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City of Waste—Importance of Scale

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Abstract: By 2050, the world population is expected to reach 9.7 billion, almost 90% of which will live in urban areas. With such a fast growth in population and urbanization, it is anticipated that the annual waste generation will increase by 70% in comparison with current levels, and will reach 3.40 billion tons in 2050. A key question regarding the sustainability of the planet is the effect of city size on waste production. Are larger cities more efficient at generating waste than smaller cities? Do larger cities show economies of scale over waste? This article examines the allometric relationship between the amount of municipal waste (total and per capita) and the populations, city area, density, and wealth of city residents. The scope of the research concerned 930 Polish cities. Using the allometric equation, the waste scaling factors were calculated for selected parameters, and the Hellwig method was used to optimize their selection for cities with more than 50,000 inhabitants. The calculations show that the parameter population (1.059) and then the city area (0.934) are important elements influencing the scaling of the amount of municipal waste in cities of all sizes, but none came close to the value of the animal metabolism model (0.75). In response to the question of whether larger cities show benefits from economies of scale, it should be stated that, for the model of city size in Poland, such a regularity does not exist.

Keywords: municipal waste; city; scaling; population; population density; city area; GDP

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1. Introduction

Urbanization is the hallmark of the 21st century, which is characterized by tremendous demographic changes and a rapid development of urban areas and the built environment on a large scale. Most of the future population growth in the remaining part of this century will occur in urban areas. The increase in global waste production due to population growth and wealth will have a significant impact on the sustainable development of cities.

The world produces 2.01 billion tons of municipal solid waste each year, with at least 33 percent not being managed in a safe way for the environment. All over the world, the amount of waste generated per person per day averages 0.74 kg but varies widely from 0.11 to 4.54 kg. Although they constitute only 16 percent of the world's population, high-income countries (high-income countries—78 countries with GDP above 12,000 $/year) generate about 34 percent, or 683 million tons, of the world's waste [1,2].

Considering the fact that urban populations will have increased by 2–3 billion by the end of the 21st century, understanding the way in which the size of cities affects the municipal waste volume can provide us with an insight into how city size can be part of a larger regional or national strategy for waste reduction [3]

1.1. The Importance of Scale for the Production of Municipal Waste

Galileo developed the idea of allometric growth in his treatise 'Discorsi e demonstrazioni matematiche, intorno a due nuove scienze', which was published during his house arrest in 1638 [4]. He noticed that the bones of larger animals grew thicker at a faster rate than they grew in length compared to the same bones in smaller animals. Thus, the height-to-circumference ratio decreases along with the animals' growth.

Therefore, what is 'scaling'? In its most elementary form, it simply refers to the reaction of the system when its sizes change [5].

Scaling characterizes the way a given system quantity, y, depends on the size of the system. The scaling law is shown in the form of the following exponentiation relation:

$$y = ax^b \tag{1}$$

where x is the linear size of the system and y is its measure, whereas a is the proportionality coefficient, and b is the exponent specifying the exponentiation law.

The scaling laws apply to both natural phenomena and those resulting from human activity [5].

In particular, the scaling laws refer to models of spatial organization of cities and their growth—a well-known example of a scaling relation is 'Zipf's Law', which states that a city's population decreases inversely with its rank among other cities in the same city system [6] (Zipf's Law or Estoup–Zipf's Law—the law that describes a frequency principle of using individual words in any language. Zipf's law was mathematically expressed in Zipf's equation: r × f = constans, where: r is the rank of a word in a text or a group of texts, and f is its frequency of occurrence. [6]).

Cities offer benefits resulting from the economy of scale. Concentrations of people, large-scale infrastructure, and economic activities enable innovation and efficiency. Recent studies have shown that cities may exhibit different types of scaling in different urban phenomena or properties [7]. Nonlinear scaling (when exponents take a value less than 1) resembles the parallel allometric scaling laws observed in living organisms, and represents the benefits of the scale resulting from the increase in efficiency by sharing infrastructure; it is exposed, inter alia, in electric networks (by the length of electric cables) and road systems (length of roads or amount of road surfaces). Superlinear scaling (when the exponent b is greater than 1) seems to be unique to social systems, and is connected to the concept of network effects which lead to human ingenuity and creativity. Superlinear scaling has been identified in the number of new patents, inventors, research and development, employment, total salaries, etc. Linear scaling (when the exponent b is approximately equal to 1) means a proportional increase in urban phenomena/measures along with the size [8].

The size of a city's population, as well as its spatial organization and structure, can influence the amount of waste. Data from cities around the world suggest that climate, technology, density, and wealth are important determinants of waste generation.

