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Analysis of the Composition and Properties of Municipal Solid Waste from Various Cities in Kazakhstan

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Abstract: According to the Bureau of National Statistics of the Republic of Kazakhstan, by the end of 2023, approximately 120 million tons of municipal solid waste (MSW) had been generated across over 3200 landfills in the country. About 4.5 million tons are generated annually, of which only about 15% are recycled. The accumulation of both unsorted and sorted waste poses significant environmental risks, primarily through the generation of methane, a greenhouse gas that is 28 times more dangerous than carbon dioxide in contributing to the planet's greenhouse effect over a century and 84 times more effective over a 20-year timeframe. The objective of this research is to examine the physicochemical composition, as well as the physical and thermal-chemical properties, of municipal solid waste from six cities in Kazakhstan: Astana, Almaty, Shymkent, Aktobe, Karaganda, and Ust-Kamenogorsk. Unlike existing studies, this study has a uniform waste sample, which includes the complete emptying of dozens of containers from different areas of the cities under consideration. Thus, the average composition of solid waste across the cities was maintained. Analysis of the physicochemical composition was conducted for both unsorted and sorted municipal solid waste from all cities, determining the total and analytical moisture content, ash content, and volatile matter, as well as the higher and lower calorific values. The calorific value of unsorted waste by city was as follows, in kJ/kg: Astana,8850.37; Almaty, 9244.57; Atobe, 9596.41; Shymkent, 9425.48; Karaganda, 8902.8; Ust-Kamenogorsk, 9669.07. The calorific value of sorted waste was as follows, in kJ/kg: Astana, 11,922.79; Almaty, 11,692.31; Atobe, 11,913.13; Shymkent, 12,494.38; Karaganda, 11,671.92; Ust-Kamenogorsk, 12,462.52. The efficiency of sorting was estimated as the first stage of MSW processing. The efficiency factor of the manual sorting process in practice was 0.4–0.8. The results obtained enable the evaluation of technologies for the effective management of municipal solid waste and facilitate experimental investigations into semi-industrial pyrolysis, combustion, plasma processing, and composting facilities.

Keywords: waste-free production; waste recycling; household waste; pyrolysis; energy-efficient technologies; synthesis gas; thermal energy; methane; carbon dioxide; greenhouse gases

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1. Introduction

According to data from the Bureau of National Statistics of the Republic of Kazakhstan, by the end of 2023, approximately 120 million tons of municipal solid waste (MSW) had accumulated in over 3200 landfills across the country [1]. Annually, around 4.5 million tons of waste are generated, with only about 15% being recycled [2]. The continuous accumulation and storage of both unsorted and sorted municipal solid waste leads to significant environmental repercussions, including the release of greenhouse gases such as methane (contributing 50% to 75%), carbon dioxide (25% to 50%), and water vapor, along with nitrogen oxides, hydrogen sulfide, and organic matter (approximately 5% to 15%) [3]. Methane is particularly concerning, being 28 times more effective than carbon dioxide in contributing to the greenhouse effect over the next century, and 84 times more effective over a 20-year period [4]. Carbon dioxide poses its own risks due to its long atmospheric lifespan, during which it influences various processes. Since 1750, the concentration of CO_2 in the atmosphere has increased by nearly 50% [5]. Furthermore, the greenhouse potential of nitrogen oxides surpasses that of carbon dioxide by a factor of 264 and negatively impacts the planet's ozone layer [5].

There are various technologies for the disposal of solid municipal waste:

- composting [6];
- pyrolysis [7];
- plasma treatment [8,9];
- incineration [10].

Composting of MSW—the method involves biological processing utilizing anaerobic microorganisms, representing an exothermic biooxidation process of the organic components within waste. Exothermicity is achieved by a biological oxidation process in which the organic substrate is subjected to aerobic biodegradation by a mixed population of microorganisms, resulting in an increase in temperature under humid conditions. The application of this technology yields up to 50% biofertilizers (compost), as well as approximately 50% of various gases (such as biogas and carbon dioxide) and up to 10% of other byproducts.

There are two types of composting: aerobic composting [11] and industrial composting of solid waste [12].

Anaerobic bacteria proliferate during the aerobic composting process as decomposition occurs within the deeper layers of waste, accompanied by fermentation that generates thermal energy [11]. Consequently, insect eggs, helminth eggs, and larvae, along with pathogenic microorganisms, are eliminated due to exposure to temperatures ranging from 50 to 70 °C. The decomposition of solid waste results in the release of carbon dioxide and water vapor.

Disadvantages of the method: active emission of greenhouse gases without their utilization.

Industrial composting of solid waste has been developing since the 1930s [12]. It has become popular in such EU countries as Denmark, Austria, Germany, Belgium, and the Netherlands [13], where a total of about 400 recycling enterprises operate.

Centralized composting can be categorized into three distinct technologies:

- In piles in field conditions [14];
- In a static stack [15];
- In a horizontal reactor [16].

Composting in piles (roll-shaped heaps) means that waste is placed in the air and regularly turned over by special machines. A pile is created up to 3 m high, 3 to 6 m wide and several hundred meters long. Oxidation of organic matter occurs at a depth of 1 m, where air with oxygen freely flows.

Disadvantages of the method:

- The compost formation period is from 4 to 6 months or more;
- A large area is required for composting;
- Spread of unpleasant odor, spillage of filtrate, etc.

Pyrolysis of MSW is the thermal decomposition of the organic part of waste in the absence or lack of oxygen, resulting in the formation of pyrolysis gas and solid carbon residue [17]. The amount and composition of pyrolysis products depends on the composition of the waste and the decomposition temperature. The use of pyrolysis instead of waste incineration allows for a sharp reduction in the volume of gas emissions and the content of toxic components in them.

Pyrolysis is noted for its versatility, enabling the generation of a combination of solid, liquid, and gaseous products in varying proportions simply by adjusting operational parameters such as temperature or heating rate. The thermal decomposition of waste can be conducted in a manner that either minimizes or completely eliminates the production of resin, or it can be optimized to produce resin as one of the desired end products [18]. Pyrolysis facilities are classified based on the thermal conditions under which the process operates [19]:

- low-temperature (450–500 °C), characterized by minimal gas output, maximum amount of resins, oils, and solid residues [20];
- medium-temperature (up to 800 °C), characterized by increased gas output with reduced amount of resins and oils;
- high-temperature (over 800 °C), characterized by maximum gas output and minimum amount of resins [21].

Technologies for the disposal of MSW using the pyrolysis method are highly environmentally sustainable.

The operating principle of the *plasma treatment facility for MSW* is to expose waste to extremely high temperatures of at least 1200 °C, while isolating oxygen, creating optimal pressure and treating the waste mass with a low-temperature plasma flow [22]. Strict adherence to temperature conditions allows for avoiding the appearance of a liquid fraction in the synthesis gas during the disposal process, as well as resin, which is formed when processing waste at lower temperatures. Moreover, the application of exceptionally high temperatures enables the complete breakdown of toxic or resistant waste components and prevents the formation of particularly hazardous substances [23].

The operational principle of a plasma gasification facility can be outlined as follows [8,9]:

- Waste is placed in the loading shaft. The feeding process occurs through a sealed accumulation lock, where both the speed and volume of waste inflow are controlled.
- Air and water vapor are supplied to the reactor, where the mixture is then processed using a low-temperature plasma flow.
- The supply of synthesis gas from the bottom of the reactor chamber is carried out continuously.
- The resulting synthesis gas can subsequently be directed to a gas boiler for combustion, or it can be routed to a quencher for cooling, followed by cleaning and filtration.
- Following the cleaning process, the synthesis gas is directed to a compressor, where moisture is removed, filtered, and subsequently supplied to a gas turbine.
- The ash residue and certain non-combustible materials settle at the bottom of the water tank, where the slag cools before being removed.

For continuous operation of a plasma gasification plant, it is necessary to constantly maintain the plasma jet, as well as periodically supply the air-steam mixture and monitor the level of waste in the reactor as it is converted into synthesis gas.

Advantages of plasma processing:

- The processing is carried out at extremely high temperatures—more than 1200 °C, due to which organic and inorganic waste decomposes without releasing toxic hazardous dioxins and furans into the atmosphere. The emission of hazardous substances is kept to a minimum due to the influence of plasma flows and the specialized design of the reactors.
- Leaching does not occur during the recycling process because the waste is dried and crushed prior to being introduced into the reactor.
- Plasma recycling is a closed process, without the need for waste storage. Incoming waste is immediately sent for recycling and is not stored to await processing.
- Plasma recycling of waste is a double benefit, since waste is safely destroyed, and the energy obtained can be used not only for the operation of the station, but also for the needs of the population.
- As a result of recycling, a solid residue is obtained from the waste. The volume of slag obtained is approximately one tenth of the original amount of waste.

