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Seasonal Changes in the Composition and Thermal Properties of Municipal Solid Waste: A Case Study of the City of Perm, Russia

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The paper presents experimental studies of municipal solid waste (MSW) composition and its thermal properties (moisture and ash content). Measurements were taken to track seasonal changes in the composition of MSW. For example, in spring, the content of organic waste was 17.0% and, in autumn, it reached 31.5% due to considerable consumption of seasonal vegetables and fruits. The share of paper in MSW changed from 21.4% in spring to 9.7% in autumn. More paper in spring is due to discarded student notebooks at the end of a school year, as well as spring household cleaning. These data indicate significant changes in waste composition during the year, which should be taken into account when planning technologies for waste management.

Laboratory studies of moisture and ash content by season allowed the range of these changes to be determined. In autumn for instance, the moisture and ash content of organic waste was about 82% and 14%, respectively, while in winter, it was approximately 73% and 22%, respectively. These figures can be explained by the organic waste origin: autumn organic waste often comes from fruit pulp and, for example, watermelon peels, and winter organic waste tends to consist mostly of dry vegetable peels such as potato peelings.

The low calorific value of certain components is based on their composition and the level of moisture and ash in different seasons. Therefore, it is important to take into account the moisture and ash content of individual components, not average values, in order to calculate the waste calorific value.

MSW thermal characteristics change significantly over the seasons: the MSW moisture content is the highest in autumn (about 49%) and the lowest in winter (32%). The ash content in MSW ranges from 20% in spring and autumn to 27% in summer. The lowest calorific value per working mass in different seasons varies from 7 to 10 MJ/kg, which must be taken into consideration when developing waste management systems in general and when designing specific energy recovery facilities.

Keywords: municipal solid waste, solid waste, waste composition, moisture content, ash content, colorific value.

Introduction

Currently, the system of waste management in the Russian Federation is moving from landfilling to more advanced technologies. This process should be based on the application of municipal solid waste (MSW) management principles and the introduction of effective technologies for MSW treatment and energy recovery in order to reduce the impact on environmental and human health. At the same time, an important aspect of planning waste management activities is obtaining detailed information on the MSW composition and its thermal characteristics (moisture and ash content, calorific value), since they determine the effectiveness of strategies employed in waste management. Furthermore, waste composition data are used in multi-criteria decision analysis of waste-to-energy technologies for municipal solid waste management (Qazi, et al. 2018) and they contribute significantly to the life cycle assessment results and the uncertainty associated with these results (Bisinella, et al. 2017).

The MSW composition and its properties depend on a number of factors including season, climate, and building amenities (Ulanova, et al. 2016). Sethi et al. (2013) present an analysis of seasonal changes in the MSW composition in Jalandhar (India). Sampling was carried out in accordance with the ASTM D5231-92 (ASTM 2008) requirements for waste disposal sites. An MSW sample was 100 kg per season. Sorting was done manually into 10 components, among which were organic waste, waste paper, plastics, glass, rubber, metals, textiles, wood, and inert fraction. The research stated that the organic waste content was significantly higher in summer (38%) and lower in winter (27%) due to an increase in local consumption of fruits and vegetables in summer. The content of inert fraction varied significantly from 28% in autumn to 38% in winter.

Denafas et al. (2011; 2010) present a study of seasonal changes in the MSW composition for several cities: Kaunas (Lithuania), Kiev (Ukraine), St. Petersburg (Russia), Kutaisi (Georgia) and the island of Crete (Greece). These seasonal changes in the MSW composition in turn affected emissions of pollutants from waste disposal facilities and incinerators. In all studied municipalities, the share of organic waste (kitchen waste with a relatively low content of garden waste) prevailed in MSW. A significant proportion of paper and cardboard was also a characteristic for Kiev (Ukraine) and St. Petersburg (Russia). It was found that the MSW moisture content was based on the food waste composition as well as winter decreases in MSW. Seasonal changes in MSW calorific value (in separate waste collection) for Kaunas (in 2010) ranged from 8 MJ / kg to 12 MJ/kg.

Researchers from the University of Oviedo (Spain) carried out experimental studies to determine MSW composition, moisture, ash, and calorific value in an annual cycle – summer, autumn, winter and spring (Castrilllon, et al. 2013). They analysed twelve samples of 250–300 kg each per season and discovered that the MSW composition values changed significantly by seasons. For example, the plastic content amounted to 8.6% in summer and 12.2% in winter. The MSW moisture content in the rainy season (spring) was higher (32%) than in the dry season (summer) when the moisture content was 25%. Seasonal changes in the calorific value ranged from 10 MJ/kg in summer to 11.7 MJ/kg in autumn. The MSW moisture and ash content, and the calorific value were determined for each season.