The subject of the research is to establish allometric dependencies between the size of a city and the production of municipal waste in 930 Polish cities. The results show that this dependency varies across cities of different size, area, population density, and per capita income. In analogy to Kleiber's law [9] (Kleiber's Law, named after Max Kleiber because of his biology in the early 1930s, is based on the observation that, in most animals, the metabolic rate increases to $\frac{3}{4}$ of the strength of the animal's weight [9]), the amount of municipal waste, along with the increase in the city's population, should decrease due to the benefits resulting from the use of the understood service and network infrastructure of cities, which, in many cases, obeys the law of allometric growth. Are larger cities more economical in terms of waste production than smaller cities? Moreover, it is important to determine the importance of the city's basic spatial and economic indicators, i.e., area, population density, or GDP per capita for municipal waste produced. The knowledge of these relations can be fundamental to the optimization of the size of waste collection and processing facilities in cities.

1.2. Universal Quantifiable Features of Cities

Parysek [10] claims that, since the formulation by Ludwig von Bertalanffy [11] of the general theory of systems, it has been increasingly used in determining the subject of research in various fields of knowledge. The systemic approach to the subject comes from biology, where systems are living organisms. He further states that, by analyzing the spatial and functional structure of the city, we can conclude that the organism is an adequate model for the city system.

In a city, as in any living organism, there is a conversion of matter and energy. It is a specific form of metabolism, consisting not only of the consumption of various forms of energy of materials, but also of capital flow, knowledge, skills, information, etc. This form of metabolism can be identified with urban metabolism and, similarly to living organisms, can be studied using the scaling law [12]. Organisms, as metabolic engines, are characterized by indicators of energy consumption, growth rate, body size, and lifetimes, and therefore have a clear reference to urban systems [13,14]. Bettencourt states that cities manifest remarkably universal, quantifiable features. As to be expected, "size is the major determinant of most characteristics of a city; history, geography and design have secondary roles" [8,15,16].

The basic discoveries of allometric relationships describe the relationship between the total area of a city and its number of inhabitants [17–19] and the relationship between the city's area and the total length of its borders (fractal nature) [20,21]. Other relations concern the relationship between the city's surface and the total surface of its roads [22].

Kennedy [23] and others have quantified the energy and material flows across 27 megacities worldwide with a population of over 10 million people since 2010. It was confirmed that the flows of resources and waste generation across megacities largely follow the laws of scaling.

Few studies have investigated the scaling performance of solid waste disposal through statistical analysis with empirical data. Pan, Yu, and Yang [24] tested a sample of 651 cities in China using a correlation analysis and grouping model that determined the characteristics and overall trends of solid waste generation in five city groups of varying scales between 2007 and 2016.

Kleiber's law of allometry says that the metabolic rate is based on body weight with an exponent of 0.75. It should be assumed that the elimination of waste from the body is a system proportional to the metabolic process, that is: the more metabolic waste is produced, the more metabolic waste must be excreted [25]. Similarly, in an urban "organism", the amount of waste generated should be scaled to the number of inhabitants (or other city parameters) with an exponent of 0.75.

1.3. Municipal Waste Problem

Waste collected by or on behalf of municipalities includes household waste originating from households (i.e., waste generated by the domestic activity of households) and similar waste from small commercial activities, office buildings, institutions such as schools and government buildings, and small businesses that treat or dispose of waste at the same facilities used for municipally collected waste [26]

The amount of generated municipal waste depends on many factors, of which the most important are life standard, population rate, and goods consumption scale and intensity.

Municipal solid waste is remarkably diverse in terms of physical and chemical composition. It mainly depends on the equipment of buildings with technical and sanitary devices (mainly the heating method), the type of buildings, and the living standards of the inhabitants. Most often, municipal waste contains approx. 40–50% of organic substances, approx. 50–60% are mineral parts. Waste composition in the OECD region (The Organization for Economic Co-operation and Development (OECD) is an international organization that works to build better policies for better lives. It counts 37 member countries that span the globe, from North and South America to Europe and the Asia-Pacific.) is slightly different due to high income, and for organic waste it is below 30% [27].

The components contained in municipal waste, mainly organic, undergo biochemical changes, and affect the environment through decomposition products: carbon dioxide, ammonia, hydrogen sulfide, methane, nitrates, nitrites, sulphates, and others.

Municipal waste he poses a threat to the environment due to the possibility of the contamination of air, groundwater, and surface water with pathogenic microorganisms, for which it is a medium [28]. Solid muncipal waste varies greatly in terms of physical and chemical composition.

Based on the volume of waste generated, its composition, and how it is managed, it is estimated that 1.6 billion tons of carbon dioxide (CO_2) equivalent greenhouse gas emissions were generated from solid waste treatment and disposal in 2016, driven primarily by open dumping and disposal in landfills without a landfill gas capture system. This is about 5 percent of global emissions. Solid waste-related emissions are anticipated to increase to 2.6 billion tons of CO_2 equivalent per year by 2050 if no improvements are made in the sector [2].

