Environmental Science

AIMS Environmental Science, 7(6): 575–588.
DOI: 10.3934/environsci.2020036
Received: 09 October 2020
Accepted: 15 December 2020
Published: 18 December 2020

http://www.aimspress.com/journal/environmental

Research article

Solid waste management in urban space: the volume-weight relationship

Patrycja Przewoźna[1,*], Piotr Jankowski[1,2], Alfred Stach[1]

[1] Department of Geoinformation, Institute of Geoecology and Geoinformation, Adam Mickiewicz University in Poznań, Poland
[2] Department of Geography, San Diego State University, United States

* **Correspondence:** Email: pwysocka@amu.edu.pl; Tel: + 618296178; 608172288.

Abstract: One of the most significant and growing negative pressures on the environment is the amount of generated waste. Surprisingly, the literature on this topic is mainly focused on monitoring the waste weight instead of volume, which is crucial for waste management in urban space. This paper is dedicated to this issue in two ways. First of all the study shows the difference in waste generation rates monitored in Poznań - a major city in Poland, during one year of field research focused on waste volume and its relationship to administrative data about waste weight. Secondly, it describes the volume-weight relationship based on the collection point sensors and a dynamic weighing system installed on a garbage truck and proposes a more accurate weight to volume conversion method.

Keywords: waste generation; monitoring; solid waste management; volume-weight relationship; seasonal variability

1. Introduction

The efficient management of municipal solid waste (MSW) in large cities is a challenge due to their significant and continuously increasing share in the global human population. Despite the developing technologies and continuously expanding operational knowledge, a precise prediction of the amount of waste generated by their residents poses many difficulties.

Many papers have tackled various aspects of this problem at a regional scale [1–3]. The analysis unit used in these studies ranges from a city to an entire country through region/province. In some cases, the studies concentrate on settlement areas based on building type [4–6], and only rarely the phenomenon of waste generation is investigated at a household level [6–8].

This deficit of studies on waste generation patterns at a household level also influences the type of indicators used for measuring the waste generation. When the precision of waste monitoring reaches the point of waste collection, two types of models estimating waste generation may be applied: volume-based and weight-based. The volume is generally the most straightforward solution for guiding Pay-As-You-Throw (PAYT) management strategies [9]. Nevertheless, obtaining weight information is easier, primarily when larger waste collection areas are used. The regulations in different countries such as the US [10] or the EU countries [11], requiring from local municipalities to report the weight of generated wastes, not volume, support this trend. Some attempts have been made to develop frameworks for more effective monitoring and efficient local waste management policies by increasing the accuracy of control and incorporating volumetric information into daily practice [12,13]. However, they remain in the sphere of recommendations, not official regulations, and consequently data on the volume of waste is typically not collected, which presents a challenge to research in the field of MSW management. The limited literature on the subject shows that waste volume is not considered at all [1,3], although knowledge about it may be crucial for effective planning.

From the technical standpoint there is no shortage of monitoring techniques, which could enable efficient waste management at the city scale. There are multiple advanced methods that rely on Information and Communication Technologies (ICTs) allowing for precise determination of the amount of generated waste, but they are rarely used as data sources in forecasting models [14]. The advanced methods that optimize waste collection routes, minimize waste overflow and reduce system costs based on waste volume rather than weight [15–17]. Different system architecture designs applying GSM (Global System for Mobile Communications from fr. Groupe Spécial Mobile) technologies, wireless sensor networks, or even the Internet of Things (IoT) have been proposed in order to collect this type of information [18]. It should also be emphasized that precise knowledge about the amount of waste generated at collection points opens the possibility for including geospatial data in spatial-temporal waste management analysis, which is crucial for effective MSW management [19]

Nevertheless, the mentioned-above technologically advanced solutions remain too expensive, and only a small number of municipalities in a median income country such as Poland can afford them [20]. Thus, the information about waste volume is rarely incorporated into public administration and national sustainable development policies [22].

This situation is additionally exacerbated by reporting obligations, which emphasize waste weight [21]. As a result, volume (rather than weight) monitoring is related to additional measurements that are costly and time-consuming. Given that none of the reviewed studies has dealt with the issue of using waste weight as the basis for waste management planning, the central question for this research becomes: is it reasonable to base waste management planning at a city scale solely on general knowledge about the weight of generated waste?

The presented study addresses this question by examining the range of differences that may occur in analysis results based on different methods of collecting information about the weight and volume of waste. The study shows the results of field measurements of MSW volume conducted in one of the largest Polish cities using an ultrasonic sensor in a selected area. The collected information is compared with authoritative data about weight waste generation published by the local administration. Additionally, the weight-volume relation is investigated based on the volume information obtained with sensors and the actual weight measured by a dynamic weighing system installed on a garbage truck. Finally, to enable the comparison between waste weight and volume, a probabilistic conversion method from waste weight to volume is proposed.