A specific calorific value of MSW is an important parameter of thermal treatment systems, in particular at incineration plants (IP) for energy recovery (Vlaskin, et al. 2016). Untreated MSW calorific value is about 9.0 MJ/kg (Zhao, 2016). According to the World Bank (Rand, et al. 2000), MSW calorific value should be 7 MJ/kg on average, but not lower than 6 MJ/kg at any time of the year, so that waste can be burnt at incineration plants without additional caloric fuel. However, at modern incineration plants in Europe, the lowest MSW calorific value is much higher and usually exceeds 10.0 MJ/kg. For example, the MSW low calorific value at an IP in Naples (Italy) is 15.1 MJ/kg; in Aarhus (Denmark), it is 10.5 MJ/kg; and in Berlin (Germany), it is 14.5 MJ/kg. Rather high calorific values are achieved through the preliminary sorting of MSW (i.e., separation of combustible components) and the preparation of MSW for incineration, which includes drying, crushing, and further steps (Main, Maghon, 2010). The study (Komilis, et al. 2014) shows that moisture content affects the self-sustaining flammability and calorific value of MSW. Therefore, the predominance of components with a higher or lower moisture value can either intensify or slow down thermal treatment processes (Gorinov, et al. 2010). The main objectives of the study were the following: (a) to measure changes in the composition of MSW by season; (b) to determine moisture and ash content of MSW components by season; (c) to calculate thermal properties by season on the basis of moisture and ash values in MSW.

Methods

Waste composition analyses

Experimental studies of waste were carried out to determine MSW components and the fractional composition in the city of Perm, Russia. The research was based on earlier methodological approaches which outlined key parameters: the list of components, accuracy and margin of error, sampling location, source stratification, time indicators, minimum sample mass, total number of samples, requirements for instruments, and methods of processing primary data (Ilinykh, et al. 2012). The studies were conducted in every season of the year (spring, summer, autumn, winter) for 7 days with daily sampling and analysis of 5 waste samples, which were taken from waste bins of households after some degree of sorting at the source. The samples' weight of 100 ± 20 kg was determined by the research requirements. Technical scales with accuracy up to 0.02 kg were used for weighing samples. Sieves with cells of several sizes, i.e., 250, 80, 20 mm, were used to determine the fractional composition of MSW. The overall list of components included 41 items, which were divided into 13 categories (organic waste, wastepaper, plastic, glass, metals, textiles, wood, composite materials, hazardous materials, inert materials, other materials, fines, and "water"). The category of "water" was additionally made up of water from bottles, cans, and containers since its evaporation consumes heat and thereby decreases total calorific value of MSW (Polygalov, et al. 2018).

Moisture and ash content of MSW components, calculation of MSW calorific value

Sampling for laboratory studies of moisture and ash was carried out in accordance with GOST 33626-2015 "Solid fuel from household waste. Sampling methods" (EN 15442: 2011). To ensure representativeness, sample preparation of components for laboratory analyses was carried out in accordance with GOST 33509-2015 "Solid recovered fuel. Methods of laboratory sample preparation "(EN 15443: 2011). Laboratory studies of the moisture content of MSW individual components were performed according to GOST 33512.3-2015 (EN 15414-3: 2011) "Solid recovered fuels. Determination of moisture content using the oven dry method. Part 3. Moisture in general analysis sample". The MSW ash content was tested according to GOST 33511-2015 (EN 15403: 2011) "Solid recovered fuel. Determination of ash content". Integral moisture or ash content of MSW was calculated as an average based on the proportion of individual components in MSW and moisture or ash content of individual components. Moisture and ash content of hazardous materials were not determined.

The lowest MSW calorific value was calculated with the formula proposed by the All-Russian Thermal Engineering Institute (Tugov 2012). It is based on the

MSW composition as well as the moisture and ash content of the individual components:

$$Q_i^r = \sum[K_n^r (1 - W_{tn}^r/100)(1 - A_n^d/100) \times Q_{in}^{daf}] - 0.02442 \times \sum(K_n^r \times W_{tn}^r) \quad (1)$$

Where: Q_i^r – MSW calorific value, MJ/kg
K_n^r – component fraction, %
W_{tn}^r – moisture, %
A_n^d – ash in dry mass, %
Q_{in}^{daf} – low calorific value on dry ash-free mass, MJ/kg.