In the European Union (EU), the amount of municipal waste generated per person in 2018 amounted to 492 kg, 5% less compared with its peak of 518 kg per person in 2008. In total, 220 million tons of municipal waste were generated in the EU in 2018, and this was slightly higher than in 2017 (218 million tons). With 766 kg, Denmark generated the most municipal waste per person among the EU Member States in 2018. At the other end of the scale, Romania generated 272 kg of municipal waste per person in 2018 and Poland generated 329 kg per person [29]. There was a perceptible change in trends in municipal waste management in the EU-28, with an apparent shift from disposal methods to prevention and recycling. Less waste is being landfilled because of reductions in the generation of some wastes and increases in recycling and energy recovery. Municipal waste landfilled decreased by almost 43% [30], but still corresponded to about 3% of total EU greenhouse gas emissions [31].

The correlation analysis of the population in the individual EU countries and the total volume of municipal waste and volume of waste per capita and GDP per capita in 2018 indicates that, in the first case, the Pearson coefficient (Rp) is 0.98, and 0.60 in the second (28 countries with the UK). The coefficients of determination (Rp^2) are 0.97 and 0.52, respectively, which proves that the correlation model in the first case is very good and works 97%, and in the second case it is worse and works 52%.

In the case of Poland, a detailed analysis of the relationship of GDP per capita to the volume of waste per capita indicates that Poland produces much less municipal waste in comparison with other EU countries with a similar GDP per capita.

The question about the reasons for such a phenomenon, in view of the insufficiently developed waste management infrastructure in Poland, remains unanswered and requires further research.

In 2018, the European Commission (CE) presented the amended content of the Waste Framework Directive, setting new targets for increasing the reuse and recycling of municipal waste to a minimum of 65% by 2035. [32].

In the face of the growing amount of municipal waste generated in European countries in recent years, it has become especially important to search for sustainable methods of municipal waste management. CE activities in waste management are recommended based on the ReSOLVE framework (regeneration, sharing, optimization, loop, virtualization, and replacement) [33] (The ReSOLVE framework was developed by the Ellen MacArthur Foundation and McKinsey, which are important bodies in the development of tools supporting the transformation process towards a circular economy in the EU. The circular economy has been described as a concept that mimics living systems. A helpful reframing, consistent with a circular economy approach, is to think of cities as living systems that rely on a healthy circulation of resources [33]).

It should be noted that in the European Union legislation on new urban waste management programs, there is no direct reference to urban planning issues, for example, regarding elements of city infrastructure, city area, or population density.

2. Materials and Methods

2.1. Database

The analyses used data on the volume of municipal waste, population, area, population density, and GDP of inhabitants from 930 cities and municipalities at the city level in Poland from 2018, ordered from the Central Statistical Office (Data from the Central

Statistical Office on 03/09/2019: GUS-DK02.601.1481.2019—municipal waste [34].) and obtained from the 2018 statistical yearbook of the Republic of Poland [34]. A city in Poland is defined as a settlement unit with a predominance of compact development and nonagricultural functions, having town privileges or the status of a city granted in accordance with the regulations [35] (the act of 29 August 2003 on the official names of settlements and physiographic objects (Journal of Laws of 2019, item 1443). Pursuant to the Act on Municipal Self-Government of 1990, the Council of Ministers decides by means of an ordinance on granting or abolishing the status of a city [35]). According to the act, for a settlement to receive town privileges, over 2000 people must be registered in it, it must have urban buildings (not farm buildings), and at least 2/3 of the inhabitants cannot be employed in agriculture. Not all cities in Poland meet this definition. Among 930 cities having over 2000 inhabitants, there are 863 cities, and below 2000, there are 67 cities. Both the total number of cities and, according to the definition, cities with more than 2000 inhabitants were examined. Among the 863 cities with over 2000 inhabitants, 4 groups of cities with the following number of inhabitants were specified (Table 1):

- small cities: from 2000 to 20,000 inhabitants—645 cities
- medium cities: from 20,000 to 50,000 inhabitants—134 cities
- big cities: from 50,000 to 100,000 inhabitants—46 cities
- large cities: over 100,000 inhabitants—38 cities

Table 1. The amount of waste and the number of inhabitants for the groups of cities in percentages.

Size of the City by Number of Inhabitants	Number of Cities	Amount of Waste T	% Share of Municipal Waste in a Group of Cities	Population for Categories of Cities	% Share of the Number of Inhabitants in a Group of Cities	Average Amount of Waste for Cities kg/inhab.
Large >100,000	38	4,356,281	49.33%	10,705,482	46.40%	389.0
Big from 50,000 to 100,000	46	1,120,595	12.69%	3,116,448	13.51%	357.0
Medium from 20,000 to 50,000	134	1,594,406	18.05%	4,246,564	18.41%	374.0
Small from 2000 to 20,000	645	1,723,621	19.52%	4,894,832	21.21%	342.0
Very small <2000	67	36,093	0.41%	108,648	0.47%	335.0
∑ values	930	8,830,996	100%	23,071,974	100%	349.0

In the research of the impact of GDP on the production of municipal waste, due to the scope of available data from the Central Statistical Office, the analysis was limited to the cities with more than 50,000 inhabitants.