2. Material and methods

2.1. Case study area

Poznań is one of the largest Polish cities in terms of area (261.91 km^2) and population density (2082 people/km^2 -according to the data provided to us by the Poznań City Hall in 2013, when the study began). It is also highly diversified in terms of the building type - there are five types distinguished by Urban Atlas in terms of population density. It is also one of the best-examined cities in terms of municipal waste generation due to the relatively recent investment into a large-scale waste incineration facility. Consequently, detailed quantitative and qualitative analyses for the design of the incinerator [5] are an ideal reference point for checking the effectiveness of the measurement methods presented in this paper. They provide useful complementary information to seasonal variability for the whole city that can be determined based on reports provided monthly by waste collection companies.

The studies conducted by Mamełka [5] focused on areas diversified in terms of the building type, following the existing guidelines in Poland [12], which also served as a reference point for the presented herein research. When creating the detailed rules of diversification, the German experience described in the guide 'Best Practice Municipal Waste Management,' reissued by Bilitewski et al. in 2018, was also considered.

Additionally, the building types used in this research were defined using the following criteria: type I - high-rise apartment buildings (8 floors or more) - multi-family housing where smaller households dominate, premises with a small area hindering selective waste collection; often equipped with chute chambers, type II - low-rise building (multi-family housing in downtown or buildings up to 7 floors) - more diverse in terms of both the size of households and the size of the premises; often compact buildings, making it more difficult to locate more selective collection points; no chute chambers, type III - single-family or multi-family housing - large premises and favorable conditions for segregation (especially selective collection "at source"), as well as additional possibilities for biodegradable waste recovery (home composters).

Using this classification, Poznań was divided into 342 areas. Of these, 44 were classified as "other areas" (e.g., agricultural land, forests) and were excluded from further research. The rest was identified as one of the above housing types: 24% were type I, 44% were type II, and 32% were type III (Figure 1).

Most inhabitants of Poznań live in low-rise buildings. The median population density in this dwelling type is 10’566 inhabitants/km^2, according to the data provided by the Poznań City Hall. Three out of ten areas with density values between 10’000–11’000 were in one of the housing cooperatives, located in the northern part of Poznań. All three were operated by one waste collection company, which enabled monitoring the filling of containers with waste at a similar time. Therefore, seasonal variability measurements were carried out in all three areas (Figure 2).

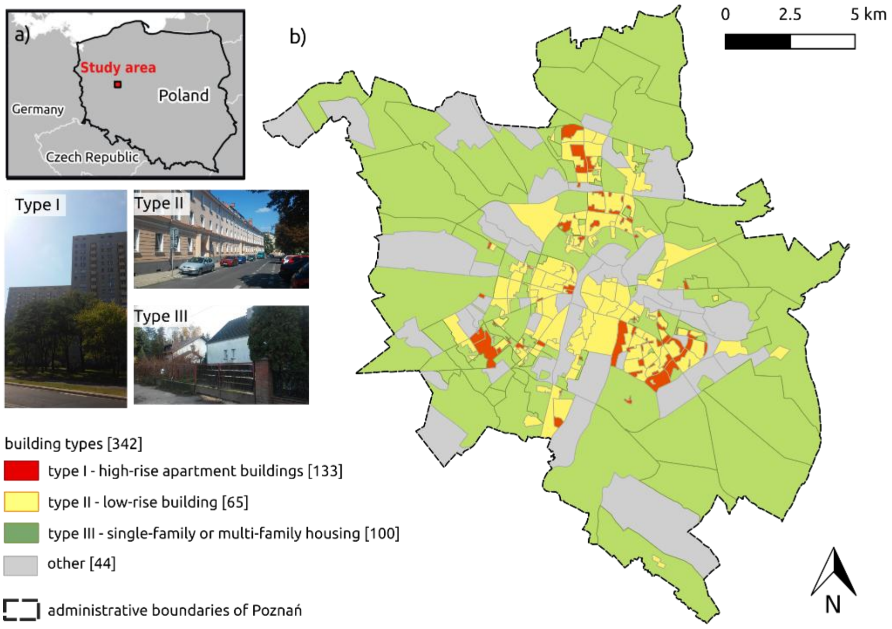

Figure 1. Location of a) study area relative to Polish borders; b) adopted division into building types within the city's administrative boundaries and sample photos.

