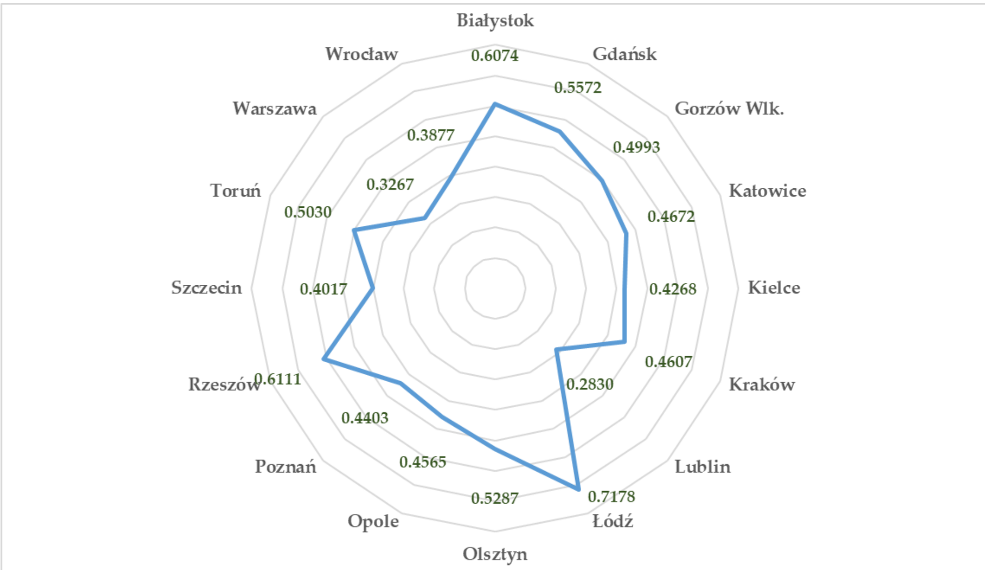

Figure 3. Aggregate results of multi-criteria analysis for the analyzed cities.

The worst rating is given to Lublin, Warsaw and Wrocław (below 0.4). Lublin has the lowest and fastest-growing cost efficiency of waste collection, as well as a rapid rate of increase in waste per capita. Warsaw receives the lowest marks for cost efficiency (both for its level and growth rate) and a high average share of mixed waste in total waste. Wrocław, on the other hand, has the highest volume of waste per capita and its rapid growth rate, as well as a high share of mixed waste in total waste.

It is clear from the above analysis that cities recognized as smart in the *Cities in Motion Index 2019* perform very poorly in terms of the basic parameters characterizing urban waste management. They should work hard on reducing the volume of waste per capita, increasing the fraction of segregated waste in total waste, and rationalizing the cost of municipal waste collection. This is because, compared to the other surveyed units, they can hardly be considered intelligent and focused on pro-environmental municipal management.

5. Discussion

The results obtained quite clearly suggest that the increasing urbanization and attractiveness of cities considered smart means an increase in the amount of municipal waste and some difficulties with its segregation and, consequently, recycling. Indeed, in the final efficiency ranking, the two Polish cities on the prestigious *Cities in Motion Index 2019* list fare worst.

The above observations confirm the objections of opponents of the development of Smart City [32–49] concepts regarding their negative impact on the environment [8–10], which in this case is related not only to the accumulation of waste, but also to the need to increase the scale of its storage or processing, which entails further environmental consequences (CO_2; soil and water pollution). In the development of the Smart City concept, environmental aspects are given a lot of attention. They are also present in the evaluation in smart city rankings. Nevertheless, due to their significant impact on the quality of life and the sustainability of smart cities, they should be given more importance.

It is also worth noting that the problem of municipal waste growth is marginalized in the literature. Contemporary researchers focus primarily on the technological aspects of waste management, including, in particular, the issue of waste disposal [72–86], as if the problem of systematic waste growth were not important. Of course, this has the intended primary effect of effective waste removal and may create the impression of an improved quality of life due to an immediate improvement in the cleanliness of the city [87,88]. Nevertheless, in the long term such an approach may result in an ecological catastrophe in areas that are admittedly outside the city, but are not unaffected (degradation of forests, green areas or surface and groundwater pollution).

Therefore, the following measures are recommended:

- Monitoring of municipal waste levels over time and space;
- Focusing attention on practice and theory, not only on the problem of waste collection in smart cities but also on aspects of preventing waste growth and related to segregation and recycling [87];
- Raising awareness among residents and conducting environmental education aimed at halting the growth of municipal waste, to say the least [90,91].