Table 1. *Summary data of MSW samples in the city of Perm, Russia*

Season	Mass, kg			
	> 250 mm	80–250 mm	0–80 mm	Total
Summer	446.3	1,592.7	848.1	2,887.1
Autumn	370.3	1,400.4	1228.3	2,998.9
Winter	440.7	1,652.4	795.9	2,889.0
Spring	194.4	1,705.6	919.5	2,819.5
Total	1,451.7	6,351.1	3,791.7	11,594.5

Results and Discussion

MSW component and fractional composition

A total of 140 MSW samples (about 11.6 tons) were selected and sorted in the city of Perm, Russia within an annual cycle in order to obtain accurate and reliable information on MSW.

Table 1 presents the percentage of fractions of different sizes in the MSW total mass: a coarse fraction over 250 mm, 250–80 mm and 0–80 mm, which account for 13%, 55% and 33%, respectively.

Based on field studies, an individual fraction component composition was calculated for each sample and a MSW component composition was calculated in each season of the year. The results were averaged by the number of days sampled for the particular waste category.

The consolidated calculations are summarised in 13 categories and are presented in Table 2.

Table 2. *Seasonal variation in MSW component composition in the city of Perm, Russia*

Name	Content, wt.%				
	Summer	Autumn	Winter	Spring	Average
Organic waste	25.8	31.5	19.0	17.0	23.3
Paper	9.3	9.7	17.4	21.4	14.5
Plastics	15.9	17.2	22.0	25.6	20.1
Glass	12.2	10.3	12.5	8.9	10.9
Metal	1.8	1.6	1.6	1.3	1.6
Textiles	5.0	2.1	3.8	2.8	3.4
Wood	1.3	0.8	2.5	1.7	1.6
Composite materials	1.1	1.4	1.9	1.7	1.5
Hazardous materials	1.3	0.7	0.7	0.7	0.8
Inert materials	1.8	2.2	2.4	1.5	2.0
Other materials	6.3	6.6	5.2	5.2	5.8
Fines*	18.2	15.8	10.9	11.9	14.2
Extra (water)	0.0	0.1	0.2	0.3	0.2
Total	100.0	100.0	100.0	100.0	100.0

** fraction under 20 mm*

The studies of the MSW component composition show that MSW material potential (the total content of waste paper, plastics, metals and glass) is about 47%.

The analysis of the MSW composition by season established changes in the content of individual components. Seasonal changes in the MSW composition are characterised by:

- high content of organic waste in the composition of MSW in autumn (about 32%), which is associated with an increase in the consumption of vegetables and fruits in this season (spring organic waste content is 1.8 times lower than in autumn);
- an increase in the amount of fines in summer by almost 1.7 times compared with winter, since in summer, the maximum amount of small inert fraction (sand) is gathered from the territory;
- a 2.2–2.3 times increase in the amount of waste paper in spring compared with autumn and summer seasons;
- high content of plastics in spring make up about a quarter of the MSW total composition, while the minimum content of plastics in summer is about 16%;
- relative stability of glass content in MSW throughout different seasons of the year (from 9% in spring to 13% in winter, with an average of 11%).

The waste composition in the annual cycle was broken down into 23.3% of organic waste, 20.1% of plastics, 14% of paper, and 14.2% of fines. Plastics were mainly represented by polyethylene and polypropylene films (about 37–57% of all plastics contained in MSW). Among the selected waste paper fractions, the "other paper" category (about 30–42%), which has a low resource potential was the most significant. Sorting out glass (8.8–12.5%) by color showed that about 50% of the entire glass category was transparent. The metal content in the MSW was about 1.3–1.8% and was mainly represented by tin cans (49.6–54.2% of the total metal).

It is important to note that within seasons both components' weight fraction and their composition undergo changes. For example, plant waste in autumn is represented by tree foliage, in spring by dry grass from the territories, and in summer and winter by dead flowers. These features significantly change the thermal properties of both individual components and waste as a whole. Therefore, it is critical to conduct seasonal studies not only of MSW composition but also of their thermal properties.

MSW moisture content by seasons

Laboratory studies proved that the moisture of individual components varies by season. Table 3 presents

Table 3. *Seasonal variation in MSW component moisture content*

Name	Content, wt.%				
	Summer	Autumn	Winter	Spring	Average
Organic waste	80.0	81.8	72.7	77.6	78.5
Paper	36.4	41.3	26.7	33.4	34.1
Plastics	24.4	30.7	19.7	21.8	23.3
Glass	3.5	3.5	3.5	3.5	3.5
Metal	3.5	3.5	3.5	3.5	3.5
Textiles	38.1	29.0	28.4	12.1	30.1
Wood	24.3	17.8	10.5	19.3	18.0
Composite materials	11.2	13.5	11.3	13.4	12.4
Inert materials	7.0	6.9	2.0	11.0	5.2
Other materials	16.6	24.1	19.0	21.2	20.6
Fines	45.4	65.3	55.1	56.9	55.7

the averaged values of the MSW moisture content obtained during the annual cycle (spring, summer, autumn, winter).

