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Integrated Gasification of Municipal Solid Waste for Cogeneration and Sustainable Energy Production

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Keywords:
Municipal solid waste; Gasification; Syngas; Cogeneration; Thermal conversion; Waste-to-energy; Emission reduction; Energy efficiency.

Highlights:

- *Gasification of municipal solid waste at 1050°C produced syngas with a calorific value reaching 16.2 MJ/m³.*
- *The experimental integration of syngas in a 5 MW Siemens gas turbine demonstrated stable combustion and low NOx emissions.*
- *Comprehensive modeling with ChemCAD confirmed strong agreement with laboratory results, validating process scalability.*

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Abstract: This study investigates the energy potential and technological feasibility of using municipal solid waste as a fuel source through gasification and cogeneration. A comprehensive morphological and elemental analysis of waste samples revealed significant fractions of paper, polymers, and wood, with average carbon and hydrogen contents of 32.3% and 5.2%, respectively, supporting their suitability for thermal conversion. Experiments were conducted using a shaft-type gasification reactor operated at temperatures ranging from 750 to 1050 °C. The results demonstrated that increasing the gasification temperature enhanced the yield of volatile compounds up to 67.9% and raised the syngas calorific value to 16.2 MJ/m³. The syngas composition was characterised by carbon monoxide concentrations up to 27.8% and hydrogen concentrations up to 17.1%. Additional trials confirmed the stable combustion of produced syngas in a Siemens SGT-100 gas turbine, with NOx emissions measured between 45 and 57 mg/Nm³. Modeling outcomes using ChemCAD aligned closely with experimental data, validating the process parameters. The findings confirm that integrating gasification-based cogeneration systems can effectively reduce reliance on landfills and improve energy efficiency in municipal infrastructure.

1.INTRODUCTION

In recent decades, the problem of municipal solid waste (MSW) disposal has become a global issue and a priority task in sustainable urban development. According to international organizations, over 2 billion tons of municipal waste are generated annually in the world, and only about 20% of it is recycled or used as raw materials. In the context of the ongoing growth of the urban population and rising consumption, this situation is worsening each year. For example, according to Russian statistics, approximately 70 million tons of MSW are generated annually in the country. At the same time, only 8-9% is sent for recycling and reuse, and most of it ends up in landfills, resulting in the depletion of land resources and significant environmental impacts [1-4]. The scientific and technical community offers several primary approaches to solving the problem of municipal solid waste management. The most traditional method remains the burial of MSW, which is attractive for its minimal infrastructure costs and the simplicity of its technological solutions. However, this approach has obvious disadvantages, including high environmental risks: groundwater pollution, methane and dioxin emissions into the atmosphere, the infectious disease outbreaks, and the degradation of large areas. In addition, burial results in the complete loss of secondary materials and energy resources. Another standard method is composting, i.e., accelerated biodegradation of organic fractions of waste with or without oxygen. This method produces a valuable product: compost suitable for agricultural use. Still, it substantial energy to supply heated air and to process the resulting toxic fractions. In addition, up to 30% of waste remains non-compostable and is subject to subsequent burial. Waste incineration has also been widely applied in European and Asian practice [5-7]. Thanks to this method, the volume of garbage can be reduced by 80-90%, and its remaining material is converted into slag and ash. The average net calorific value of MSW across regions of Russia ranges from 7500 to 8000 kJ/kg, with a moisture content of 30–40% and an ash content of 25–30%, indicating that the waste is a potential low-grade fuel. Incineration significant challenges. The main disadvantages are the need for high-tech systems to remove dioxins and furans from flue gases, the formation of a large volume of ash requiring specialised disposal, increased equipment wear, and the difficulty of maintaining stable combustion conditions with an uneven fuel composition. In recent years, gasification of municipal solid waste has become an increasingly promising direction. This technology allows, at high temperatures and controlled access to oxidizers, the synthesis gas from the organic part of MSW, i.e., a fuel gas mixture with a high calorific value that can be burnt to generate heat and electricity. Gasification has several advantages. In particular, it is characterized by relatively low capital costs, high process energy efficiency (up to 95%), and the possibility of almost destruction of the organic part of the waste. Synthesis gas is easier to purify of impurities than direct combustion products due to its lower volume, higher pollutant concentration, and lower temperature. Gasification also helps to reduce emissions of nitrogen oxides and dioxins [8-10]. However, this technology is not yet well established in Russian practice and requires the development of a complex system for the preparation and purification of secondary fuel [11,12]. Against this background, the development of cogeneration energy systems based on MSW gasification is particularly relevant. Cogeneration, i.e., the simultaneous generation of heat and electricity within a single technological cycle, can significantly increase fuel efficiency and reduce specific energy costs. The work under consideration assesses the morphological and elemental composition of MSW typical of municipalities: according to the experimental results, the mass fraction of paper and cardboard is 23.5%, 15% of that of polymers, 16.3% of that of wood waste, and the moisture content of the entire waste mass is about 18.1%. The average carbon content is 31.1%, confirming the high potential of waste as an alternative fuel source. In addition, gasification and combustion processes were modelled using the Aspen Plus software package, which demonstrated that the production of synthesis gas stabilised the fuel's calorific value and enabled adaptation of gas turbine operation. As a pilot solution, a 100 kW cogeneration unit consuming about 100 kg/h of organic waste was considered. The calculation schemes enabled estimation of the heat and material balances. They confirmed the feasibility of integrating such units into existing boiler houses and heat supply systems of small settlements [13-16]. Therefore, the direction of solid municipal waste disposal using gasification technology in cogeneration energy systems is a modern and essential step in solving several urgent problems at once: increasing fuel independence, reducing the load on landfills, minimizing greenhouse gas emissions, and using secondary resources. Its implementation could significantly enhance environmental safety and energy efficiency in municipal infrastructure. Recent studies in comparable economic contexts corroborate the technical and financial viability of MSW gasification for CHP. For instance, a Waste-Integrated Gasifier–Gas Turbine Combined Cycle (WIG–GTCC) was assessed for Chile delivers 19.6