Disadvantages of plasma processing:

- The solid residue is subject to special disposal.
- The operation of the plasma generator requires a lot of electricity costs.
- The use of this method involves the complete destruction of the category of waste that can be used as secondary raw materials.
- The specific costs of purchasing equipment and operating costs are higher than with other methods of waste disposal, therefore the payback period is longer.

The technology of incineration of solid municipal waste includes the following stages [10,24]:

- Sorting of waste in order to isolate components that can be used as secondary raw materials; separation of components that are not incinerated (metal, batteries, etc.), as well as those prohibited for incineration (plastic, mercury-containing, etc.) [25].
- Low-temperature pre-treatment of solid waste [26].
- Incineration of sorted solid municipal waste to obtain electrical energy [27].

Scientists of the Republic of Kazakhstan have developed technologies and solutions for the complete utilization of gaseous, liquid, and solid waste generated during the incineration of sorted solid municipal waste. This innovation has led to a waste-free approach for disposing of solid municipal waste.

To determine the appropriate disposal technology, information on the composition and characteristics of solid municipal waste is required. In the Republic of Kazakhstan, each city has its unique average waste composition, which varies from that of other cities.

The purpose of the research is to analyze the physicochemical composition and physical and thermal properties of solid municipal waste from six cities in Kazakhstan: Astana, Almaty, Shymkent, Aktobe, Karaganda, and Ust-Kamenogorsk.

Unlike existing studies, this study has a uniform waste sample, which includes the complete emptying of dozens of containers from different areas of the cities under consideration. Thus, the average composition of solid waste across the cities was maintained.

As stipulated in the Environmental Code of the Republic of Kazakhstan, enacted in 2021, certain components of MSW are not subject to energy utilization [28]:

- Liquid waste [29];
- Hazardous waste that is explosive, corrosive, oxidizable, highly flammable, or flammable [30];
- Waste containing persistent organic pollutants [31];
- Mercury-containing lamps and devices [32];
- Electronic and electrical equipment [33];
- Scrap of non-ferrous and ferrous metals [34];
- Lithium batteries, lead-acid batteries [35];
- Construction material waste [36].

The disposal of all listed materials must be carried out by licensed enterprises using specially approved technologies.

Currently, the population lacks accountability for the mixed waste deposited in collection bins, leading to all solid waste arriving at the sorting facility together. Despite the fact that items like light bulbs, devices, batteries, and construction waste should not be placed in solid waste bins, individuals still occasionally dispose of these prohibited materials in the bins.

On the other hand, at existing solid waste sorting plants, the percentage of sorting is only about 12%, with the required minimum being about 40%. In other words, it is currently impossible to predict the composition of even sorted solid waste planned for disposal.

Garbage collection occurs only in larger settlements, while rural areas often lack such services. Additionally, waste sorting facilities have not been established in every city.

The results obtained enable the analysis of technologies for the efficient disposal of solid municipal waste, as well as the conduction of experimental studies on semi-industrial pyrolysis, combustion, plasma processing, and composting facilities.

2. Materials and Methods

2.1. Theory

Figure 1 illustrates the share of the population coverage of the Republic of Kazakhstan in terms of volumes of MSW collection. Figure 2 shows the share of MSW recycling.

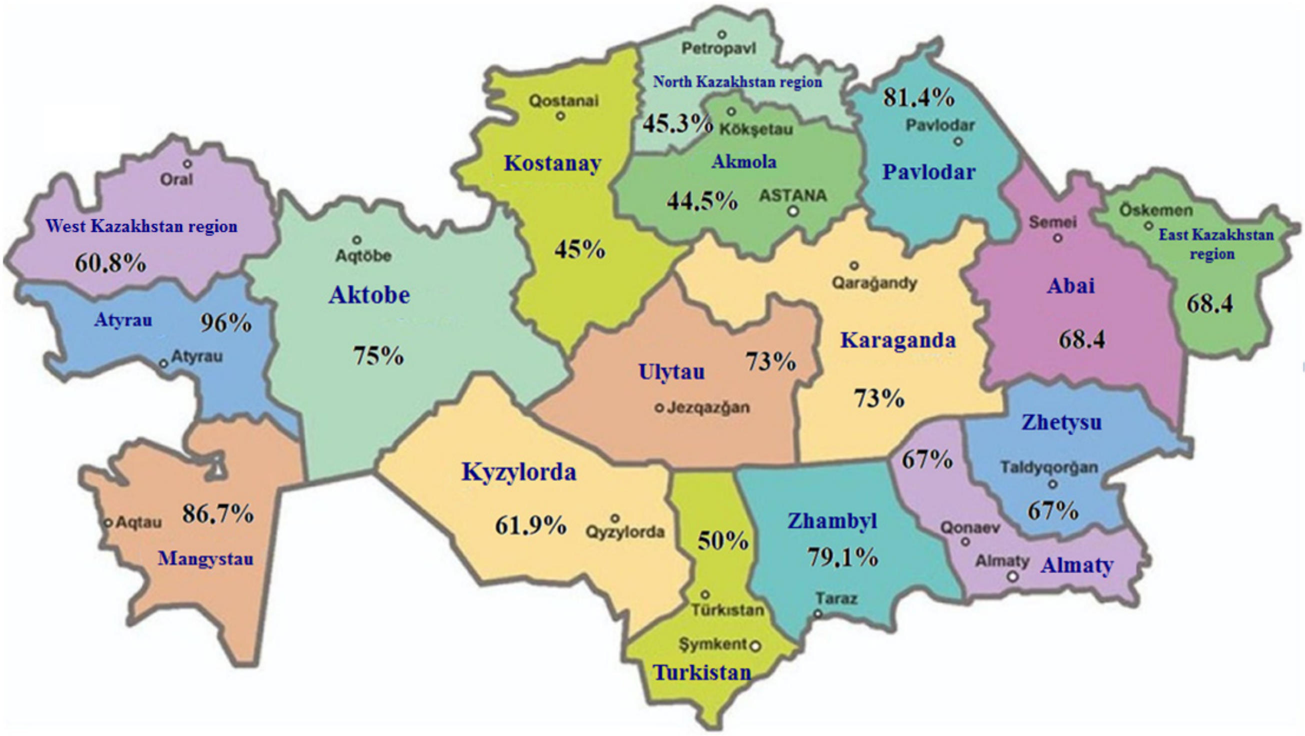

Figure 1. Proportion of the population covered by MSW removal services in the Republic of Kazakhstan.

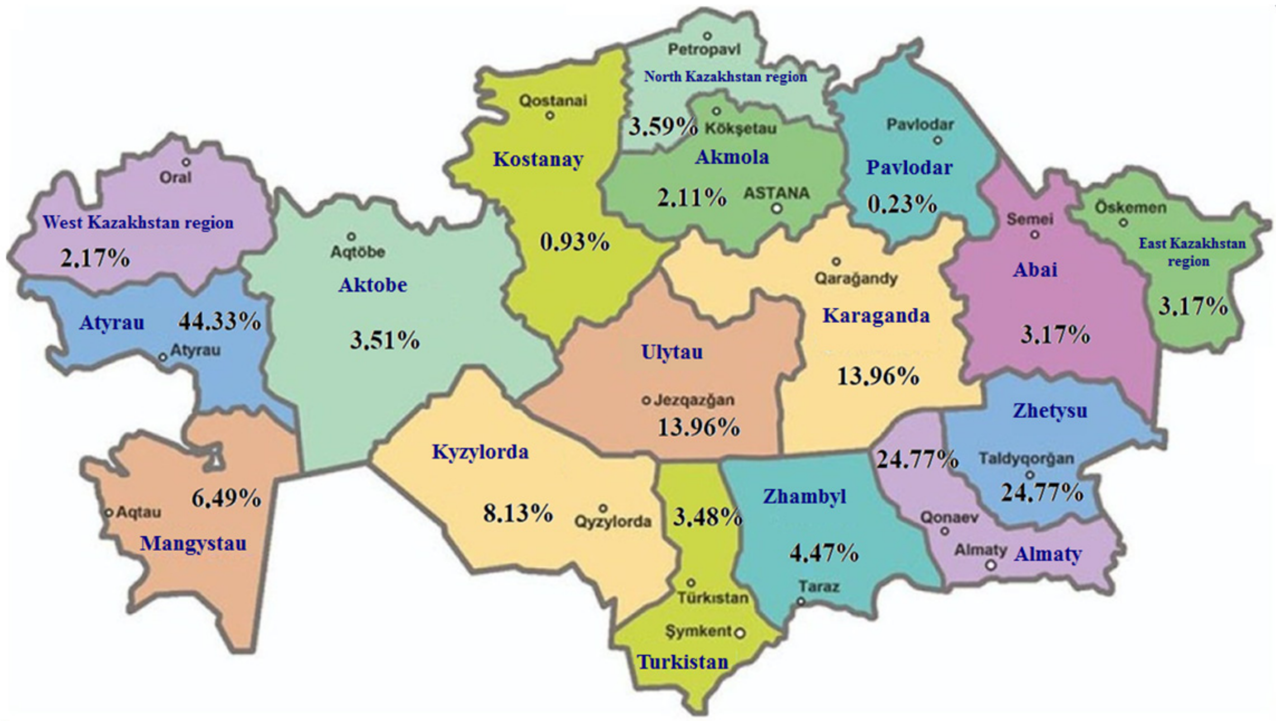

Figure 2. The proportion of MSW recycling across the regions of the Republic of Kazakhstan.