In 38 large cities with over 100,000 inhabitants, the total amount of municipal waste accounted for about 50 percent of the waste from all cities in the research period (2018), and for 84 cities with over 50,000 inhabitants, it accounted for over 62 percent. This indicates that most of the municipal solid waste in Poland is produced by large- and medium-sized cities.

Total municipal waste is generated in large cities, although not directly proportional to the number of inhabitants—there is about 6% more of it than expected in relation to the number of inhabitants. In the remaining groups of cities, it is quite the opposite, namely, these differences are insignificant in favor of less waste by percentage in relation to the percentage of inhabitants. The data analysis shows a significant deviation in the average volume of waste per capita in the group of cities with 50,000 to 100,000 inhabitants.

2.2. Method

The subject of the analyses focused on the interrelationships between the amount of waste and the number of inhabitants, population density, city area, and GDP per capita. The exponentiation equation in the form of $y = ax^b$ (1) was applied. For exponentiation regression curves, a transformation to a linear model was performed, the exponentiation regression curve is computed according to equation $y = ax\ \hat{}\ b$, which is converted to

$ln(y) = ln(a) + bln(x)$. For each case, the coefficient of determination, otherwise known as the coefficient of specificity, or R-squared, was calculated, which is a measure of what percentage of the variability of the dependent variable is explained by the independent variable.

In the analyzed problem of the urban scaling of waste, a cross-sectional analysis was used: "it produces exponents and residuals with greater temporal stability and the quality of fitting for scale-invariant relations is consistently better" [36].

Hellwig's method was chosen (for a set of cities >50,000) to determine a subset of predictors that are independent of each other, but strongly correlated with the dependent variable (section Discussion) [37,38].

All calculations were performed using Excel 2019.

3. Results of the Analysis

The results are presented in Table 2. The results were divided into groups depending on the size of the cities, but the first group applies to all cities. The exception here is the dependency between the number of inhabitants and GDP/capita due to the limited availability of data—this dependency applies only to cities with over 50,000 inhabitants.

Table 2. Waste scaling calculation results (by the author).

No.	Description of Dependencies	Exponent of Scaling b	Exponentiation Equation $y = ax^b$	Coefficient of Determination R^2
		All Cities (930 Cities)		
1.	Number of inhabitants/total waste	1.057	$y = 0.1978x^{1.057}$	0.935
2.	Number of inhabitants/waste per capita	0.061	$y = 191.18x^{0.061}$	0.051
3.	City area/total waste	0.934	$y = 3.5089x^{0.934}$	0.454
4.	City area/waste per capita	0.049	$y = 233.029x^{0.049}$	0.021
5.	Population density/total waste	0.924	$y = 7.5866x^{0.924}$	0.368
6.	Population density/waste per capita	0.058	$y = 227.19x^{0.058}$	0.025
		Cities >50,000 Inhabitants (84 Cities)		
7.	GDP per capita */total waste	1.527	$y = 0.0033x^{1.527}$	0.383
8.	GDP per capita */waste per capita	0.164	$y = 63.715x^{0.164}$	0.124
		Cities Over 2000 Inhabitants (863 Cities)		
9.	Number of inhabitants/total waste	1.055	$y = 0.2022x^{1.055}$	0.987
10.	City area/total waste	0.929	$y = 3.9643x^{0.929}$	0.475
11.	Population density/total waste	0.905	$y = 9.2308x^{0.905}$	0.341
		Cities From 2000 To 20,000 Inhabitants (645 Cities)		
12.	Number of inhabitants/total waste	1.069	$y = 0.1785x^{1.069}$	0.822
13.	City area/total waste	0.375	$y = 145.12x^{0.375}$	0.126
14.	Population density/total waste	0.464	$y = 119.53x^{0.464}$	0.192
		Cities From 20,000 To 50,000 Inhabitants (134 Cities)		
15.	Number of inhabitants/total waste	1.197	$y = 0.0469x^{1.197}$	0.475
16.	City area/total waste	0.209	$y = 2161.8x^{0.209}$	0.068
17.	Population density/total waste	0.057	$y = 7319.9x^{0.057}$	0.004
		Cities From 50,000 To 100,000 Inhabitants (46 Cities)		
18.	Number of inhabitants/total waste	1.227	$y = 0.0285x^{1.227}$	0.683
19.	Number of inhabitants/waste per capita	0.227	$y = 28.392x^{0.227}$	0.069
20.	City area/total waste	0.198	$y = 4484.4x^{0.198}$	0.195
21.	Population density/total waste	−0.107	$y = 51.759x^{-0.107}$	0.046
22.	GDP per capita/total waste	0.211	$y = 2.5174x^{0.211}$	0.054
		Cities >100,000 Inhabitants (38 Cities)		
22.	Number of inhabitants/total waste	1.059	$y = 0.1867x^{1.059}$	0.959
23.	Number of inhabitants/waste per capita	0.061	$y = 181.6x^{0.061}$	0.073
24.	City area/total waste	1.079	$y = 2.9992x^{1.079}$	0.707
25.	Population density/total waste	0.842	$y = 161.08x^{0.842}$	0.211
26.	GDP per capita/total waste	1.424	$y = 0.015.7x^{1.424}$	0.445