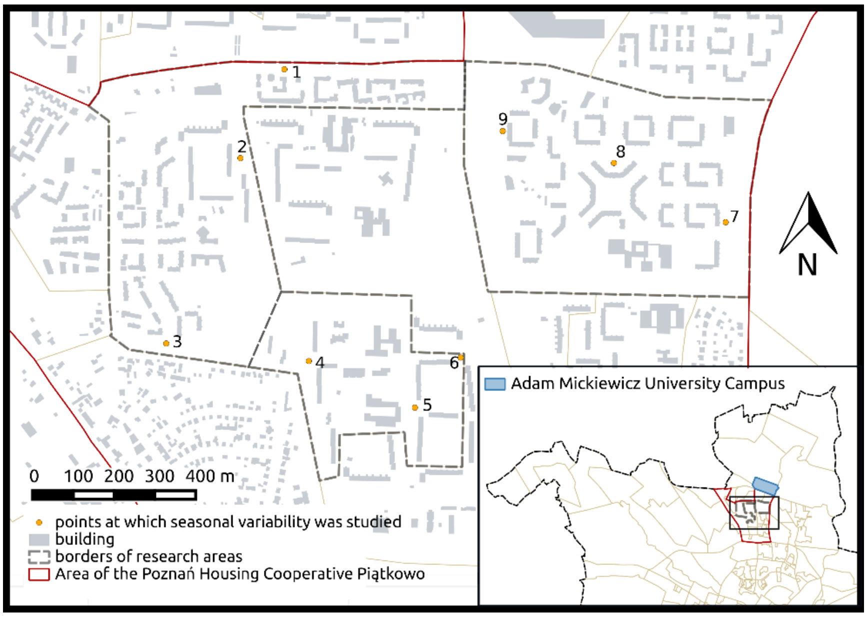

Figure 2. The locations of monitored points in the chosen research areas.

The chosen areas were characterized by typical low-rise buildings with a small presence of commercial and service outlets. Due to the closeness of the Adam Mickiewicz University Campus, they were also more often than other areas inhabited by students, who are a significant group of city residents generating waste in Poznań - over 121 000 students in 2013, which amounts to almost 240 students per 1000 inhabitants. Thus, the chosen areas guarantee that this group's impact on the amount of generated waste is considered.

2.2. Field research of household waste with the ultrasonic sensor

Measurements of the volume of waste are made based on the assessment of the level of container filling. They can be made based on modern technologies such as ultrasonic sensors [16,17] or imaging [23]. The sensors allow for more precise measurements and direct transmission of information about the level of fill-in waste container with the help of GSM / GPRS technology or wireless network. A cheaper, but less accurate method used in Poznań [5] is the visual assessment of the level of fill by a researcher. In this research, the decision was made to combine the accuracy of ultrasonic sensors with traditional fieldwork based on visual assessment.

The mobile ultrasonic sensors, specially designed for this study, were used to measure the average level of fill-in waste containers based on the distance separating the sensor from the surface of the waste (Figure 3.). Each sensor was mounted on a measuring pole, moved from container to container by a researcher. The data was recorded on an SD (secure digital) card. This semi-automated approach reduced data collection costs and minimized the risk of sensor theft or destruction.

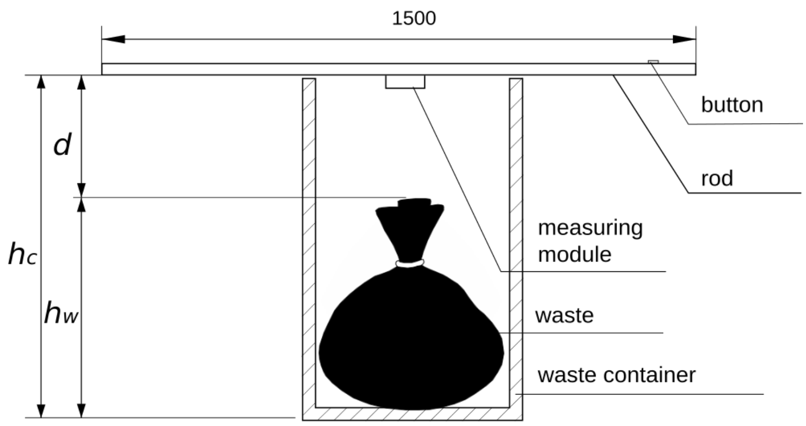

Figure 3. The diagram shows the idea behind measuring the level of waste fill with the sensor positioned at the top of the container, where: h_w - the waste height, h_c - the height of the container, d - the distance between the sensor and the surface waste (dimensions are in mm); pressing the button starts the measurement.

The waste volume V_w can be calculated based on the measurement results and the container dimensions using the Eq 1 where: h_c- the height of the container, h_w - the height of the waste fill level.

$$V_w = \frac{h_c - d}{Hc} \times V_C = \frac{h_w}{h_c} \times V_c \quad (1)$$

For comparison purposes, the volume needed to be expressed as a waste generation rate (dm^3/capita/day). It was calculated with the Eq 2 for each monitored point containing the n number of the containers. The calculations included the number of days D elapsed since the last waste disposal and the number of people using the collection point P_A (based on administrative data: The data regarding the number of people living at adres points were taken from the Civil Affairs Department of the City Hall Poznan).

$$waste\ generation\ rate = \frac{\sum_{i=1}^{n} V_{wi}}{D \times P_A} \tag{2}$$

The measurements were carried out daily at constant times, one week per month, on the monthly basis throughout 2014.