Organic waste and fines contribute the most to the MSW total moisture content. The organic waste moisture content varied by season: from 72% in winter to 82% in the autumn. The seasonal fines moisture content fluctuated from 45.4% to 65.3%, with the maximum in autumn. A reduction of moist waste in a season decreased the total MSW moisture content.

The highest paper and plastics moisture content was in autumn and was about 42% and 31%, respectively due to increased air humidity, precipitation, and contact with moist food waste, which was about one third of the total MSW mass.

Glass and metals moisture content is usually created by the remains of drinks in containers.

Seasonal variation in MSW ash content

Laboratory studies determined the ash content in dry mass for various MSW components which experience seasonal fluctuations during the year (Table 4).

Table 4 illustrates that waste paper had the highest ash content (at dry weight) among combustible components, which varied from 13.3% in autumn to 15.8% in winter; wood had the lowest ash content (at dry weight) which fluctuated by season from 3.0% to 12%, with an average of 5.0%; textiles had a weight from 2.9% to 9.6% (5.3% on average). However, no strong correlation between ash content and season was identified, as it was for moisture content.

Table 4. *Seasonal variation in MSW component ash content (dry mass basis)*

Name	Content, wt.%				
	Summer	Autumn	Winter	Spring	Average
Organic waste	15.0	14.2	21.9	16.5	16.1
Paper	13.6	13.3	15.8	15.5	14.6
Plastics	4.7	3.3	7.1	6.5	5.9
Glass	100.0	100.0	100.0	100.0	100.0
Metal	100.0	100.0	100.0	100.0	100.0
Textiles	9.6	3.8	2.9	5.4	5.3
Wood	11.8	3.8	4.6	3.2	5.0
Composite materials	33.7	28.8	33.5	29.2	31.3
Inert materials	100.0	100.0	100.0	100.0	100.0
Other materials	31.0	15.9	23.8	24.9	23.6
Fines	63.9	52.2	56.8	50.1	55.8

Seasonal variation in MSW component calorific value

Benchmark analysis of MSW components, as well as the moisture and ash content of individual components by all four seasons was performed on the results of laboratory studies. Figures 1–4 show the variation in the composition and the calorific value of the MSW principal components. Typical characteristics were identified for both organic waste and fines, as well as paper and plastics. The former makes up a large proportion of the MSW composition and has a high moisture value. The latter are the main combustible components in the composition of MSW.

Figure 1 presents the fluctuations of a low calorific value per organic waste working mass from 0.8 MJ/kg in autumn to 2.1 MJ/kg in winter. The low value of organic waste in autumn is caused by its high moisture content (about 82%). The decreasing moisture content of organic waste in winter increased the combustible component to 21%, which affected its calorific value.