Source: the author. * GDP per capita data apply to cities > 50,000 inhabitants (no data for other cities).

3.1. Characteristics of the Dependency between the Size of Waste and the City Population

The dependency between the amount of municipal waste and the constant population for all cities is on the superlinear level, with a scaling factor of 1.06 and a determination factor of 0.935 (Table 2). This means that an increase in the number of inhabitants by one unit causes an increase in the amount of waste by an exponent of 1.06 in relation to the previous value, i.e., that the increase in waste in cities is faster than the increase in its population. Analyzing the dependence in the four groups of cities, it can be concluded that the scaling factor increases for cities with 50,000 to 100,000 inhabitants, where it is 1.23, then decreases to a level of 1.06 for cities with over 100,000 inhabitants. The lack of more cities with sizes exceeding 1 million inhabitants makes it impossible to study the problem of the further impact of increasing population on the amount of waste in Poland.

However, the scaling factor is different for waste per capita—the scaling factor is 0.06, with an exceptionally low level of determination of 0.051. This shows that there is no correlation between these values, while the adopted model is not sufficiently useful for determining dependencies. In this case, the values are spread on both sides of an almost horizontal trend line, which means that an increase in the city's population does not result in an increase in the amount of waste per capita. This means that the amount of waste per capita fluctuates around an average value, independent of the city's population size. The indicators in particular groups of cities are similar, where the highest scaling factor is for the group of cities with 50,000 to 100,000 inhabitants, and amounts to 0.23, with low determination amounting to 0.2 (Table 2).

3.2. Characteristics of the Relation between the City Area and the Size of Waste

Empirical analyses of the scaling relations for many urban systems suggest that there are quantitatively coherent agglomeration effects in different sizes of cities in many urban systems. Bettencourt and Lobo [19] carried out research on the properties of systems of European cities in terms of agglomeration and scaling effects for the systems, which showed, in most cases, a distribution in accordance with Zipf's law. For example, the analysis of the dependency between the number of inhabitants and the area of an urbanized area of cities shows that, for a city system, the European average scaling exponent is subline and amounts to 0.93. The developed city systems in Germany, France, Italy, Great Britain, and Spain were researched [19].

In the case of the dependency between the area of cities and the amount of municipal waste analyzed, here, we obtain the result of sublinear scaling with an exponentiation exponent of 0.93, with a determination coefficient of 0.45 (Table 2). This indicates a limited impact of city area increase on waste growth, at least lower than the previously presented result of the allometric dependency of the population and waste volume (which is 1.1). A more detailed analysis of this problem for various groups of city sizes proves the differentiation of scaling in a very wide range, from 0.2 in the group of cities from 50,000 to 100,000 inhabitants up to 1.1 for cities with over 100,000 inhabitants. In the first case, it means that there is a significant mismatch of the dependency between the city area and the amount of waste [15] (Systems reach final equilibrium when the allometric scaling exponent is close to 1. Otherwise, the system loses balance [15]).

The analysis of the allometric correlation of the city area and the amount of waste per capita (Table 2) leads to the conclusion that such a correlation is very weak (the scaling exponent is 0.05), with practically almost zero determination value (0.02). This correlation is even lower than the previously discussed correlation between the population and waste per capita, which indicates that there is no impact of urbanized area increase on the amount of waste per capita.

3.3. Characteristics of the Dependency between the City's Population Density and the Amount of Waste

Table 2 shows that the dependency between the amount of waste and the population density is sublinear (the exponent is 0.92), which proves that the weight of waste grows slower than proportionally to the increase in population density, revealing the benefits of the scale (Table 2).

The analysis of correlation in groups of cities shows a slight negative dependency of the amount of waste on the density in the group of cities with 50,000 to 100,000 inhabitants, with a scaling factor value of −0.107, but with an exceptionally low determination coefficient of 0.05 (Table 2). This shows a certain tendency in the correlation of the population density with the amount of total waste, namely, an increase in density means a decrease in waste mass.