2.2.1. Volume to weight comparison

The information about monitored seasonal variability was compared with citywide waste generation rates expressed by the weight observed monthly in Poznań in 2014. Those data (henceforth called administrative data) were compiled by the municipal waste and sanitation authority in Poznań. Direct comparison between volume and weight requires weight to volume conversion, but there is no simple way to do it. The US Environmental Protection Agency published the conversion factors for different types of waste, including mixed municipal waste [24]. They are, however, very general and do not take into account the distinction between rural and urban municipalities, which highly vary in terms of waste generation rates [25], and do not consider different building types distinguished in this research. There are also no universal conversion factors for Poland. The report created for the planning needs of a waste incineration plant in Poznań contained information about waste density [5]. It was, however, calculated only based on the summary results of volume to weight conversion measurements done at collection points in four test areas. Thus, the data obtained in 2008 may not represent the entire city, and they do not take into account the local diversity of waste density. Therefore, no direct conversion between weight and volume was used to compare the seasonal variability in the amount of generated waste. Instead, we calculated the ratio of monthly waste generation to the annual average. It was done for both weight and volume. Thanks to this, it was possible to identify months, in which the amount of generated waste was higher/lower than the average. Separate comparisons were made for weight data and the volume of waste to establish whether the indicators would differ significantly.

2.2.2. Determining the volume to weight ratio

Important information for the interpretation of results is the weight of waste to their volume ratio obtained with ultrasonic sensors' help. It can be calculated only by comparing waste volume to weight at the given collection point. It requires precise measurements with a dynamic weighing system installed on garbage trucks. Given that the garbage trucks equipped with the dynamic weighting system were only operating outside Poznań in Pobiedziska - a small town located 30 km north-east from the city, the comparison of weight to volume ratio was made with the data from 34 collection points in Pobiedziska obtained in September 2014. The area where the collection points were located was characterized by a low-rise building type similar to the research area chosen in Poznań, but with a lower number of inhabitants. The obtained waste density distribution was analyzed with descriptive statistics in R. It was also compared with theoretical distributions and densities of waste in Poznań [5]. Those additional measurements allowed checking the range of possible waste density values and illuminated the discussion of results obtained in Poznań.

3. Results

The comparison of volumetric waste generation rates obtained from three research areas with the administrative data shows differences in the variability of waste weight and volume collected monthly (Figure 4). The significance of those differences was checked with Wilcoxon signed-rank exact test (V = 78, P-*value* = 0.0005) appropriate for small samples.

Generally, both the volume and weight of waste are characterized by lower values in winter and an increase in the amount of waste generated in spring. However, in the case of volume, the jump in values recorded in the spring-summer season of 2014 compared with the annual average was more significant than it would appear from the administrative data on waste weight. In the latter case, the waste weight in the summer months was average, and the values above the average were observed only in the autumn of 2014.

Detailed analysis of these results shows that differences in volumes observed for each month were statistically significant, which was confirmed by the Kruskal-Wallis test (H = 22.7901, P-*value* = 0.01892). The average values of waste generation rates obtained for individual months ranged between 3.33 and 4.63 dm^3/capita/day. The lowest mean and median values of waste volume were observed in April, while the most significant increase was in July. The most significant differences between the observations made at individual collection points were also observed mainly in summer. The volume values measured in each of the nine monitored points ranged from 0.32 to 12 dm^3/capita/day. While the weight of waste shows slight fluctuations, the difference between the smallest and largest recorded values is only 0.26 kg/capita/day. Unfortunately, the method of reporting information about waste generation by the company collecting waste does not allow for examining the scale of variability between different areas of the city within one month (Table 1).

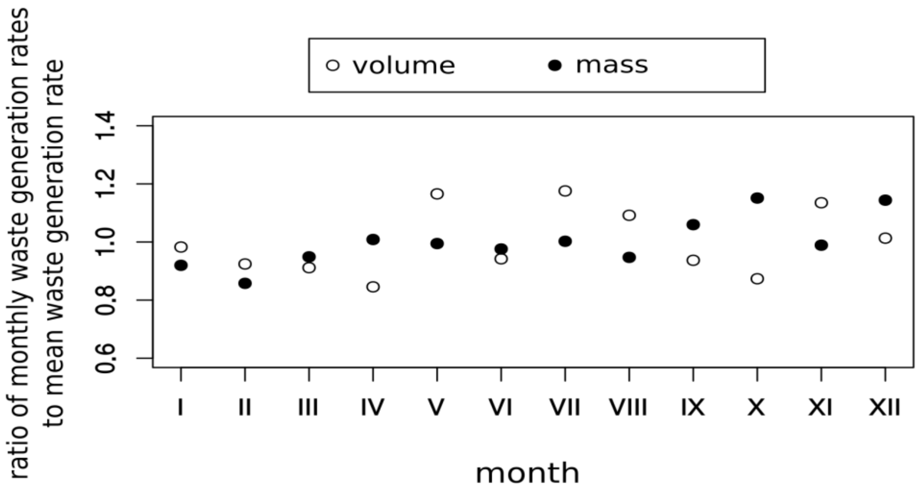

Figure 4. The comparison of volumetric waste rates obtained in tested areas (the average of the measurements done during field research) with weight rates observed in the city of Poznań in 2014 (based on administrative data).