Fig. 1. *Changes in organic waste composition and thermal properties by season*

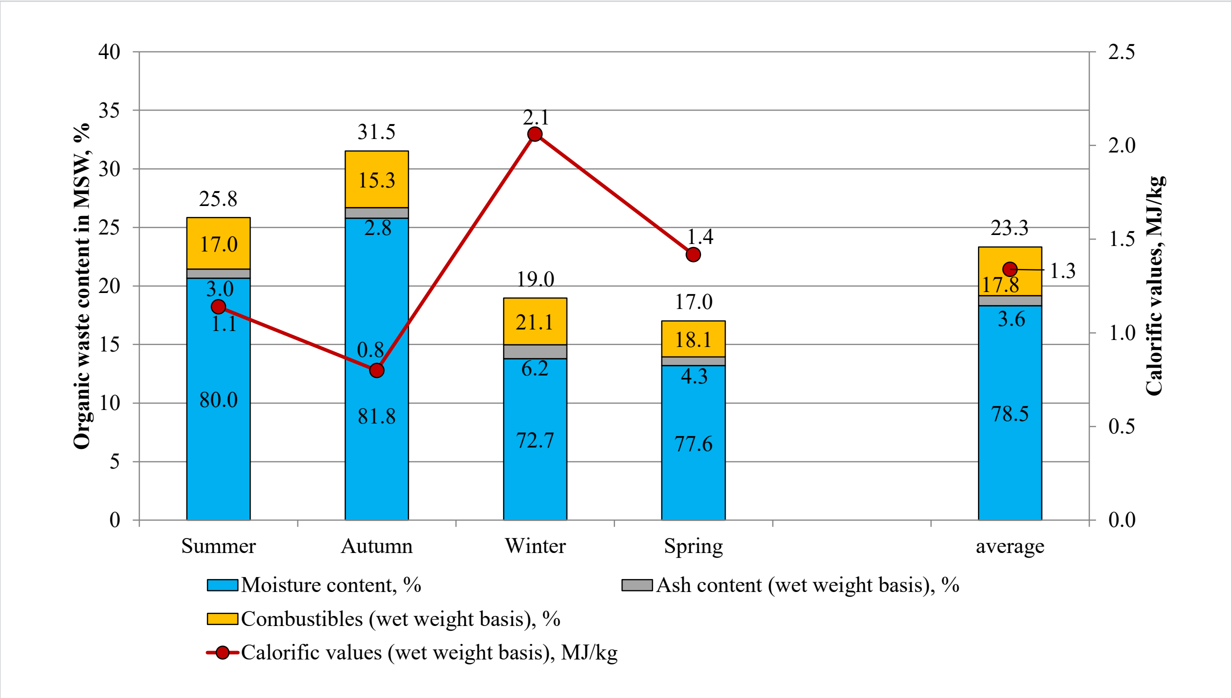


Fig. 2. *Changes in paper composition and thermal properties by season*