In the group of cities with over 100,000 inhabitants, the scaling factor for the correlation of population density and waste mass is 0.842, which demonstrates the benefits of reducing the amount of waste in the case of population density increase in large cities (Table 2).

3.4. Characteristics of the Dependency between GDP Per Capita and the Amount of Waste

The analysis was based on data from 84 cities with over 50,000 inhabitants. For such limited data resources, the analysis showed a good correlation between the amount of GDP per capita and the total amount of waste generated in cities. The scaling factor is superlinear, and amounts to 1.53, which means that it is the highest of all the dependencies analyzed. In this model, the coefficient of determination (0.38) explains the waste amount variable at 38% (Table 2).

The scaling factor for the correlation between GDP per capita and the weight of waste per capita is 0.166 for a 12% determination, and indicates an insignificant impact of the GDP level on the generation of waste per capita.

3.5. Results Verification

To verify the obtained scaling results, an analysis of the significance of all variables was carried out in relation to the total amount of waste generated in cities with more than 50,000 inhabitants. The Hellwig [37,38] method was used to choose optimal predictors in the analysis of municipal waste production as the results of the influence of four variables (population, city area, population density, and GDP/capita) in 84 cities for which all data were available (>50,000 inhabitants).

As a result of the implementation of Hellwig's algorithm, a list of predictor combinations in descending order of the integral index of information capacity H was obtained. Results of 15 combinations of the values of this index are given in Table 3.

Table 3. Integral index of information capacity calculated using the Hellwig method.

Integral Index of Information Capacity (H)	Combination of Predictors	Combination of Predictors
0.987	C1	population (optimal value of a single variable)
0.937	C11	population + city area + population density (optimal value of many variables)
0.937	C5	population + city area
0.911	C15	population + city area + population density + GDP/capita
0.907	C13	population + city area + GDP/capita
0.885	C8	area + population density
0.884	C7	population + GDP/capita
0.832	C14	city area + population density + GDP/capita
0.820	C12	population + population density + GDP/capita
0.817	C6	population + population density
0.783	C9	city area + GDP/capita
0.767	C2	city area
0.539	C4	GDP/capita
0.520	C10	density + GDP/capita
0.088	C3	population density (lowest value)

It was identified that one-element combination C1—city population, provided the highest classification accuracy in the combination set. The best combination of more than one element turned out to be C11, i.e., a combination of three predictors: city population, city area, and population density. The combination of C5, two predictors: population and city area, had the same value of the integral index of information capacity as the previous C11.

The lowest value of the integral index was calculated for the one-element C3 combination, i.e., population density.

The result of the search for the optimal predictor confirms the previous findings from the scaling analysis about the dominant role of the population in generating municipal waste.

3.6. Analysis of Municipal Waste and Population Fluctuation over the Time

Bettencourt [36] described a method for analyzing urban scaling over changing time. He pointed to the problems appearing in the time analysis, which consist of the fact that "temporal exponents are sensitive to the intensive growth and circumstances when population growth is vanishes, leading to instabilities and infinite divergences". Bettencourt claims that this effect does not occur in cross-sectional scaling.

Time analysis requires a large amount of data, which is missing for the analyzed problem of scaling municipal waste in Polish cities.

The Polish Central Statistical Office (GUS) has complete data on the weight of waste in individual cities only for 2017, 2018, and 2019. Therefore, the comparative analysis of the waste scaling exponent in cities applies only to the period of these three years.

The waste scaling exponent calculated for 2017 in relation to the population was 1.072, and its determination was 0.935. In 2019, the waste scaling exponent was 1.057, and the determination was 0.947.

Comparing both exponents to the exponent of 1.057 tested for 2018, it can be concluded that it is identical to 2019, and slightly lower than in 2017. Additionally, the coefficient of determination for 2018, amounting to 0.935, is similar to the one obtained for 2017 and 2019. It can therefore be concluded that there is a coincidence of the scaling and determination exponents (Table 4).

Table 4. Waste scaling exponent results by year.

Year	Description of Dependencies: All Cities (930–946 cities)	Exponent of Scaling b	Exponentiation Equation $y = ax^b$	Coefficient of Determination R^2
2017	Number of inhabitants/total waste	1.072	$y = 0.1643x^{1.072}$	0.947
2018	Number of inhabitants/total waste	1.057	$y = 0.1978x^{1.057}$	0.935
2019	Number of inhabitants/total waste	1.057	$y = 0.2057x^{1.057}$	0.935

Source: the author.

Due to the lack of data on the amount of waste in cities over a longer period of time, the annual data available from 2005 was used to analyze changes in the amount of waste in subsequent years, and was correlated with the size of the population in cities in the corresponding years (Figure 1).