The obtained differences in waste volume should not be related to the applied measurement method. If this were the case, we would expect that a direct comparison of the measured volume to the actual weight of waste would give completely random results. However, additional measurements from Pobiedziska show that the distribution of density values obtained with the same sensors is regular (Figure 5). It is very similar to normal distribution as confirmed by various normality tests: Shapiro-Wilk (*W* = 0.97204, *P-value* = 0.52), Shapiro-Francia (*W* = 0.96654, *P-value* = 0.3161), Anderson-Darling (*A* = 0.30715, *P-value*= 0.5448), Lilliefors (*D* = 0.086536, *P-value* = 0.7473), and Pearson chi-square (*P* = 2, *P-value* = 0.9197). The mean and median values are also similar (0.124 and 0.121 dm^3/capita/day, respectively). However, the probability resulting from the tests ranges between 32% and 92%, and other basic descriptive statistics (skewness = 0.55 and kurtosis = 0.45) are not typical for normal distribution. Thus it is not necessarily the best description of the relationship between the weight and volume of waste.

Table1. Seasonal variability of waste generation rates expressed in terms of volume and weight.

Source of data:	Field research (dm^3/capita/day)[a]			Reported data (kg/capita/day)[b]
Month	Mean	Median	SD	Total
January	3.87	3.78	1.11	0.82
February	3.64	3.38	1.15	0.77
March	3.59	2.99	0.86	0.85
April	3.33	2.83	1.47	0.90
May	4.59	3.67	1.58	0.89
Jun	3.71	3.06	1.46	0.87
July	4.63	4.09	1.87	0.90
August	4.30	3.90	1.50	0.85
September	3.69	3.41	0.95	0.95
October	3.44	3.04	1.17	1.03
November	4.47	3.76	1.59	0.89
December	3.99	3.76	1.87	1.02

Notes: a - results of field research done in all collection points during week time each month; b - the weight of waste collected by the local authorities in each month; blue color - the lowest value, red color - the highest value.

An additional test conducted with the distribution fitting software (EasyFit) enabled checking 48 other theoretical distributions for the data at hand. The fitting quality of empirical to theoretical distributions was assessed using three criteria: Kolmogorov-Smirnov, Anderson-Darling, and Chi-square. It turned out that the Wakeby distribution shows the best empirical to theoretical fit based on the first two criteria. It is also the fourth best distribution according to the Chi-square criterion, while the normal distribution was 7th, 26th, and 26th, respectively, according to the three criteria. This observation is important for the accuracy of estimating the amount of waste based on statistical methods.

4. Discussion

4.1. Volume-weight relationship

The distribution of waste density values obtained from measurements in Pobiedziska, showing significant similarity to the Wakeby distribution, indicates a certain asymmetry of the obtained results. Although highly concentrated around the average, as indicated by the value of kurtosis, they are slightly positively oblique. This indicates a more frequent occurrence of a situation, in which a larger volume of waste is related to a smaller weight than would be theoretically expected. The question arises whether or not this situation has been confirmed in the subject literature. The issue is confounded by limited field research about the relationship between volume and waste density. In the Poznań agglomeration, the most accurate source of knowledge in this respect is the mentioned study from 2008 [5].

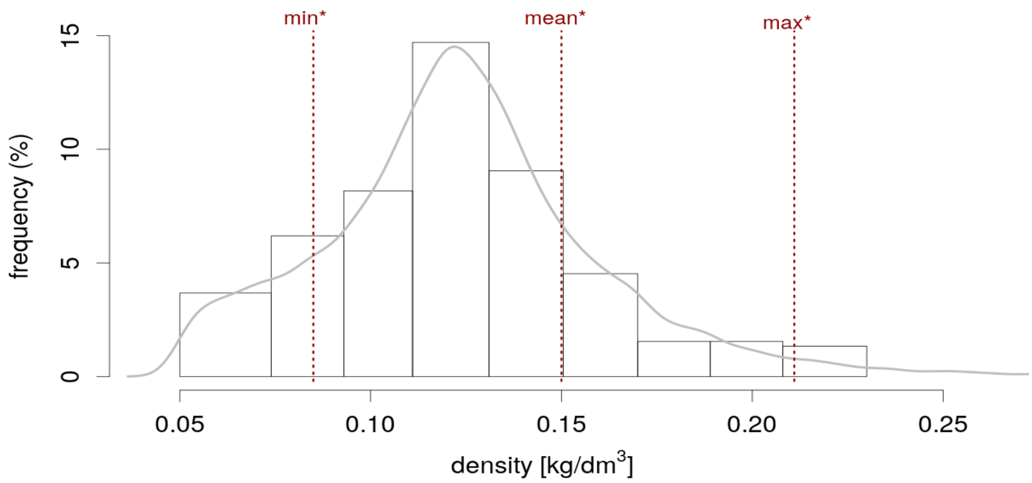

Figure 5. The comparison of the density distribution of waste resulting from fieldwork carried out in Pobiedziska in September 2014 with the data from Poznań* (Mamełka, 2008), marked on the graph by red dashed lines. The grey line shows the graph of Wakeby distribution fitted to measurement data.