Assessing the physicochemical composition of MSW should come before formulating a waste management strategy for a city or region. Accurate and reliable data on waste composition are essential for evaluating its resource (material and energy) potential and justifying the adoption of specific technologies for utilization or disposal. Specifically, understanding the presence of individual components enables predictions regarding the environmental and economic effectiveness of waste sorting, composting, or incineration [28].

The planning of strategies for the recovery of secondary raw materials and energy from MSW must be grounded in comprehensive data regarding their composition and properties. Consequently, investigations into the quantitative and qualitative characteristics of waste are of significant importance [37].

Research on the physicochemical composition of waste can be used to assess the thermal properties of solid waste, which are essential for evaluating its energy potential and the suitability of thermal processing methods for recovery and utilization, as well as the feasibility of producing secondary fuel [38]. In this regard, the relevance of adequate methods for calculating the thermal properties of solid waste based on their physicochemical composition increases.

The main thermal properties of solid municipal waste include moisture, ash content, and calorific value.

All moisture contained in waste is divided into external and hygroscopic [39]. External moisture is moisture lost by a substance when drying it to an air-dry state. Air-dry waste is conventionally considered to be waste that does not change its weight at room temperature (about 15–20 °C) and normal relative humidity (50%). Hygroscopic moisture is the moisture lost by an air-dry substance when dried at 105 °C. It represents the water vapor that is firmly retained by the particles.

Measuring external humidity is a labor-intensive process that necessitates the use of specialized drying cabinets and the analysis of large samples over extended periods (5–8 days). As a result, the total humidity of the waste is typically assessed instead. Total humidity is calculated as the ratio of the difference between the initial mass of the waste sample and the mass of the dry sample to the initial mass of the waste sample. The ratio of external humidity to total humidity generally falls within the range of 0.8 to 0.9, with an average of approximately 0.85 [37].

The moisture content of waste is influenced by various factors, such as air humidity, precipitation, and the collection system in use, as well as the physicochemical composition of the waste itself. Certain components of MSW, like food waste, can have high moisture content (ranging from 60–70%), whereas the moisture content of other materials, such as glass and PET bottles, can be considered negligible [37].

Ash content is usually defined as the percentage of non-combustible (anhydrous mass) residue that is created from mineral impurities in fuel during its complete combustion. Ash content has a direct impact on biomass pyrolysis [40]. In laboratory conditions, the ash content of MSW is determined gravimetrically by the difference in the mass of the original MSW and the ash residue when burning a dry waste sample.

The calorific value is measured in terms of the higher heat of combustion (higher calorific value), which represents the total heat released during the complete combustion of a substance, including the heat of condensation of water vapor during the cooling of combustion products. Alternatively, it can refer to the lower heat of combustion (lower calorific value), which is the heat released during complete combustion, excluding the heat of condensation of water vapor [41].

The gross calorific value Q_{GCV} and lower calorific value Q_{LCV} (in kJ/kg) of combustion are related by the ratio

$$Q_{LCV} = Q_{GCV} - 25.1 \cdot (9H + W), \quad (1)$$

where $25.1 \cdot (9H + W)$ is the heat expended on the evaporation of moisture W (kg/kg) of the substance and water formed during the combustion of hydrogen H (kg/kg) of the combustible substance, kJ/kg. Moisture W and hydrogen H can be found in Table 1.

The experimental method for determining the higher calorific value is based on the complete combustion of the waste mass in a calorimetric bomb. The lower calorific value is recalculated using Equation (1). However, this requires the preparation of a laboratory sample of MSW weighing several grams, which should be representative of the composition of all MSW. In this regard, various approaches have been developed to assess the calorific value indirectly through moisture, ash content, and the calorific value of individual components.

In the absence of data on the elemental composition of solid waste, data on the gross formulas of individual components are used.

The All-Russian Thermal Engineering Institute ("VTI" JSC) has developed a method for the experimental determination of the main thermal characteristics of solid waste [37]. The method involves identifying groups of components (such as paper, textiles, plastics, metals, other inorganic materials, and food waste) and determining their mass fractions within the overall waste stream. Subsequently, under laboratory conditions, the moisture and ash content per dry mass of each group are measured, and the overall specific heat of combustion for each group is calculated (Table 1).

The extended list of components of the MSW composition allows for a more accurate determination of the combustion heat for each component.

The results derived from reference data on the properties of an extended list of components yield a gross calorific value (12,100 kJ/kg) [42]. This discrepancy can be attributed to the overestimation of the combustion heat values for individual components and the underestimation of their moisture content.

Table 1. Concentration of individual elements within the composition of MSW.

MSW Component Name	Humidity, %	Ash Content per Row Mass, %	Elemental Composition Based on Dry, Ash-Free (Combustible) Mass, %					Lower Calorific Value Q_{LCV}, kJ/kg	References
			C	*H*	*O*	*N*	*S*		
Paper	6.0/24	6.0/4.8	40.7/32.8	5.6/4.6	41.2/33.4	0.3/0.3	0.2/0.1	22.4/13.5	[43–45]
Plastic	2.0/13.3	10.0/4.7	58.7/67.5	7.0/10.2	22.3/3.9	0/0.2	0/0.2	27.8/33.4	[43–45]
Food waste	70.0/65.4	5.0/3.8	12.6/15.8	1.7/2.4	9.9/11.3	0.7/1.2	0.1/0.1	3.1/7.3	[43–45]
Textile	10.0/12.4	2.5/5.9	49.4/44.9	5.9/5.7	28.0/27.9	4.1/2.9	0.1/0.3	23.5/20.4	[43–45]
Wood	20.0/14.8	1.5/2.4	39.5/39.9	4.7/5.1	34.1/37.1	0.2/0.6	0.1/0.1	19.8/16.8	[43–45]
Rubber	2.0	10.0	86.2	1.1	0	0.2	0.5	29.9	[43]
Leather	10.0	10.0	53.4	7.1	10.3	8.9	0.4	23.4	[43]
Disposable diapers	66.9	1.4	16.1	2.5	12.9	0.2	0.1	7.5	[45]
Inert materials	0	100	0	0	0	0	0	0	[45]
Fine fraction (screenings)	33.0/41.1	34.2/15.0	19.0/22.1	2.4/3.1	10.1/17.5	0.6/0.9	0.7/0.3	7.3/9.6	[44,45]
Solid fuel from waste (SFW)	15/7.3	8.4/14.0	45.5/43.7	6.4/5.8	24.0/28.5	0.5/0.5	0.2/0.2	20.2/18.7	[44,45]

On the other hand, these calculations also consider the contributions of less significant components in terms of calorific value (such as combined packaging like "Tetra Pak" diapers, etc.), in addition to the "traditional" calorific fractions (like waste paper and polymers). Collectively, these components contribute to an overall increase in the total calorific value of MSW by 10–15%. Thus, the assessment of the thermal properties of MSW by calculation can be performed using different methods, which can give different results. In this case, it is necessary to critically assess possible errors and inaccuracies, as well as the reasons for their occurrence, so that the calculations performed are sufficiently reliable. The calculations performed confirm that, when assessing calorific value, the key initial data are information on the content of individual components, including not only those significant in content and calorific value, but also others contained in relatively smaller quantities.

The physicochemical composition of fuel can be determined in various types of masses: row mass components (r), analytical mass components (a), dry mass components (d), dry ash-free (combustible) mass components (daf) and organic mass components (o) (Figure 3).