MW_e from 14.6 $t \cdot h^{-1}$ MSW with ~44–45% CHP efficiency, i.e., about 1.34 kW of electric capacity per $kg \cdot h^{-1}$ of feed [17]. In Pakistan, a simulation study highlighted the strong sensitivity of syngas quality to moisture and the oxidant ratio, underscoring the importance of pre-drying and air/steam optimization [18]. Systematic reviews, published since 2020, report H_2 and CO ranges and LHV values consistent with those obtained here for mixed MSW streams [19,20], while process-integration papers show that low-temperature drying upstream of gasification can further improve cold-gas efficiency and power output under municipal operating constraints [2]. These findings provide external validation of the operating windows and assumptions adopted in this work. The purpose of this work is to develop energy-efficient process schemes for using solid municipal waste as a fuel to generate heat and electricity, and to subsequently integrate these solutions into the existing energy systems of small settlements.

2.RESEARCH METHODS

During the study, a set of experimental and computational methods was employed to comprehensively characterise the morphological and elemental composition of municipal solid waste and to determine the energy potential of its gasification and the feasibility of using the resulting synthesis gas in cogeneration plants. The general work plan included successive stages of sampling, raw material preparation, thermal treatment of waste in various modes and modeling the thermal characteristics of processed products using specialized software. A laboratory gasification unit, Termolab GVR-200, equipped with a vertical shaft-type reactor with a volume of 250 l and an automated temperature control system, was used to conduct thermal experiments. The reactor was equipped with an air and water vapor supply system with the ability to regulate their ratio in the range from 10 to 90%. The reaction zone was heated by electric heating elements with a total power of 18 kW, thereby maintaining the gasification temperature in the range of 700–1100 °C with a control step of 10 °C. To assess the effect of temperature on the yield of gaseous products, a series of experiments was conducted at 750, 900, and 1050°C, with isothermal holding times ranging from 30 to 90 minutes. Simultaneously with gasification in the Termolab GVR-200-unit, waste pyrolysis experiments were conducted at 500°C under nitrogen, with an inert gas flow rate of 1.5 m^3/h. This enabled data to be obtained on the yields of pyrolysis liquids, gases, and solid residue. In addition to the main experiments, a series of experiments was carried out on the oxidative combustion of prepared fractions of solid municipal waste in a Carbolite Gero ELF 11/14 muffle furnace, the working volume of which is 14 liters. This furnace provided uniform heating to 1150°C at a rate of 8 °C/min. During these tests, heat release, ash mass yield, and bound carbon content in the residue were measured.