Unfortunately, data about volume and weight from 2008 were generalized for the entire research area. Therefore, the distribution of density values for individual collection points, which would be crucial for comparative purposes, can not be established. We see only a slight shift in the density of waste received in select areas in 2008 towards higher values. The range of waste density values obtained from the individual collection points in Pobiedziska varies from 0.05 to 0.23 kg/dm^3, while the values based on the aggregated data from Poznań range between 0.085 and 0.211 kg/dm^3 [5] (Figure 5). The comparison of average waste densities shows a similarity between Pobiedziska and Poznań with the average densities of 0.15 kg/dm^3 (Poznań) and 0.12 kg/dm^3 (Pobiedziska). The slight difference may be explained by the discrepancy in average household income, which is crucial for the observed generation rates [25]. The per capita income in Poznań (https://poznan.stat.gov.pl/vademecum/vademecum_wielkopolskie/portrety_miast/miasto_poznan.pd f) is PLN 6007 in Poznan and PLN 4045 in Pobiedziska (https://poznan.stat.gov.pl/vademecum/vademecum_wielkopolskie/portrety_gmin/powiat_poznanski/gm_pobiedziska.pdf) according to the data of the Statistical Office in Poznań. It may also be the consequence of changes in waste production behavior in Polish society resulting from the 2011 update in the law regulating disposal and utilization of municipal wastes. The regulations have imposed waste utilization fees promoting recycling and waste-conscious behavior at the household level.

However, small differences between the results obtained in Pobiedziska and Poznań in 2008 [5] support the reliability of the measurement method. They also indicate that mixed municipal waste volume does not increase linearly with the increase in their weight. The most significant difference between those two indicators is when containers are barely full (which means that the volume of waste is about 1100 dm^3). That was the case of 14 containers, in which the weight of waste ranged from 60 to 250 kg. Therefore, it is the first signal that municipal waste management policy solely based on weight information is insufficient, which is corroborated by the analysis of seasonal variability.

4.2. Seasonal variability of waste generation

Waste generation rates vary significantly on the monthly bases, depending on whether they are expressed in weight or volume. This may be due to the research area, in which the seasonal variability was analyzed, since only one of three building types was taken into account. Nevertheless, a similar study on the seasonal variability of waste volume that was carried out in recent years in a single-family housing in Białystok [26] did not indicate this. Białystok is a city in Poland with a similar to Poznań administrative status, but almost half the area and the number of inhabitants as in Poznań. The results of research mentioned above show that the most significant amount of waste is generated in the spring season followed by summer. The authors explain it by the increased number of cleaning and renovation projects resulting in the amount of waste collected - mainly disposable plastic packaging that affects the volume of waste. Such activities occur less often in autumn and the least in winter, which directly impacts the observed fill level of wastes in containers. Grygorczuk-Petersons and Wiater [26] indicate that in terms of the volume of waste in single-family housing, the autumn-winter season is less important. Therefore, the differences in seasonal variability of generated waste expressed in volume and weight are unlikely to be the function of a specific study area.

Thus, it is more likely that the seasonal variability was caused by the change in the morphological composition of waste varying throughout the year [5,27]. The most significant contributing factor can be the share of plastics in the total waste stream. The research carried out in Poznań in 2007–2008 showed that plastics constituted a significant part of mixed waste [5]. The study conducted by Gómez et al. [27] during the months of April, August, and January showed that the largest share of plastic packaging fallout occurred in August (from 5% to almost 10% depending on examined socio-economic level). It was significantly higher than in the other two examined months (for which obtained values varied from 2.5% to about 4%). Therefore, it is probable that the share of plastics increased the volume of waste in the summer months while this increase was not reflected in the administrative data concerning weight. It follows that creating a waste collection system based on waste weight information or converting weight into volume using simplistic conversion factors can lead to erroneous conclusions.

4.3. Effective waste management in urban space

Differences between the weight and volume of generated waste may be less significant when entire agglomerations are analyzed using aggregated waste data. However, effective waste management planning occurs at the local level with the accuracy of a housing estate or collection point. In this case, the precision of estimation is of great importance for waste management. The costs related to waste collection, transport, and subsequent utilization depend on it. In Poland, since the responsibility for waste collection and utilization has been transferred to local authorities in 2011, the correct estimation of costs and their fair passing on to customers (residents) is still a challenge. The Market Analysis Department report [28] indicates that although many years have passed since the changes were fully implemented, municipal budgets for waste management are still unbalanced. According to the report, in 10% of municipalities the inhabitants' fees cover at most 75% of expenses. This means that at least some of the municipalities contribute less than their fair share to the system. This drives the need to increase the garbage collection fees on all.

Such a situation has also occurred in Poznań, where the waste collection fees for residents have risen above the reasonable level. The problem would have been less acute if the city based its system on one of the Pay-As-You-Throw models [9], which would allow for the equitable distribution of costs and optimal estimation of the actual amount of garbage generated by different collection areas of the city. However, such solutions are expensive. Moreover, the presented results show that the range estimates of the level of container fill in individual locations can fluctuate greatly, making the forecasts based only on the weight of waste prone to error.