It should also be emphasized that given the conclusions obtained and the literature review conducted, it should be concluded that the humanistic, social and ecological strands of smart city considerations and research are still underexposed, and despite declarations about the humanization of smart city solutions, they still remain highly technicized. Topics that are less convenient—precisely such as the problem of growing municipal waste—are not only described less frequently, but also treated as non-existent. For these reasons, this article is an important voice in the discussion on the greening and humanization of smart cities.

In addition, the results document a systematic increase in the cost of municipal waste collection and management in most of the cities studied. The continuous increase in costs with the increasing amount of waste per capita generates a growing burden on municipal budgets, which, especially now in the post-pandemic period, are extremely modest, especially in emerging and developing economies.

Hence, in the future, we should expect either a deterioration in the care of waste management in order to minimize costs, or an increase in garbage collection fees (passing the costs on to residents) [89]. Neither of these circumstances is associated with an improvement in the quality of urban life. In the financial context, the following are therefore recommended:

- Conducting benchmarking on the cost-effectiveness of waste management (studies show that some cities are able to achieve very low levels of waste management fees) aimed at reducing costs;

- Educating residents about sustainable consumption and greening their purchases, as well as reducing food waste;
- Using a holistic (rather than piecemeal) approach to the waste management process that takes into account both residents as a trash generator and the recyclability of the waste generated;
- Considering monetary penalties for non-ecological behavior and habits.

6. Conclusions

Based on the results of the analysis, the following diagnostic conclusions can be made regarding the efficiency of waste management in the surveyed cities aspiring to be smart or being smart:

- The amount of waste per capita is increasing in most (11 out of 16) of the surveyed cities, with per capita levels in smart cities being high and growing rapidly over time;
- The average share of mixed waste in total waste is 63.92%, but most (10 out of 16) of the surveyed cities are systematically reducing it; in Warsaw and Wrocław (smart cities according to the *Cities in Motion Index 2020*) the indicated share is above average and shows no clear downward trend;
- The cost-effectiveness of total collected municipal waste services varies widely and increases significantly over time (the average increase in 2021 compared to 2019 was more than 48%), which illustrates both the increase in input prices and the monopolistic power of municipal waste collection companies;
- In a holistic assessment of waste management effectiveness, the best performing cities were less urbanized and industrialized, i.e., Łódź, Rzeszów and Białystok, and the worst were Lublin and Warsaw and Wrocław, cities recognized as smart in the *Cities in Motion Index 2019*, suggesting that they have problems at the basic level of municipal waste management.

In the context of the above statements, more attention should be paid to the effectiveness of waste management in cities. The smartness of cities in this respect should not be limited only to technological issues. It should also include an assessment of the impact of waste management on the environment and economic efficiency. The latter factor is important for decision-makers, city authorities, and therefore is and will be an important determinant of decisions regarding waste management.

In the context of the results obtained, the need for a more comprehensive assessment of smart cities should be emphasized. This is because it turns out that like Warsaw or Wrocław, these cities can generate an above-average amount of waste per capita and have problems with waste segregation and the efficiency of municipal services, despite modern and advanced, but fragmented technological solutions. This destroys the image of smart cities and may provide arguments for opponents of their creation.

The scientific originality of undertaken research results from the following circumstances:

- Filling the research gap in the area of holistic and dynamic assessment of the effectiveness of waste management in smart and aspiring cities;
- Supplementing previous research with an analysis of the cost-effectiveness of urban waste management;
- Locating the research in the socio-ecological area of the SC concept—less frequently exposed in the literature;
- Analysis of the determinants of waste management in developing economies.

The practical contribution of research to the development of the Smart City concept, in turn, comes from:

- Verifying the thesis of green and effective waste management in smart cities;
- Providing knowledge about the process of waste collection in cities and the scale of waste segregation;
- Conducting a comparative analysis of 16 Polish cities in waste management providing a basis for benchmarking in this regard;

- Formulating recommendations for improving waste management in cities.

The main limitation of the presented research is the narrowing of the analysis area to Polish cities. Nonetheless, the results obtained allow us to look at the results of municipal waste management from the perspective of the entire emerging economy, since the research conducted is on the 16 largest Polish cities representing each province. This allows future studies to compare the Polish economy to other emerging and developing economies, and provides a basis for international comparisons. Further studies can also be conducted to assess the impact of smart technological solutions on the effectiveness of waste management. An important research topic is the assessment and modification of the environmental awareness of urban residents, including, in particular, that of waste reduction and the need for waste segregation.

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