A Retsch PT 100 automatic sample divider was used to collect and prepare feedstock samples, ensuring uniformity and representativeness. The morphological composition was determined by manual sorting followed by weighing individual fractions on an Ohaus Explorer analytical scale with an error of no more than 0.001 g. The ChemCAD 7.1 software package was used to simulate the gasification process with the calculation of the qualitative and quantitative composition of the synthesis gas. Process overview (textual schematic, labels, and parameters). The pilot line operates as follows: presorted MSW, dried to <10 wt% moisture, is fed to a vertical shaft-type gasifier (Termolab GVR-200, 250 L) at set points of 750/900/1050 °C. Primary oxidant is metered air or air–steam at controlled ratios consistent with the laboratory modes. The raw syngas is cooled and analyzed online; the same composition windows are used to parameterize ChemCAD so that operating points match the experiments. Conditioned syngas with LHV = 13–17 $MJ \cdot Nm^{-3}$ is then supplied to a Siemens SGT-100 combustor; flame stability is maintained with excess-air coefficients of λ = 1.6–1.8 as verified in the tests reported below. For reader clarity, the model and experiments reference the following labeled parameters throughout this section: a reactor type and volume (shaft, 250 L), an oxidant composition (air; air/steam), temperature set points (750/900/1050 °C), target syngas ranges (CO is 20–30%, H_2 is 12–20%), and turbine operating (λ). In the simulations, we adopted average ultimate and proximate compositions derived from the experimental dataset (120 samples; moisture harmonized with the laboratory methods). Morphological fractions were averaged across all sampling rounds to represent a realistic municipal 'baseline' stream. Multiple composition scenarios were not explicitly simulated. Instead, variability was addressed indirectly through experimental sampling across time and through parametric sweeps of gasification temperature (750–1050 °C) and an oxidant ratio (air versus steam–air). This modeling choice is stated to clarify that the reported results represent an average-case municipal feed. Composition-dependent scenario analysis is identified as future work. The software environment made it possible to analyze the calorific value of the gas mixture, the content of carbon monoxide, methane, hydrogen, and carbon dioxide with a change in the air/steam ratio, gasification temperature, and feedstock moisture content. The simulation was carried out for conditions identical to the laboratory experimental modes, which ensured comparability of the results. Additionally, the obtained synthesis gas was tested for its suitability for use in a Siemens SGT-100 gas turbine unit with a capacity of 5 MW, during which the ignition stability and uniformity of fuel combustion were evaluated with gas having a calorific value of 13–17 MJ/m³.