Additionally, the analysis described herein showed that the conversion of weight to volume solely based on an individual conversion factor does not reflect the whole variability of waste density. That is confirmed not only by the data from Poznań [5]. The range of density values provided by the US Environmental Protection Agency [24] is even narrower, ranging from 0.15 to 0.18 kg/dm^3. It yields the difference of 0.03 kg/dm^3 between the smaller and the larger value of the conversion factor, which is only less than 17% of the total variability shown in Pobiedziska. Thus, when volume or weight is estimated based solely on one or two conversion factors, it is difficult to arrive at the full range of density variability, which can be important when planning waste management at the city level.

A solution to this problem might be the application of simulation methods. We propose that conversion relies on Monte Carlo simulation based on a theoretical distribution presenting the best fit with empirical data. In the example presented earlier in the paper, this would be the Wakeby distribution. Thus, the results are not limited to a few values but are represented by a range of probable values whose distribution and statistics can be compared to field data. This method was used in the doctoral dissertation [29], and its effectiveness will be described in the forthcoming publications.

5. Conclusions

The weight of MSW is the primary information collected by administrative units in charge of waste management, but in and of itself, it is insufficient for effective waste management planning. The results show that volume (which is the leading indicator of waste container filling) and weight accumulation rates vary significantly by seasons. Some months were characterized by a greater weight of generated waste, while other months were dominated by greater volume. In the latter case, the containers were the most filled with waste during the summer months, most likely related to the larger amount of plastic packaging thrown away in mixed waste containers than during the other months. The summary of information on weight and volume also shows that we can indirectly infer significant changes in the morphological composition of waste from monitoring both these indicators. In turn, this information would allow for more effective monitoring of the effectiveness of the conducted selective collection programs. Identifying the months or collection points associated with large variations in weight and volume of waste would facilitate learning about the potential sources of problems related to irregularities in the collection carried out and the search for appropriate solutions.

Moreover, the presented study indicates that estimating the waste volume based on their weight with universal conversion factors may be misleading, since waste density varies depending on the waste morphological composition. We have shown that this can cause differences in the density of collected waste from 0.05 to almost 0.25 kg / dm3. Meanwhile, the MSW management is based on information about the weight of the collected waste. That can directly translate into many environmental problems associated with waste management, such as overfilled waste containers that pollute the urban landscape. Estimation errors due to weight-based systems can also lead to an incorrect estimate of the municipal waste collection budget. However, monitoring the filling of containers with waste is time-consuming, thus the alternative way of weight-volume conversion has been suggested.

The topic raised in the paper requires further work. More attention should be paid to other methods that enable monitoring of both weight and volume of waste. The distribution of waste density at different locations should be analyzed and the potential of probabilistic methods for more effective estimation of waste container filling should be examined. The presented differences between weight and volume of waste indicate the relevance of this topic. Moreover, precise information of volume creates new possibilities for more efficient waste management at the city level based on spatial analysis. However, this potential has been so far neither fully exploited by scientists nor practitioners.

Acknowledgments

The research project was financed by the National Science Center (grant UMO-2012/05/N/HS4/00509).

Conflict of interest

The authors declare no conflict of interest.

References

1. Beigl P, Lebersorger S, Salhofer S (2008) Modelling municipal solid waste generation: A review. *Waste Manag* 28: 200–214.
2. den Boer E, Jędrczak A, Kowalski Z, et al. (2010) A review of municipal solid waste composition and quantities in Poland. *Waste Manag* 30: 367–377.
3. Kolekar KA, Hazra T, Chakrabarty SN (2016) A Review on Prediction of Municipal Solid Waste Generation Models. *Procedia Environ Sci* 35:238–244.

4. Emery AD, Griffiths AJ, Williams KP (2003) An in depth study of the effects of socio-economic conditions on household waste recycling practices. *Waste Manag Res* 21: 180–190.