The Pearson linear correlation plot (Figure 1) is almost horizontal (0.055), so there is no correlation between the population and the amount of waste over the past 15 years (2005–2019). Slight fluctuations (increases and decreases) in the population of cities had practically no effect on the amount of municipal waste generated. The lack of population growth inhibits the growth of cities, and results in slight increases in the amount of waste caused by the increase in the living standard of the inhabitants and the demand for consumer goods (higher GDP) and the enlargement of the city area for the needs of low-intensity development. Based on the time analysis, we can conclude that the dynamics of changes in the population and in the production of municipal waste was small and consisted of frequent changes—increase and decrease—in individual values. On this basis, we can assume that the cross-sectional method on which the analyzes are based is correct, and its results indicate a constant trend in waste scaling independent of time.

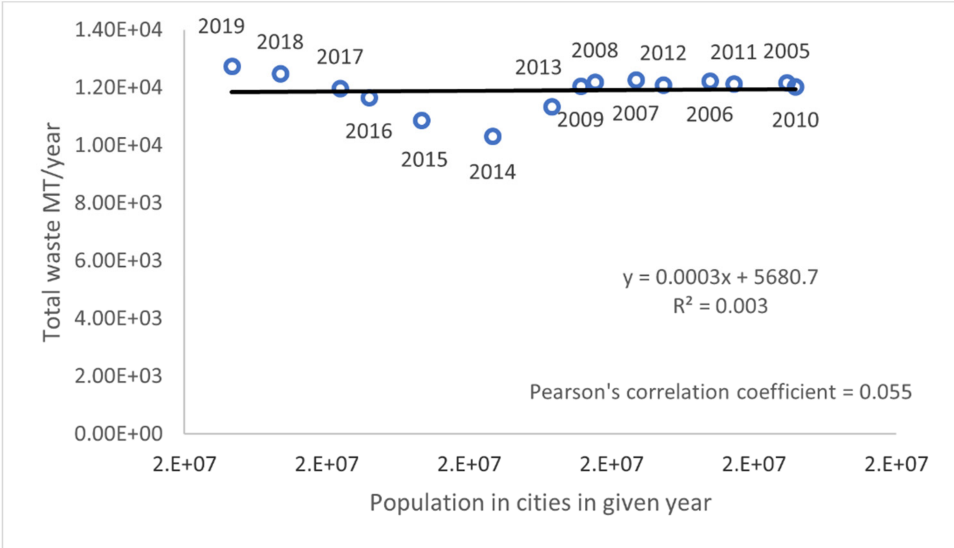

Figure 1. Correlation between municipal solid waste per year and the total population of cities in a given year (period of time 2005–2019).

Slight increases in the amount of municipal waste in the last dozen or so years in Poland go hand in hand with the better management of this waste. The amount of waste deposited in landfills decreased from 61% in 2010 to 43% in 2019. At the same time, recycling increased, which in 2019 was 26%, compared to 14% in 2010. The greatest increase was recorded in thermal waste treatment, with the use of waste for the production of electricity and heat, incineration increased from 1% to 23% (There are 9 thermal waste treatment installations operating in Poland (2021), producing electricity and heat from waste, 4 more are under construction and 10 new incinerators are planned.) The biological disposal of waste in composting plants has significantly decreased in recent years from 16% in 2016 to 9% in 2019.

4. Discussion

The hypothesis assumed at the outset that, along with the increase of the population, the amount of generated waste will decrease; however, this was not confirmed in Polish cities. The specificity of Polish cities consists of the fact that there are not enough big cities for this hypothesis to be either rejected or confirmed.

The choice of a region of the world to explore major cities does not matter, because cities manifest remarkably universal, quantifiable features: size is the major determinant of most characteristics of a city [14].

To check this additional hypothesis, large cities located in Central and South America, Asia, and the Middle East with populations of over 100,000 were researched [28]. The results of scaling the population of 508 cities in Central and South America, Asia, and the Middle East and municipal waste per day for each city are presented in the scatter plot below. The plot shows that in the sample of large cities with over 100,000 inhabitants, the scaling of the amount of waste occurs on a superlinear level. The calculations indicate that, along with the increase of the population, the amount of waste increases by 114% per unit of increase in the population, with the verifiability of such a model amounting to almost 89% (Figure 2). This shows that in large cities, the amount of waste is growing much faster than the population.