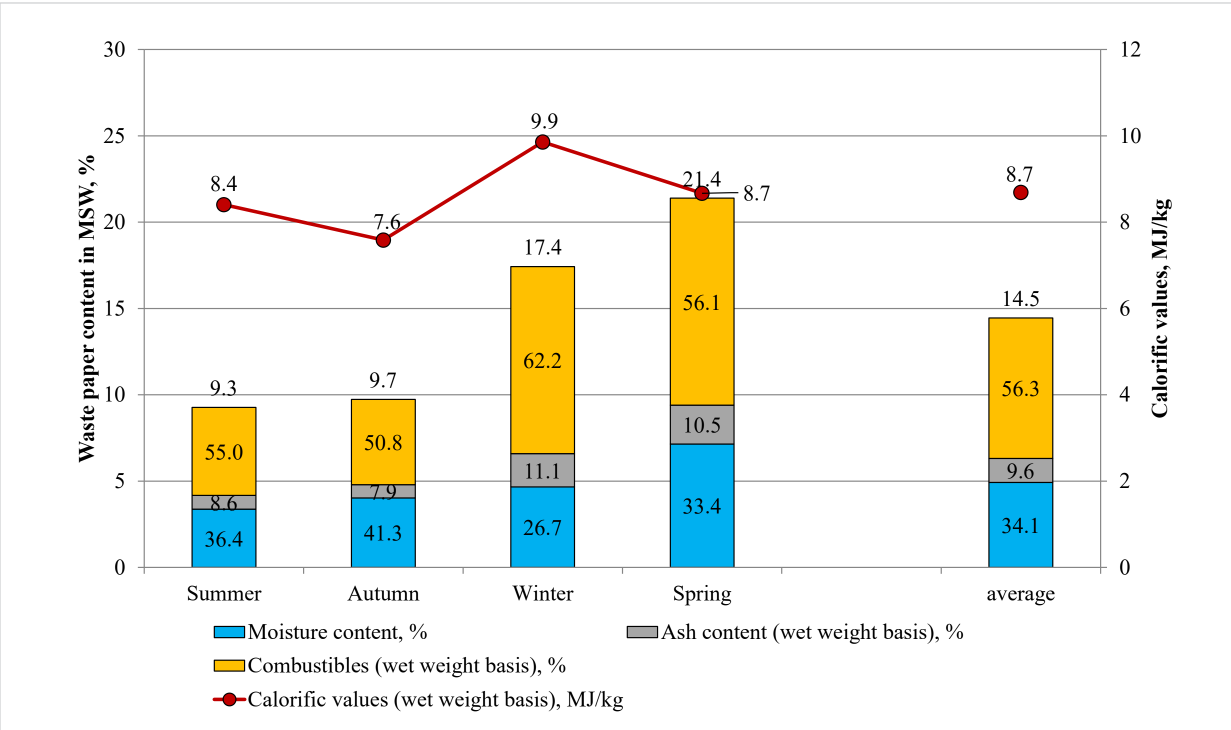


Fig. 3. *Changes in plastics composition and thermal properties by season*

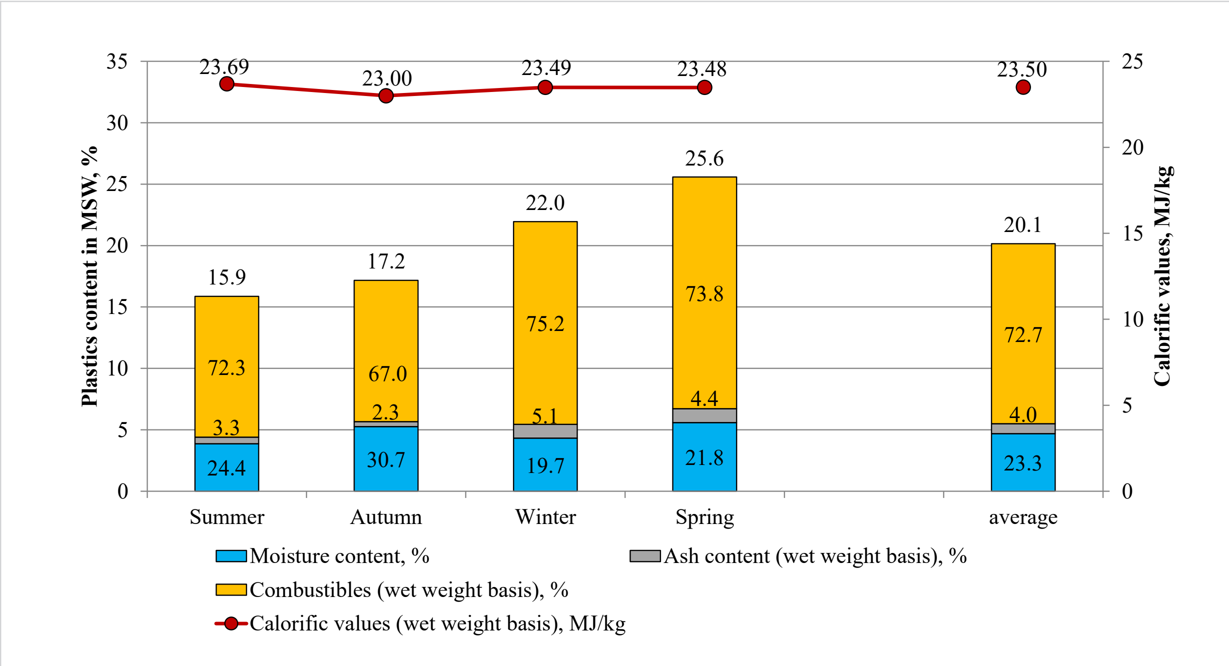
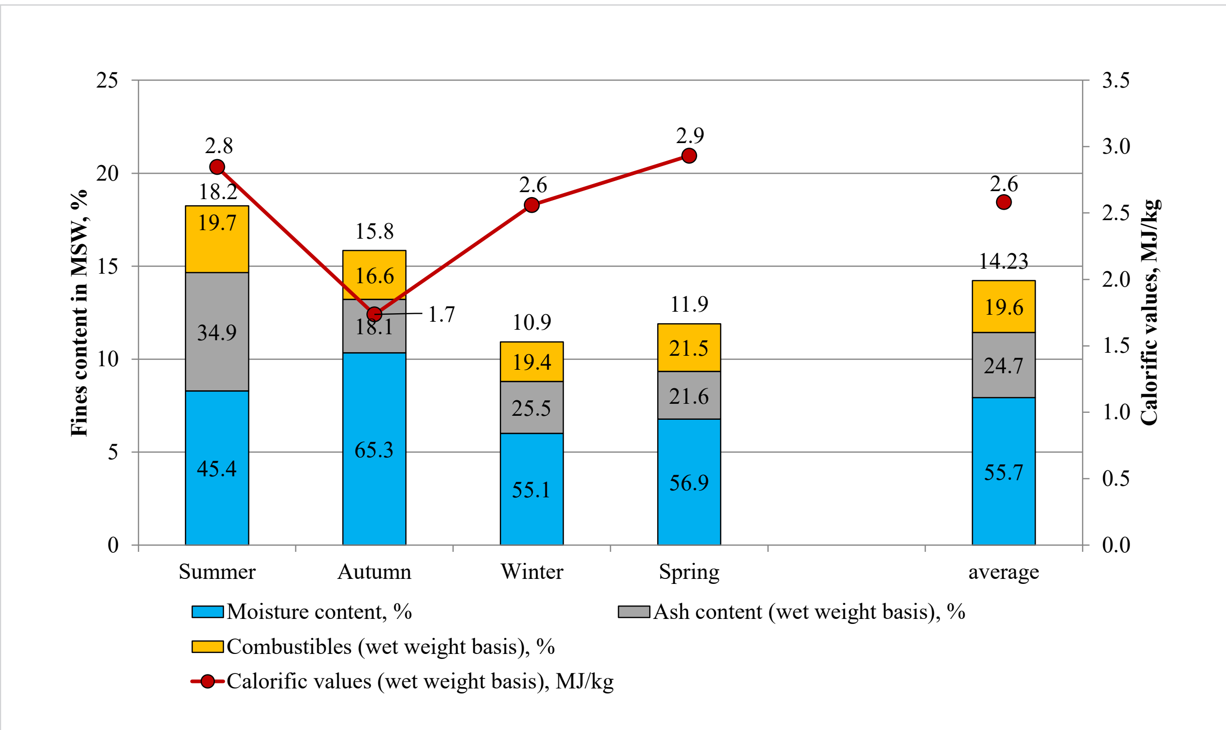