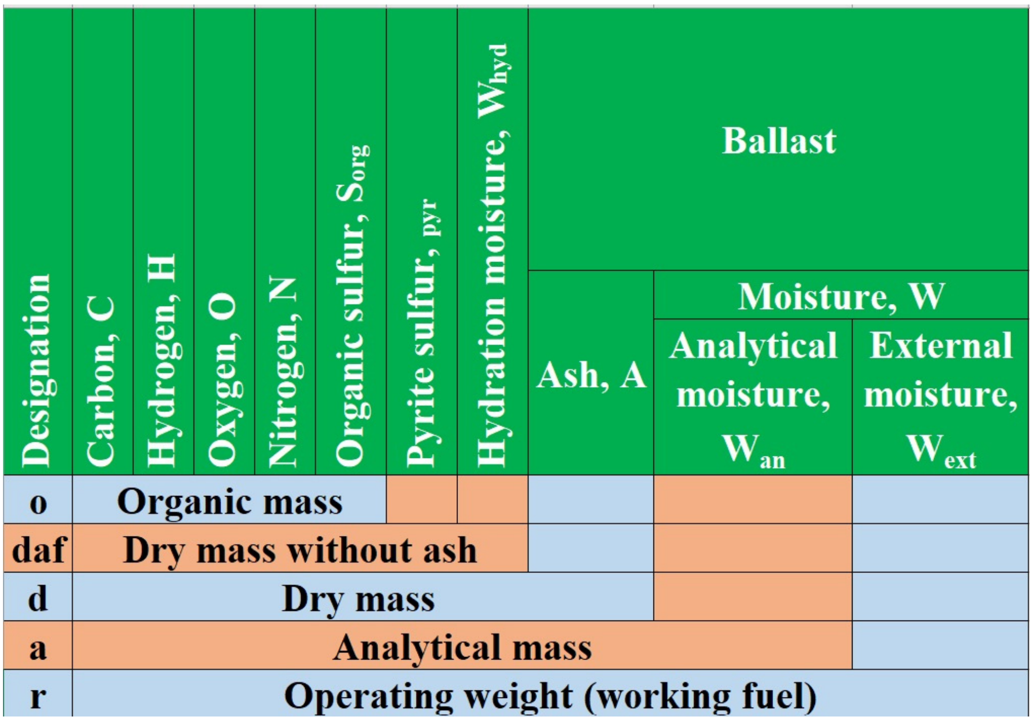

Figure 3. Physicochemical composition of fuel.

The lower calorific value Q_{LCV} per dry ash-free (daf) mass of MSW is calculated using the equation:

$$Q_{\mathrm{LCV}} = 4.1868 \cdot [81 \cdot C^{\mathrm{daf}} + 246 \cdot H^{\mathrm{daf}} - 26 \cdot (O^{\mathrm{daf}} - S^{\mathrm{daf}})]\ \mathrm{kJ/kg}, \quad (2)$$

Content of carbon C^{daf}, hydrogen H^{daf}, oxygen O^{daf} н, and sulfur S^{daf} can be found in Table 1. The lower calorific value per row components (r) from the dry ash-free calorific value (daf), is recalculated using the formula:

$$Q^{r}_{LCV} = Q^{daf}_{LCV} \cdot \frac{100 - W^{r} - A^{r}}{100} - 25 \cdot W^{r},\ \mathrm{kj/kg} \quad (3)$$

The total fuel moisture per row components W_{total} consists of the sum of analytical moisture W_{a} and external moisture W_{ext}. Analytical and total moisture are taken from the results of laboratory studies.

Where the external moisture of the fuel is calculated by the formula:

$$W_{\mathrm{ext}} = W_{\mathrm{total}} - W_{\mathrm{a}}. \quad (4)$$

Ash content per row mass composition is calculated based on the conversion formula from analytical mass

$$A^{r} = A^{a} \cdot \frac{100 - W_{ext}}{100}. \quad (5)$$

2.2. Equipment

Determination of ash content. First, empty porcelain crucibles were kept in a muffle furnace at a temperature of (550 ± 10) °C for 60 min. The mass of the crucibles was measured on analytical scales (balance) with an accuracy of 0.1 mg after cooling the crucibles to room temperature. Further, all weight measurements were taken in a similar way. Then the amount of MSW weighing 1 ± 0.01 g was placed in the crucibles. After that, these crucibles with a sample were placed in a cold furnace. The furnace heated the space inside itself to a temperature of (250 ± 10) °C. This temperature was maintained inside the furnace for 60 min to release volatile substances. The procedure was repeated at a level of (550 ± 10) °C for 120 min. After drying and cooling, the crucibles were weighed. Ash content (A^d) in a dry state (*d*) was calculated using the formula:

$$A^d = \frac{(m_{Ash} - m_1)}{(m_2 - m_1)} \cdot 100 \cdot \frac{100}{100 - W^a} \, [\%], \tag{6}$$

m_{Ash} is the mass of the crucible with ash residue in kg;
m_1 is the mass of the empty crucible in kg;
m_2 is the mass of the crucible with the sample in kg;
W^{a} is the mass fraction of moisture in the analytical sample as %.

Determination of the yield of volatile organic compound. The muffle furnace preliminarily increases the internal temperature to (900 ± 5) °C. Empty crucibles are kept in the furnace for 7 min. Then, the crucibles are removed from the furnace, cooled, and weighed. An analytical sample weighing 1 ± 0.01 g is distributed in the crucible. The sample is kept inside the furnace at a temperature of 900 °C for 7 min. After cooling, the crucibles with non-volatile residue are covered and weighed on an analytical balance. The yield of volatile organic compounds V^a is calculated using the formula:

$$V^a = \frac{100 \cdot (m_2 - m_3)}{m_2 - m_1} - W^a \, [\%], \tag{7}$$

m_1 is the mass of the empty crucible with lid in kg;
m_2 is the mass of the crucible with the lid and sample before calcination in kg;
m_3 is the mass of crucible the with lid and non-volatile residue after calcination in kg;
W^{a} is the mass fraction of moisture in the analytical sample as %.

Determination of total moisture content. An empty weighing crucible was weighed. A sample weighing 1 ± 0.01 g was placed in the weighing crucible, weighed and kept in a drying furnace at a temperature of (105 ± 2) °C during 60 min. Then the weighing crucible was weighed in a hot state for 10–15 s to prevent moisture absorption. The mass fraction of total moisture is calculated for the average content of fuel components using the formula:

$$W_t^r = \frac{(m_2 - m_3) + m_4}{(m_2 - m_1)} \cdot 100 \, [\%], \tag{8}$$

m_1 is the mass of the empty crucible in kg;
m_2 is the mass of the crucible with the sample before drying in kg;
m_3 is the mass of the crucible with the sample after drying in kg;
m_4 is the mass of moisture collected from the packaging in kg.

Determination of the morphological composition. The original sample of SMW was placed on cardboard paper in a thin layer in a room with an air temperature of (20 ± 5) °C and a specific humidity of no more than 80%. The total mass of the sample of 18.63 kg was determined using laboratory scales. The sample was separated into its constituent components using tongs. Each individual component was placed in a separate tray (Figure 4). The morphological composition was measured gravimetrically using precise laboratory scales with an accuracy of ±10 mg. The total mass of the sample was divided into its constituent components: paper (cardboard), textiles (rag products), plastic, organic waste, ceramics, metal, rubber, wood. The content of each component of the sample was determined as a percentage of the total weight of the sample using the formula:

$$X^i = \frac{m_{\mathrm{component}}}{m_{\mathrm{total}}} \cdot 100 \, [\%], \tag{9}$$

$m_{component}$ is the mass of the sample component in kg;
m_{total} is the total mass of the sample in kg.

Figure 4. Waste Separation Procedure.

Determining the value of the heat of combustion. The laboratory experiment has several stages: 1. preparing the sample for combustion; 2. combustion of the sample; and 3. evaluation of the results, taking into account the minimization of the influence of the environment. Let us consider the stages in more detail. The pre-crushed sample was dried in a desiccator and formed under a press into a sample weighing 1 ± 0.01 g (Figure 5). The sample was placed in a calorimetric bomb and burned. The formula for determining the gross calorific value of an analytical fuel sample under a constant volume for a separate test is as follows:

$$Q^a_{s,V} = \frac{\varepsilon_{(n)}\theta - Q_{fuse} - Q_{ign} - Q_N - m_2 Q^a_{s,V,2}}{m_1} - \frac{Q_s}{m_1} \quad (10)$$

$Q_s{}^a{}_{,V}$ is the gross calorific value of the analytical fuel sample in kJ/kg;
$\varepsilon_{(n)}$ is the average value of the energy equivalent of the calorimeter, determined during calibration in kJ/K;
m_2 is the mass of the standard/etalon (if used) in kg;
$Q_s{}^a{}_{,V,2}$ is the gross calorific value of the standard (if used) at a constant volume in kJ/kg;
m_1 is the mass of the fuel sample, kg;
Q_s is the correction for the heat of the formation and dissolution of the sulfuric acid in kJ.

The energy equivalent of the calorimeter is determined by the formula:

$$\varepsilon = \frac{m_{ba} Q_{s,V,ba} + Q_{fuse} + Q_{ign} + Q_N}{\theta} \quad (11)$$

m_{ba} is the mass of the benzoic acid sample (standard) in kg;

$Q_{s,V,ba}$ is the gross calorific value of benzoic acid at a constant volume, specified in the certificate, in kJ/kg;
Q_{fuse} is the amount of heat released during combustion of the cotton thread fuse = 17,500 kJ/kg;
Q_{ign} is the amount of heat released during combustion of the ignition wire in kJ;
Q_N is the amount of heat released during the formation and dissolution of the nitric acid in water in kJ;
θ is the corrected temperature rise in K or conventional units.

Figure 5. Samples formed under a press.