5. Mamełka D (2008) Sprawozdanie z poboru prób oraz z przeprowadzonych badań morfologicznych i własności technicznych odpadów komunalnych z terenu Miasta Poznania w okresie październik - grudzień 2007 oraz kwiecień - maj 2008r. (Report on sampling and on morphological tests and technical properties of municipal waste from the city of Poznań in October - December 2007 and April - May 2008), Warsaw: Miej. Lab. Chem. przy Urzędzie m.st. Warszawy.
6. Dennison GJ, Dodd VA, Whelan B (1996) A socio-economic based survey of household waste characteristics in the city of Dublin, Ireland. I. Waste composition. *Resour Conserv Recycl* 17: 227–244.
7. Dennison GJ, Dodd VA, Whelan B (1996) A socio-economic based survey of household waste characteristics in the city of Dublin, Ireland. II. Waste Quantities. *Resour Conserv Recycl* 17: 245–257.
8. LXiao L, Lin T, Chen S, et al. (2015) Characterizing Urban Household Waste Generation and Metabolism Considering Community Stratification in a Rapid Urbanizing Area of China. *PLoS One* 10: 1–16.
9. Elia V, Gnoni MG, Tornese F (2015) Designing Pay-As-You-Throw schemes in municipal waste management services: A holistic approach. *Waste Manag* 44: 188–195.
10. Center for Sustainable Systems University of Michigan (2018) Municipal Solid Waste Factsheet Pub. No. CSS04-15. Available from: http://css.umich.edu/factsheets/municipal-solid-waste-factsheet.
11. Eurostat - Statistical Office of the European Communities (2015) Waste statistics. Available from: http://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics.
12. Jędrczak A, Szpadt R (2006) Określenie metodyki badań składu sitowego, morfologicznego i chemicznego odpadów komunalnych (Specific methods for testing the sieve, morphological and chemical composition of municipal waste). Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej na zamówienie Ministra Środowiska, Kamieniec Wr. - Zielona Góra.
13. Bilitewski B, Wagner J, Reichenbach J (2018) Best Practice Municipal Waste Management. Umweltbundesamt, Available from: https://www.umweltbundesamt.de/en/publikationen/best-practice-municipal-waste-management.
14. de Souza Melaré AV, González SM, Faceli K, et al. (2017) Technologies and decision support systems to aid solid-waste management: a systematic review. *Waste Manag* 59: 567–584.
15. Al Mamun MA, Hannan MA, Hussain A (2014) A Novel Prototype and Simulation Model for Real Time Solid Waste Bin Monitoring System. *J Kejuruter* 26: 15–19.
16. Gutierrez JM, Jensen M, Henius M, et al. (2015) Smart Waste Collection System Based on Location Intelligence. *Procedia Comput Sci* 61: 120–127.
17. Hassan SA, Jameel NGM, Şekeroğlu B (2016) Smart Solid Waste Monitoring and Collection System. *Int J Adv Res Comput Sci Softw Eng Sci Softw Eng* 6: 7–12.

18. Ramani H, Mehra L (2016) Technologies and Their Usage in Solid Waste Monitoring and Management Systems. National Conference on Road Map for Smart Cities of Rajasthan (NC-RMSCR) (Conference proceedings): 350–353.
19. Bani MS, Rashid ZA, Hamid KHK, et al. (2009) The development of decision support system for waste management; a review. *World Acad Sci Eng Technol* 37: 161–168.
20. Stępień M, Białecka B, Stalmachova B (2018) IT Systems Supporting Waste Management in Municipalities – Research Results. *Multidiscip Asp Prod Eng* 1: 777–783.
21. Wysocka P (2011) Przyczyny nieefektywnego planowania strategicznego gospodarki odpadami w Polsce - przykład Województwa Wielkopolskiego (What are the reasons for the ineffective strategicplanning of waste management in Poland? The example of the Wielkopolska Province). In: Kuczera, M. (Ed.) Wpływ Młodych Naukowców Na Osiągnięcia Polskiej Nauki: 210–222.
22. Official Gazette of the Republic of Poland (2010) Resolution No. 217 of the Council of Ministries of 24 December 2010 on the "National Waste Management Plan 2014" (M.P. No. 90, item 946).
23. Rovetta A, Xiumin F, Vicentini F, et al. (2009) Early detection and evaluation of waste through sensorized containers for a collection monitoring application. *Waste Manag* 29: 2939–2949.
24. US Environmental Protection Agency (2016) Volume-to-Weight Conversion Factors. Available from: https://www.epa.gov/sites/production/files/2016-04/documents/volume_to_weight_conversion_factors_memorandum_04192016_508fnl.pdf.
25. Kaza S, Yao L, Bhada-Tata P, et al. (2018) What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. The World Bank, Washington.
26. Grygorczuk-Petersons EH, Wiater J (2014) Sezonowa zmienność wskaźnika nagromadzenia odpadów w wybranym osiedlu Białegostok (Seasonal variation of the waste accumulations indicator in selected estate of Białystok). *Inżynieria Ekologiczna* 40: 82–91.
27. Gómez G, Meneses M, Ballinas L, et al. (2009) Seasonal characterization of municipal solid waste (MSW) in the city of Chihuahua, Mexico. *Waste Manag* 29: 2018–2024.
28. Market Analysis Department (2019) Raport Urzędu Ochrony Konkurencji i Konsumentów – Departament Analiz Rynku: badanie rynku usług związanych z gospodarowaniem odpadami komunalnymi w gminach miejskich w latach 2014-2019 (Report released by Office of Competition and Consumer Protection – Market Analysis Department: market research on municipal waste management in municipalities in 2014-2019) Available from: https://www.uokik.gov.pl/aktualnosci.php?news_id=15715.
29. Przewoźna P (2019) Analiza czasowo–przestrzenna ilości odpadów komunalnych powstających w Poznaniu (Spatial–time analysis of the amount of municipal waste generated in Poznań) Ph.D. dissertation availble from: http://hdl.handle.net/10593/24608.