Fig. 4. *Changes in fines composition and thermal properties by season*



As stated above (Table 2), the highest moisture content of paper waste was detected in autumn. As its moisture content in spring was also high, so the calorific value reached 8.7 MJ/kg; whereas in winter waste paper was drier and the moisture index was 9.9 MJ/kg. The ash content (at wet weight) varied from 7.9% in autumn to 11.1% in winter.

Thermal properties of plastics were relatively stable over the seasons compared with other components. For example, the plastic ash content (at wet weight) did not change significantly and amounted to about 5% in each season of the year. The plastic combustible content was an average of 73%, which caused a high calorific value that underwent virtually no changes over the seasons.

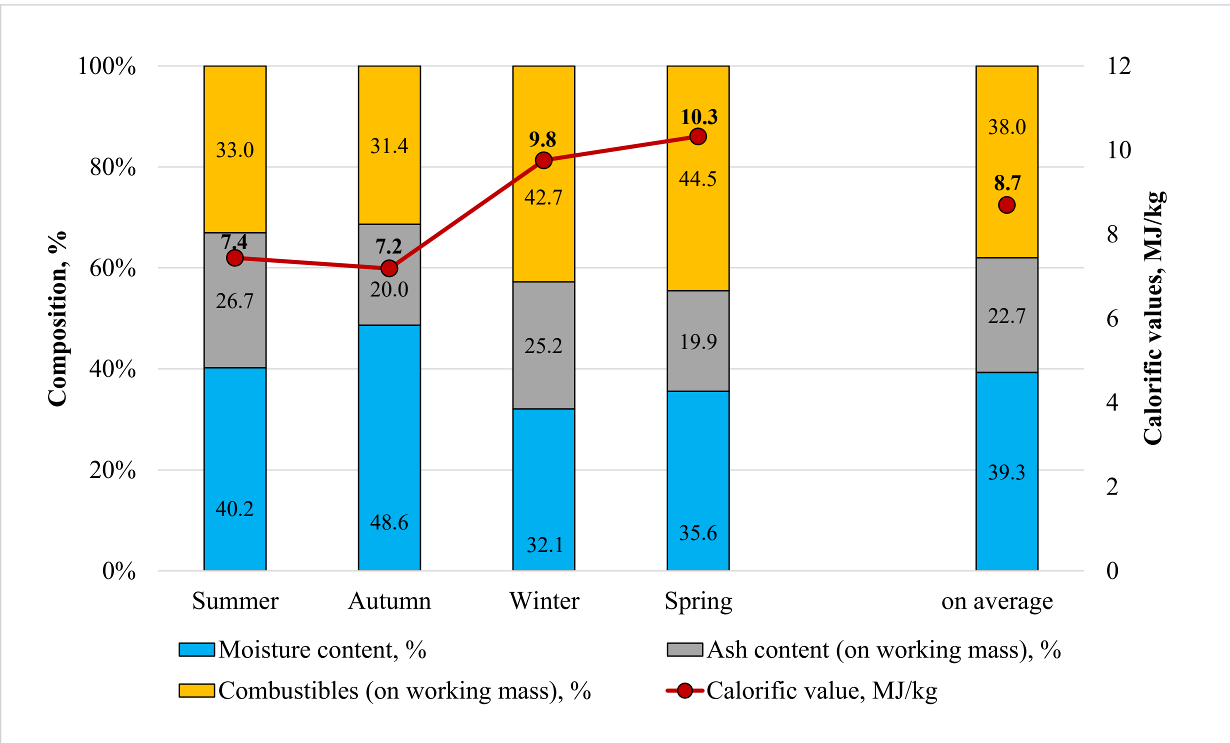
Figure 4 shows that the fines' lowest moisture content (about 45%) and the highest ash content (about 35% at wet weight) were observed in summer. This was due to the presence of sand in fines, since in this season the area is cleaned more often compared with other seasons. If we compare the ash content (at wet weight) in summer and in autumn, it is 1.9 times higher in summer. The calorific value of fines (at wet weight) ranges from 1.7 MJ/kg in autumn to 2.9 MJ/kg in spring.