The following equipment was used for the research:

- High-precision laboratory scales with the largest weighing limit of 2200 g, resolution of 0.01 g, built-in calibration mass, percentage weighing modes, piece counting of products with the ACAI function, comparator, statistical calculation function, and the ability to measure the density of substances and work with magnetic material using a standard pallet hook. Manufactured in the Republic of Kazakhstan;
- Weights G-2-210 with an accuracy class of 2.0. The nominal values of the weights included in the set were 1 g, 2 g, 5 g, 10 g, 20 g, 50 g, and 100 g. The material was carbon steel. The anti-corrosion coating material was chrome. Manufactured in the Republic of Kazakhstan;
- Combustion bomb calorimeter ABK-1, oxygen cylinder with a reducer, pressure gauges and a fan, with an output for connecting a computer, designed to measure the heat of combustion of solid, liquid, and gaseous fuels such as coal, coke, crude oil, diesel fuel oil, kerosene, gasoline, and natural gas. Manufactured in the Republic of Kazakhstan.

The objective limit of the efficiency of separate waste collection, characterized by the percentage of secondary raw materials collected, is the actual content of useful components in the waste—even the most efficient system of separate waste collection will not allow the extraction of more secondary raw materials than is actually generated.

Grasping the expected flows of secondary resources and waste upon the implementation of separate waste collection is particularly crucial because:

- the volume and quality of the obtained secondary resources must correspond to the real demand in the secondary raw materials market;
- when technically organizing separate collections, it is essential to determine the number and types of containers needed, the frequency of waste removal, the amount of equipment and labor required, and the expected productivity of the waste sorting line, among other considerations;
- economic efficiency indicators (cost price, profitability, etc.) directly depend on the volume and quality of secondary raw materials that can be obtained.

Quantitative and qualitative indicators of secondary raw material flows, which can be achieved through the implementation of separate waste collection, can be evaluated based on studies of the volumes of individual flows and their physicochemical composition.

Contemporary waste management concepts typically focus on maximizing the resource potential of the components that constitute MSW. At the same time, the composition of waste received for processing affects the degree of selection of secondary raw materials at waste sorting plants, determines the calorific value of waste when using thermal recycling methods and the efficiency of decomposition processes when using biotechnology and, as a result, affects the technical and economic indicators of a particular technology.

3. Results

The studies on the physicochemical composition of unsorted waste and MSW post-sorting yielded the following experimental data for the cities of Astana, Almaty, Karaganda, Aktobe, Shymkent, and Ust-Kamenogorsk (Tables 2–14).

Table 2. Physicochemical composition of unsorted waste in Astana.

MSW Fraction	Input Average, %	Being Removed, %	Remains After Sorting, %	Contents After Sorting, %	Calorific Value of 1 kg of Component, kj/kg	Specific Calorific Value of Unsorted MSW, kj/kg
Organic waste	40.10	34.09	6.02	24.86	3340.00	1339.34
Plastic	15.80	10.27	5.53	22.86	24,393.76	3854.21
Paper/cardboard	16.40	10.66	5.74	23.72	9705.97	1591.78
Diapers	6.20	6.20	0.00	0.00	12,000.00	744.00
Glass	5.80	5.80	0.00	0.00	0.00	0.00
Textiles and leather	3.65	0.00	3.65	15.09	17,999.41	656.98
Other fine fraction (<12 mm)	6.10	6.10	0.00	0.00	7000.00	427.00
Ceramics and construction waste	2.80	0.84	1.96	8.10	0.00	0.00
Metal	1.80	0.90	0.90	3.72	0.00	0.00
Wood	0.80	0.40	0.40	1.65	14,507.88	116.06
Waste electrical and electronic equipment	0.55	0.55	0.00	0.00	22,000.00	121.00
Total	100.00	75.81	24.20	100.00		8850.37

Table 3. Physicochemical composition of unsorted waste in Astana.

№	Component Name	Mass of Component in Sample, kg	Percentage, %	Total Mass, kg	Calorific Value of 1 kg of Component, kj/rg	Specific Calorific Value in the Sample Mass, kj/rg	MSW Fraction	Input Average, %	Being Removed, %	Remains After Sorting, %	Contents After Sorting, %	Calorific Value of 1 kg of Component, kj/rg	Specific Calorific Value of Unsorted MSW, kj/rg
1	Paper/cardboard	3.91	20.99	18.63	9705.97	2037.06	Organic waste	36.72	31.21	5.51	21.84	3340.00	1226.45
2	Textiles and leather	3.41	18.30		15,720.88	2877.52	Plastic	19.43	12.63	6.80	26.96	24,393.76	4739.71
3	Plastic	4.47	23.99		24,393.76	5852.93	Paper/cardboard	19.46	12.65	6.81	27.00	9705.97	1888.78
4	Organic waste	4.70	25.23		3340.00	842.62	Diapers	2.87	2.87	0.00	0.00	12,000.00	344.40
5	Ceramics	1.23	6.60		0.00	0.00	Glass	6.87	6.87	0.00	0.00	0.00	0.00
6	Metal	0.57	3.06		0.00	0.00	Textiles and leather	2.26	0.00	2.26	8.96	17,999.41	406.79
7	Leather and rubber	0.08	0.43		25,661.24	110.19	Other fine fraction (<12 mm)	5.69	5.69	0.00	0.00	7000.00	398.30
8	Wood	0.26	1.40		14,507.88	202.47	Ceramics and construction waste	3.26	0.98	2.28	9.05	0.00	0.00
	Total	18.63	100.00			11,922.79	Metal	1.95	0.98	0.98	3.87	0.00	0.00
							Wood	1.17	0.59	0.59	2.32	14,507.88	169.74
							Waste electrical and electronic equipment	0.32	0.32	0.00	0.00	22,000.00	70.40
							Total	100.00	74.78	25.22	100.00		9244.57

Table 4. Physicochemical composition of sorted waste in Astana.

№	Component Name	Mass of Component in Sample, kg	Percentage, %	Total Mass, kg	Calorific Value of 1 kg of Component, kj/rg	Specific Calorific Value in the Sample Mass, kj/rg
1	Paper/Cardboard	3.91	20.99	18.63	9705.97	2037.06
2	Textiles and leather	3.41	18.30		15,720.88	2877.52
3	Plastic	4.47	23.99		24,393.76	5852.93
4	Organic waste	4.70	25.23		3340.00	842.62
5	Ceramics	1.23	6.60		0.00	0.00
6	Metal	0.57	3.06		0.00	0.00
7	Leather and rubber	0.08	0.43		25,661.24	110.19
8	Wood	0.26	1.40		14,507.88	202.47
	Total	18.63	100.00			11,922.79

Table 5. Physicochemical composition of unsorted waste in Almaty.

MSW Fraction	Input Average, %	Being Removed, %	Remains After Sorting, %	Contents After Sorting, %	Calorific Value of 1 kg of Component, kj/rg	Specific Calorific Value of Unsorted MSW, kj/rg
Organic waste	36.72	31.21	5.51	21.84	3340.00	1226.45
Plastic	19.43	12.63	6.80	26.96	24,393.76	4739.71
Paper/cardboard	19.46	12.65	6.81	27.00	9 705.97	1888.78
Diapers	2.87	2.87	0.00	0.00	12 000.00	344.40
Glass	6.87	6.87	0.00	0.00	0.00	0.00
Textiles and leather	2.26	0.00	2.26	8.96	17 999.41	406.79
Other fine fraction (<12 mm)	5.69	5.69	0.00	0.00	7000.00	398.30
Ceramics and construction waste	3.26	0.98	2.28	9.05	0.00	0.00
Metal	1.95	0.98	0.98	3.87	0.00	0.00
Wood	1.17	0.59	0.59	2.32	14,507.88	169.74
Waste electrical and electronic equipment	0.32	0.32	0.00	0.00	22,000.00	70.40
Total	100.00	74.78	25.22	100.00		9244.57

Table 6. Physicochemical composition of sorted waste in Almaty.

№	Component Name	Mass of Component in Sample, kg	Percentage, %	Total Mass, kg	Calorific Value of 1 kg of Component, kj/rg	Specific Calorific Value in the Sample Mass, kj/rg
1	Paper/cardboard	5.77	27.00	21.36	9705.97	2620.61
2	Textiles/rags	1.87	8.76		15,720.88	1376.40
3	Plastic	5.76	26.96		24,393.76	6576.56
4	Organic waste	4.67	21.84		3340.00	729.46
5	Ceramics	1.93	9.05		0.00	0.00
6	Metal	0.83	3.87		0.00	0.00
7	Leather and rubber	0.04	0.21		25,661.24	52.71
8	Wood	0.50	2.32		14,507.88	336.58
	Total	21.36	100.00			11,692.31

Table 7. Physicochemical composition of unsorted waste in Aktobe.