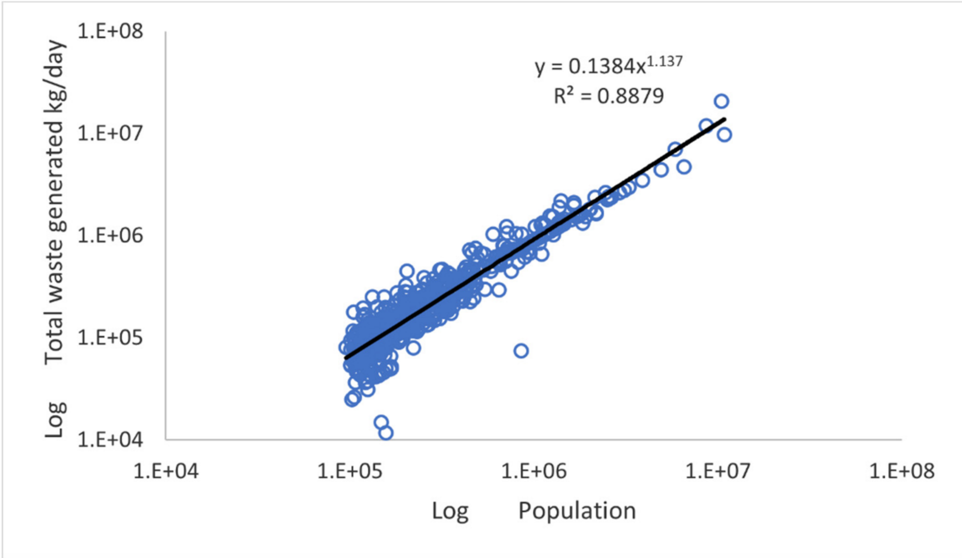

Figure 2. Scatter plot of exponentiation regression for 508 large cities located in Central and South America, Asia, and the Middle East with a population over 100,000, shows a superlinear waste growth in cities along with the population increase. The scaling exponent is 1.137 and the determination coefficient is 0.888.

Research conducted in China on a sample of 651 cities, most of which are cities over 500,000 inhabitants (491 cities), indicated that, similarly to Poland, waste is generated mainly in the group of very large cities [24]. Chinese research specified that the most influential factor in generating waste in megacities (>5 million inhabitants) is GDP per capita, similar to in Poland for the group of the largest cities (>100,000 inhabitants). In China, the city area is a common vital component that has an impact on the generation of waste in cities of all sizes. On the other hand, studies conducted for cities in Poland indicate that it is the population, and city area as second, are most influenced on the municipal waste generation (for all cities).

5. Conclusions

The main aim of the research was to define a model of municipal waste scaling depending on the population of Polish cities.

The most important conclusion about city waste scaling is that a systematic data analysis of 930 Polish cities has shown that a simple allometric scaling with a scaling exponent of 0.75 is not an appropriate method to predict "excreted" municipal waste.

For the basic model, the mean exponent of waste scaling in relation to the population shows superlinear values for all cities, and ranges from 1.06 to 1.07 (in years: 2017, 2018, 2019), with the highest value of 1.23 in the group of cities from 50 up to 100 thousand inhabitants (R^2 = 0.683).

In Poland, due to the tendency of population decrease in cities, demographic changes will not have a significant impact on changes in the amount of waste generated. However, the area of the city will be more and more important, followed by GDP (especially in the largest cities). Limiting the surface area of cities (compact cities), limiting consumption, and striving for a recirculation economy are the basic elements of the waste management strategy in cities in the near future in Poland.

5.1. Detailed Conclusions

The analysis of the scaling results of waste in individual groups of cities allows for the formulation of specific conclusions:

- the scaling exponent in the model with the city's population variable as the predictive one is the most stable in all groups of cities (R^2 > 50%),

- for the population density of cities with more than 100,000 inhabitants, the indicator was the closest to the allometric exponent (b = 0.84),
- in the next model of the correlation of the city area with the total waste mass, the scaling exponent is sublinear (b = 0.93), and the coefficient of determination is almost 50%, and, at the same time, has the greatest impact on the amount of waste in large cities with more than 100,000 inhabitants (b = 1.08).

In spatial planning, it is crucial to understand whether this relationship applies to cities in countries at different stages of development, and whether the results are similar in other countries. The analysis of scaling municipal waste carried out for large cities in selected countries of South and Central America, Asia [24], and the Middle East confirms its superlinear character in a cross-sectional study (b = 1.14).

5.2. Limitations and Further Research

The limitations of the study are mainly due to the limited access to data: detailed data on municipal waste (in all cities) concerning only the last few years, the lack of complete information on GDP for small towns, and no data on the number of permanent city users (tourists, students, etc.). These data have not been analyzed. In addition, several other parameters and indicators that can affect the amount of waste in cities have not been studied, i.e., urban road networks that affect access to services, green spaces per capita that affect biomass waste, commercial and service space per capita that affect consumption, the sale of goods over the internet, and more.

The methodology and results of this study open the way for future research. First, studies should be carried out on representative collections of cities in other countries that confirm or deny the similarity of waste production to the Kleiber metabolism model. Additionally, in selected countries with representative types of urban metabolism: energy-consuming or material-consuming, the analysis of scaling the value of municipal waste and population as well as other independent variables identified as predictive attributes of municipal waste generation, i.e., energy-consuming or material-consuming, may answer the question of which type of metabolism is more beneficial due to the reduction of waste production [39].

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