Seasonal variation of MSW thermal properties

A comparative analysis of MSW thermal properties was carried out for the summer, autumn, winter and spring seasons based on studies of MSW composition, moisture and ash content of different components (Fig. 5). It was found that in autumn the waste had the highest moisture content along with the lowest ash content and calorific value.

The MSW moisture content varied by season from 32% to 49%, with most moisture found in food waste. Due to its high moisture content in its initial state, food waste has the lowest calorific value compared with other components. The percentage of food waste and fines in the total MSW moisture content in the summer and autumn seasons was about 70–80% of the

Fig. 5. *Seasonal variation of MSW thermal properties*



total waste moisture, and in winter and spring it was about 50–60%. Therefore, the higher the food waste content, the higher the MSW moisture. The total ash content (wet waste basis) ranged from 30% to 45%, and the working mass ranged from 20% to 27% due to the high content of non-combustible components (inert materials, glass, etc.).

The average annual waste moisture amounted to 39.3%, ash content amounted to 22.7%, and the calorific value was 8.7 MJ/kg. In order to determine the lowest calorific value, it is important to take into account both the MSW composition and its thermal properties by season.

The MSW calorific value in the winter and spring seasons increases in comparison with autumn, primarily due to the decrease of moist food waste.

Seasonal variations in MSW composition are quite typical for many countries and cities with significant climate fluctuations or other conditions during the year (Denafas, et al. 2011; Denafas, et al. 2010; Castrillon, et al. 2013), but such results are rather scarce in Russia. It was found that waste properties in summer, autumn and winter are dramatically different from one another, while waste in spring is more or less the same as in winter. So, in comparison with the waste composition analysis in southern countries where there are only two seasons, i.e., wet and dry (Baba, et al. 2018), investigations in countries such as Russia require at least three seasons. The results of this research also prove seasonal changes in moisture and ash content of different components. These data are especially important for waste incineration.

According to the studies of waste composition, moisture, and ash content of individual components, the lowest MSW calorific value was 24–27 MJ/kg in combustible mass, 14–18 MJ/kg in dry mass and 7–10 MJ/kg in working mass. The MSW calorific value varied in different seasons due to the changes in the MSW moisture and ash content as well as their quality properties. Therefore, it may be necessary to dry MSW at IP to a moisture content level of 30–35% so as to increase its calorific content (up to 10 MJ/kg) before burning it in the autumn and summer seasons. In winter and spring, the drying stage can be skipped, since the lowest MSW calorific value meets the standards of modern IP. The lowest MSW calorific value can be increased by the implementation of MSW treatment technologies with the extraction of waste combustible components or the removal of fines from waste.

Conclusion

The results of the MSW composition analysis in the city of Perm, Russia, differ significantly by season. For example, the organic waste and paper content in autumn accounted for 31.5% and 9.7%, respectively, and in spring for 17.0% and 21.4%, respectively. Therefore, the annual cycle of studies (summer, autumn, winter, spring) is an important aspect in waste management planning, since one-time analysis results can lead to inaccurate planning or inefficient implementation of MSW treatment and disposal technologies.

Advanced studies of individual components' thermal properties allow obtaining detailed and reliable data on MSW moisture, ash, and calorific value, which in turn facilitates designing the quality characteristics of the outward flows of a given technological line for solid waste treatment.

MSW thermal properties in the city of Perm, Russia, also differ from each other over the seasons of the year: the highest MSW moisture content was detected in autumn and amounted to about 49%, and the lowest in winter was 32%. The ash content in MSW ranged from 20% in spring and autumn to 27% in summer. The content of hazardous materials in spring was 1.5 times higher than in autumn. The lowest MSW calorific value varied from 7.2 MJ/kg in autumn to 10.3 MJ/kg in spring, with an average of 8.7 MJ/kg. The changes identified in MSW thermal properties prove that seasonal changes in the MSW composition and its properties are a principal factor in the effective implementation of energy waste disposal technologies. In the summer and autumn seasons, waste with a high moisture content may need additional drying to increase its calorific content.

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