MSW Fraction	Input Average, %	Being Removed, %	Remains After Sorting, %	Contents after Sorting, %	Calorific Value of 1 kg of Component, kj/rg	Specific Calorific Value of Unsorted MSW, kj/rg
Organic waste	31.39	26.68	4.71	19.02	3340.00	1048.43
Plastic	18.21	11.84	6.37	25.74	24,393.76	4442.10
Paper/cardboard	19.34	12.57	6.77	27.34	9705.97	1877.13
Diapers	7.02	7.02	0.00	0.00	12 000.00	842.40
Glass	5.73	5.73	0.00	0.00	0.00	0.00
Textiles and leather	3.24	0.00	3.24	13.09	17,999.41	583.18
Other fine fraction (<12 mm)	8.77	8.77	0.00	0.00	7000.00	613.90
Ceramics and construction waste	3.29	0.99	2.30	9.30	0.00	0.00
Metal	1.85	0.93	0.93	3.74	0.00	0.00
Wood	0.88	0.44	0.44	1.78	14,507.88	127.67
Waste electrical and electronic equipment	0.28	0.28	0.00	0.00	22,000.00	61.60
Total	100.00	75.24	24.76	100.00		9596.41

Table 8. Physicochemical composition of sorted waste in Aktobe.

№	Component Name	Mass of Component in Sample, kg	Percentage, %	Total Mass, kg	Calorific Value of 1 kg of Component, kj/rg	Specific Calorific Value in the Sample Mass, kj/rg
1	Paper/cardboard	5.43	27.34	19.87	9705.97	2653.57
2	Textiles/rags	2.54	12.79		15,720.88	2010.10
3	Plastic	5.11	25.74		24,393.76	6279.48
4	Organic waste	3.78	19.02		3340.00	635.18
5	Ceramics	1.85	9.30		0.00	0.00
6	Metal	0.74	3.74		0.00	0.00
7	Leather and rubber	0.06	0.30		25,661.24	76.97
8	Wood	0.35	1.78		14,507.88	257.82
	Total	19.87	100.00			11,913.13

Table 9. Physicochemical composition of unsorted waste in Shymkent.

MSW Fraction	Input Average, %	Being Removed, %	Remains After Sorting, %	Contents After Sorting, %	Calorific Value of 1 kg of Component, kj/rg	Specific Calorific Value of Unsorted MSW, kj/rg
Organic waste	39.42	33.51	5.91	21.87	3340.00	1316.63
Plastic	19.03	12.37	6.66	24.63	24,393.76	4642.13
Paper/cardboard	18.89	12.28	6.61	24.45	9705.97	1833.46
Diapers	2.13	2.13	0.00	0.00	12 000.00	255.60
Glass	7.46	7.46	0.00	0.00	0.00	0.00
Textiles and leather	4.66	0.00	4.66	17.23	17 999.41	838.77
Other fine fraction (<12 mm)	2.43	2.43	0.00	0.00	7000.00	170.10
Ceramics and construction waste	1.32	0.40	0.92	3.42	0.00	0.00
Metal	2.18	1.09	1.09	4.03	0.00	0.00

Table 9. *Cont.*

MSW Fraction	Input Average, %	Being Removed, %	Remains After Sorting, %	Contents After Sorting, %	Calorific Value of 1 kg of Component, kj/rg	Specific Calorific Value of Unsorted MSW, kj/rg
Wood	2.36	1.18	1.18	4.36	14,507.88	342.39
Waste electrical and electronic equipment	0.12	0.12	0.00	0.00	22,000.00	26.40
Total	100.00	72.96	27.04	100.00		9425.48

Table 10. Physicochemical composition of sorted waste in Shymkent.

№	Component Name	Mass of Component in Sample, kg	Percentage, %	Total Mass, kg	Calorific Value of 1 kg of Component, kj/rg	Specific Calorific Value in the Sample Mass, kj/rg
1	Paper/cardboard	4.64	24.45	18.96	9705.97	2373.28
2	Textiles/rags	3.19	16.84		15,720.88	2647.29
3	Plastic	4.67	24.63		24,393.76	6008.90
4	Organic waste	4.15	21.87		3340.00	730.40
5	Ceramics	0.65	3.42		0.00	0.00
6	Metal	0.76	4.03		0.00	0.00
7	Leather and rubber	0.07	0.40		25,661.24	101.37
8	Wood	0.83	4.36		14,507.88	633.13
	Total	18.96	100.00			12,494.38

Table 11. Physicochemical composition of unsorted waste in Karagandy.

MSW Fraction	Input Average, %	Being Removed, %	Remains After Sorting, %	Contents After Sorting, %	Calorific Value of 1 kg of Component, kj/rg	Specific Calorific Value of Unsorted MSW, kj/rg
Organic waste	26.80	22.78	4.02	17.23	3340.00	895.12
Plastic	16.45	10.69	5.76	24.67	24,393.76	4012.77
Paper/cardboard	18.76	12.19	6.57	28.14	9705.97	1820.84
Diapers	5.87	5.87	0.00	0.00	12,000.00	704.40
Glass	11.87	11.87	0.00	0.00	0.00	0.00
Textiles and leather	2.97	0.00	2.97	12.73	17,999.41	534.58
Other fine fraction (<12 mm)	10.27	10.27	0.00	0.00	7000.00	718.90
Ceramics and construction waste	3.36	1.01	2.35	10.08	0.00	0.00
Metal	2.32	1.16	1.16	4.97	0.00	0.00
Wood	1.02	0.51	0.51	2.19	14,507.88	147.98
Waste electrical and electronic equipment	0.31	0.31	0.00	0.00	22,000.00	68.20
Total	100.00	76.66	23.34	100.00		8902.80

Table 12. Physicochemical composition of sorted waste in Karagandy.

№	Component Name	Mass of Component in Sample, kg	Percentage, %	Total Mass, kg	Calorific Value of 1 kg of Component, kj/rg	Specific Calorific Value in the Sample Mass, kj/rg
1	Paper/cardboard	5.66	28.14	20.12	9705.97	2731.01
2	Textiles/rags	2.50	12.44		15,720.88	1954.99
3	Plastic	4.96	24.67		24,393.76	6018.60
4	Organic waste	3.47	17.23		3340.00	575.38
5	Ceramics	2.03	10.08		0.00	0.00
6	Metal	1.00	4.97		0.00	0.00
7	Leather and rubber	0.06	0.29		25,661.24	74.86
8	Wood	0.44	2.19		14,507.88	317.07
	Total	20.12	100.00			11,671.92

Table 13. Physicochemical composition of unsorted waste in Ust-Kamenogorsk.

MSW Fraction	Input Average, %	Being Removed, %	Remains After Sorting, %	Contents After Sorting, %	Calorific Value of 1 kg of Component, kj/rg	Specific Calorific Value of Unsorted MSW, kj/rg
Organic waste	24.54	20.86	3.68	16.11	3340.00	819.64
Plastic	18.97	12.33	6.64	29.06	24,393.76	4627.50
Paper/Ccardboard	17.56	11.41	6.15	26.90	9705.97	1704.37
Diapers	6.74	6.74	0.00	0.00	12,000.00	808.80
Glass	8.56	8.56	0.00	0.00	0.00	0.00
Textiles and leather	2.67	0.00	2.67	11.69	17,999.41	480.58
Other fine fraction (<12 mm)	14.46	14.46	0.00	0.00	7000.00	1 012.20
Ceramics and construction waste	2.89	0.87	2.02	8.85	0.00	0.00
Metal	2.24	1.12	1.12	4.90	0.00	0.00
Wood	1.14	0.57	0.57	2.49	14,507.88	165.39
Waste electrical and electronic equipment	0.23	0.23	0.00	0.00	22,000.00	50.60
Total	100.00	77.15	22.85	100.00		9669.07

Table 14. Physicochemical composition of sorted waste in Ust-Kamenogorsk.

№	Component Name	Mass of Component in Sample, kg	Percentage, %	Total Mass, kg	Calorific Value of 1 kg of Component, kj/rg	Specific Calorific Value in the Sample Mass, kj/rg
1	Paper/cardboard	5.17	26.90	19.21	9705.97	2610.69
2	Textiles/rags	2.19	11.42		15,720.88	1794.90
3	Plastic	5.58	29.06		24,393.76	7088.22
4	Organic waste	3.09	16.11		3340.00	538.07
5	Ceramics	1.70	8.85		0.00	0.00
6	Metal	0.94	4.90		0.00	0.00
7	Leather and rubber	0.05	0.27		25,661.24	68.73
8	Wood	0.48	2.49		14,507.88	361.91
	Total	19.21	100.00			12,462.52

Based on the solid municipal waste of the city of Astana, an analysis of its physical properties was conducted, as presented in Table 15.

Table 15. Results of the analysis of the physical properties of solid waste in the city of Astana.

Sample	Analytical Moisture, W^a, % 105 ± 2 °C		Total Moisture, W_t^r, % 105 ± 2 °C		Ash Content, A^a, % 250→550 °C		Volatile Content, V^{daf}, % 900 °C	
		Average		Average		Average		Average
№ 1	4.96 5.22	5.09	19.90 22.40	21.15	25.24 25.91	25.58	64.55 60.96	62.76
№ 2	6.44 5.08	5.76	26.7 24.7	25.7	26.93 24.48	25.71	59.58 62.43	61.01

Table 16 illustrates the summary results of the studies of the calorific value of MSW by city.

Table 16. Summary table of the findings on the calorific value of solid waste by city.

City	Astana	Almaty	Aktobe	Shymkent	Karagandy	Ust-Kamenogorsk
Gross calorific value per row mass of unsorted MSW, kJ/kg	8850.37	9 244.57	9 596.41	9 425.48	8 902.80	9669.07
Gross calorific value per row mass of sorted MSW, kJ/kg	11,922.79	11,692.31	11,913.13	12,494.38	11,671.92	12,462.52
Lower calorific value per row mass of sorted MSW, kJ/kg	10,473.36	10,013.78	10,013.1	10,636.5	9734.72	10,068.68

Table 17 presents the summary results of the studies of the physicochemical composition of sorted MSW by city.

Table 17. Summary table of research findings on the physicochemical composition of sorted MSW by city, presented as %.

City	Astana	Almaty	Aktobe	Shymkent	Karagandy	Ust-Kamenogorsk
Paper/cardboard	20.99	27.00	27.34	24.45	28.14	26.90
Textiles/rags	18.30	8.76	12.79	16.84	12.44	11.42
Plastic	23.99	26.96	25.74	24.63	24.67	29.06
Organic waste	25.23	21.84	19.02	21.87	17.23	16.11
Ceramics	6.60	9.05	9.30	3.42	10.08	8.85
Metal	3.06	3.87	3.74	4.03	4.97	4.90
Leather and rubber	0.43	0.21	0.30	0.40	0.29	0.27
Wood	1.40	2.32	1.78	4.36	2.19	2.49
Total	100.00	100.00	100.00	100.00	100.00	100.00

4. Discussion

Figures 6–8 in the nomograms present the findings from studies on determining both the higher and lower calorific values of combustion, as well as the physicochemical composition of sorted and unsorted MSW by city. The results indicate variations among cities, reflecting the differences based on their respective regional contexts.

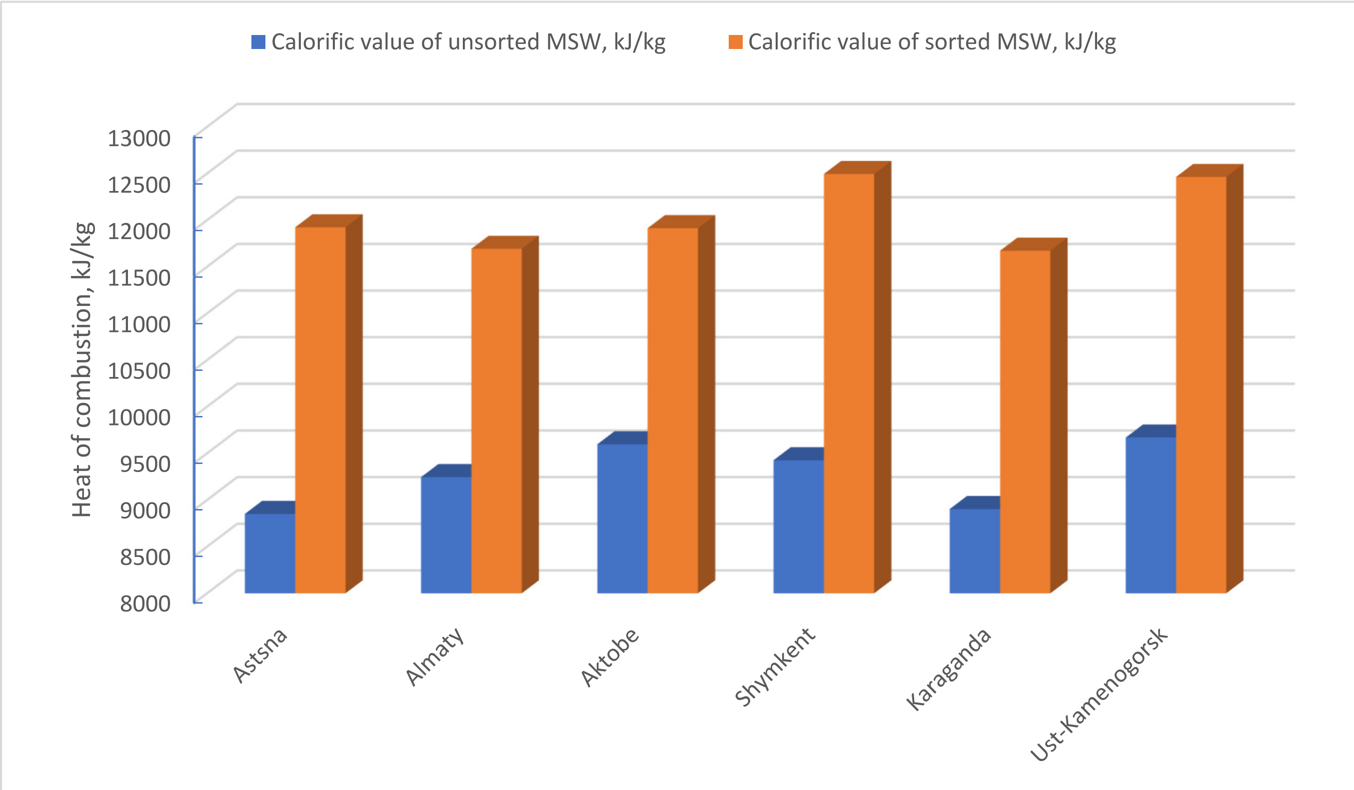

Figure 6. Analysis of the combustion heat of solid waste by city.

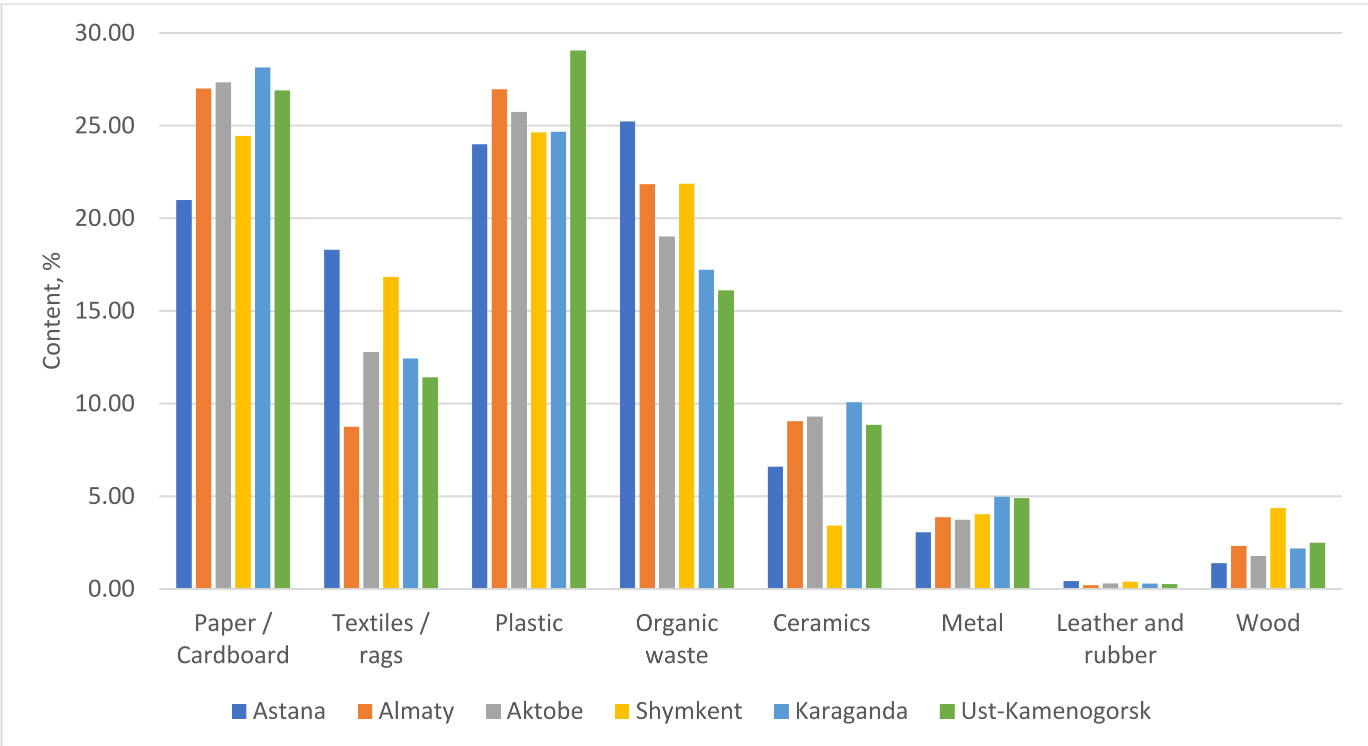

Figure 7. Analysis of the physicochemical composition of unsorted MSW by city.

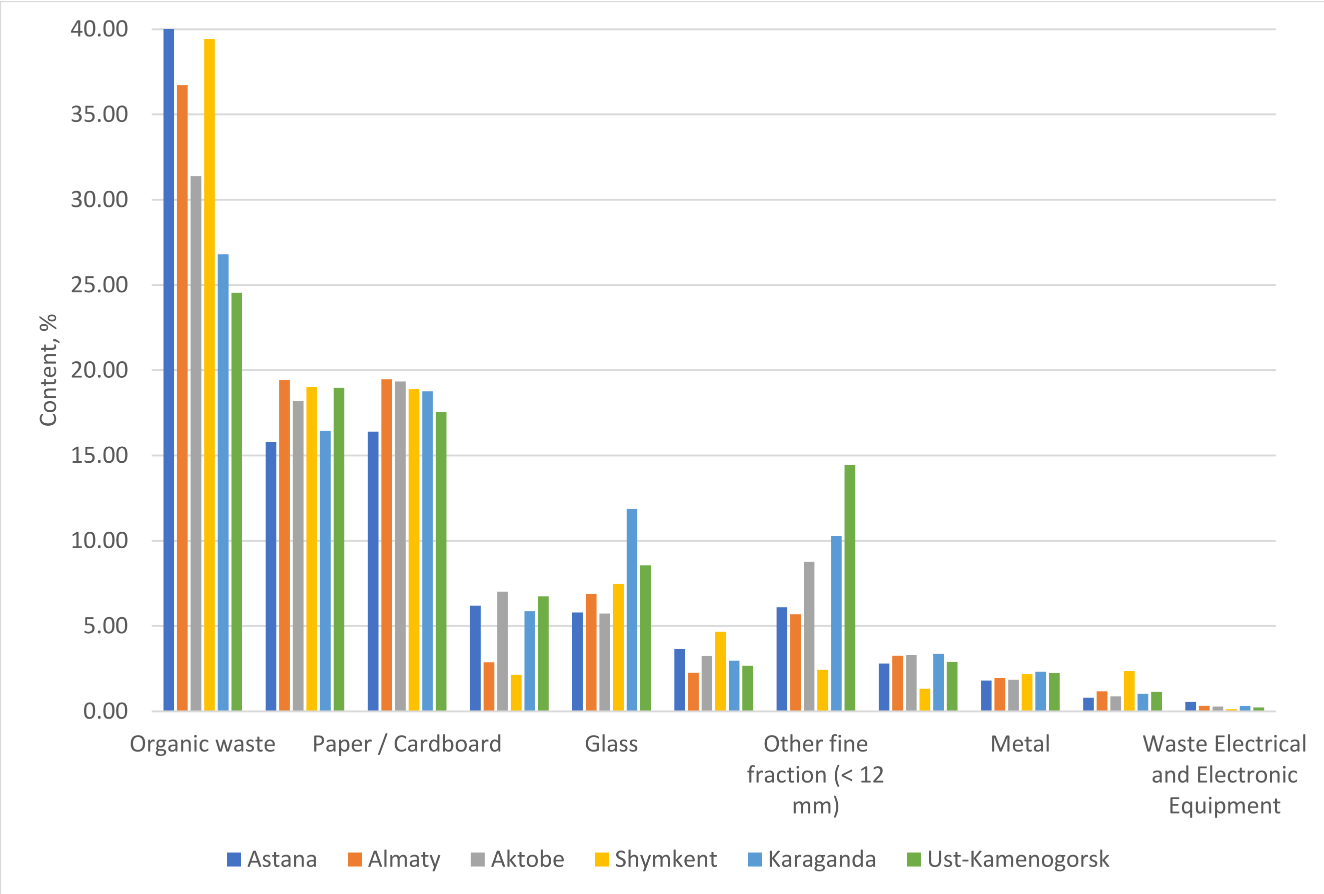

Figure 8. Analysis of the physicochemical composition of sorted MSW by city.

Previous researchers [1,2] have focused on waste mainly from the central cities of Kazakhstan, such as Astana and Almaty only. These cities are the largest in the country. The composition of MSW in these cities cannot be taken as average, since the peculiarities of life in large cities are much more different from small settlements. The difference between the current study and previous ones is a wider coverage of the geography of Kazakhstan and an analysis of solid waste using the examples of six large cities.

The authors analyzed the most effective technologies for MSW disposal for each city based on the research results. The studies were conducted in parallel for n = 5–6 measurements. In addition, each experiment was conducted from m = 10–15 series. Standard deviations and confidence intervals for the probability p = 0.95 were calculated for the experimental data samples and for each point indicated on the figures. This statistical analysis confirms the high reliability of the research results. The standard deviation of measurements does not exceed 2%.

Contemporary waste management concepts typically emphasize the optimal utilization of the resource potential inherent in the components of MSW [46]. At the same time, the composition of waste received for processing affects the degree of selection of secondary raw materials at waste sorting plants, determines the calorific value of waste when using thermal recycling methods [47] and the efficiency of decomposition processes when using biotechnology and, as a result, affects the technical and economic indicators of a particular technology.

The efficiency of the sorting process depends on many factors, including:

- the speed of waste movement along the sorting conveyor: the slower the waste moves, the better it is sorted into components;
- the thickness of the waste layer on the conveyor: the thinner the layer of waste on the sorting conveyor, the more thoroughly the waste is sorted.

However, increasing the efficiency of the process by reducing the speed leads to a decrease in productivity, so in practice, they focus not on high sorting efficiency, but on maximum productivity. The efficiency of the manual sorting process in practice is 0.4–0.8.

The component extraction effectiveness depends on several factors, including:

- the nature of the component (whether or not it is susceptible to getting wet, rotting, etc.);
- the solid waste characteristics (initial moisture content, fractional composition, etc.);
- the season of the year and weather conditions (getting wet, freezing, etc.);
- the waste collection and removal systems (general or separate waste collection, the degree of waste compaction during transportation, the presence of overloading, etc.).

The main limitations of this study are the influence of the regions where solid waste was collected and the mentality of the residents living in these regions on the composition and specific volumes of solid waste per person. These limitations do not need to be corrected, as they will be taken into account for future research. The next step is planned as an experiment on burning unsorted and sorted solid waste from all six cities. In this case, the volume and composition of flue gases formed during the combustion of solid waste will be measured, as well as the composition and properties of the resulting ash and slag during the combustion of both unsorted and sorted waste in each city.

5. Conclusions

The following results were achieved from the experiment:

1. The physicochemical composition of unsorted and sorted municipal solid waste was determined for six cities in Kazakhstan: Astana, Almaty, Aktobe, Shymkent, Karaganda, and Ust-Kamenogorsk;
2. The thermophysical characteristics of municipal solid waste from six cities were determined: ash content, humidity, as well as higher (gross) and lower calorific value.

The results of the physicochemical composition of municipal solid waste in the cities of Kazakhstan:

- The amount of organic waste differs in relation to the specifics of the food products used depending on the culinary traditions of the regions: more in the south and in the capital, less in the center and in the east of the country.
- The number of diapers and auxiliary baby materials also differs: less in the south, more in other regions.
- On average, the amounts of components are comparable for other components.

The key findings of the present research are the selection of the optimal technology for municipal solid waste disposal in each region, along with forecasts regarding its effectiveness and potential enhancements to the environmental conditions in those areas.

The most suitable and optimal technologies for the disposal of municipal solid waste are *energy-efficient and environmentally friendly pyrolysis technologies*, with the production of synthesis gas and combustion generating electrical energy and additional products. Pyrolysis is optimally used for small amounts of waste, especially if there are other types of waste besides household waste.

For large volumes of municipal solid waste, it is optimal to use the *waste-free incineration process* scheme developed by the authors. This scheme incorporates technologies for the complete disposal of solid, liquid, and gaseous products generated during the incineration process.

Both technologies enable the disposal of not only fresh waste generated by the population but also waste that has already accumulated in landfill cells in populated areas, thereby completely clearing the state's territory of solid household waste.

6. Future Research Directions

The data obtained in the study are the basis for the future full-scale study of MSW pyrolysis with the development of technology for the conditions of Kazakhstan. Thus, there are potential opportunities to expand the range of scientific research on the use of waste for power generation.

7. Patents

There are patents resulting from the work reported in this manuscript. Source: Glazyrin, S.A., et al. Method for cleaning flue gases of a drum-type power boiler. Patent of Republic of Kazakhstan, No. 5184, 2020 (in Russian) [48].

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