3.RESULTS AND DISCUSSION

As part of the study, a comprehensive experimental program was conducted to characterize the physicochemical properties of municipal solid waste, determine their morphological and elemental composition, and assess the potential for thermal processing and the subsequent use of the resulting products in cogeneration energy systems. The study began with the selection and preparation of samples, for which an automatic sample divider was used, ensuring the formation of samples representative of the target moisture content and fractional composition. A total of 120 samples, weighing 450 kg, were selected, including mixed residential waste with varying proportions of organic, polymer, and mineral components. To obtain generalized characteristics, the morphological composition of each sample was determined by manual sorting into eight fractions, including paper and cardboard, polymers, glass, wood and plant residues, food waste, textiles, metals, and a mineral fraction. During the preparation process, the samples were dried to a residual moisture content of less than 10% at a temperature of 105°C, which allowed them to be standardized by moisture content for the comparability of the results of further experiments. The average mass fractions of the main components by dry matter were wastepaper and cardboard (24.7%), polymeric materials (16.2%), wood fraction (17.3%), food waste (10.8%), glass (14.5%), metals (2.5%), textiles (4.6%), and mineral screenings (9.4%). These average morphological shares were used to construct the single baseline composition for ChemCAD calculations; no separate multi-scenario composition set was used in this study. A Termolab GVR-200 shaft-type gasification unit with a 250-litre vertical reactor was used for thermal processing. Its heating system allowed precise temperature control. Gasification was carried out at 750, 900, and 1050°C. In each mode, a series of experiments was conducted in six cycles; the isothermal holding time was 60 minutes. In the 750°C mode, the average volatile yield was 58.3% of the initial dry feedstock weight. The content of synthesis gas by main components, determined using an Agilent 7890B chromatograph, was 19.4% carbon monoxide, 12.7% hydrogen, 3.2% methane, 20.8% carbon dioxide, and 43.9% nitrogen. With an increase in temperature to 900°C, the proportion of volatiles increased to 63.8%, and the concentration of combustible components increased: 24.5% of carbon monoxide, 15.2% of hydrogen, and 4.5% of methane. The maximum values of the calorific value of the gas were achieved at 1050°C and amounted to 16.2 MJ/m³, while the proportion of volatiles reached 67.9%. In addition to gasification, a cycle of pyrolysis experiments was carried out in a nitrogen atmosphere at a temperature of 500°C, the inert gas feed rate was 1.5 m³/h (Fig. 1). As a result of pyrolysis, the yield of liquid products on average reached 23.4%, the solid residue was 39.8%, and the gas fraction was 36.8%. Analysis of the gas mixture showed that the hydrogen content reached 14.2%, methane reached 4.1%, and carbon monoxide reached 21.7%.

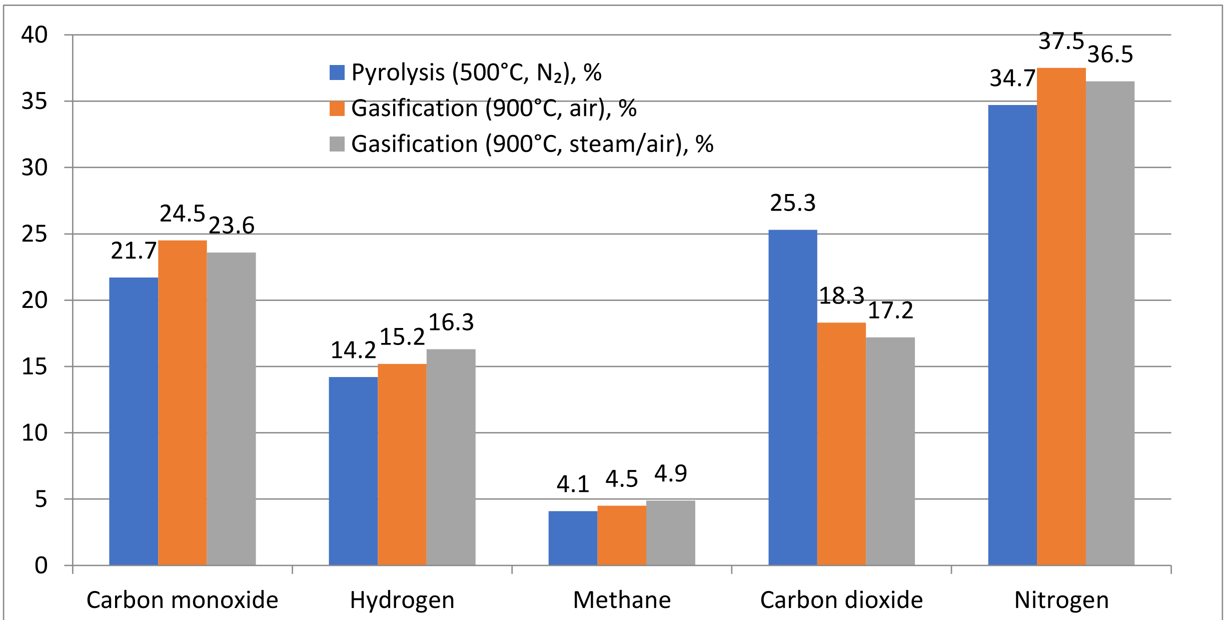

Fig. 1 The Composition of the Gas Fraction Obtained During Pyrolysis and Gasification (According to Gas Chromatograph Data).

In addition, combustion experiments with prepared fractions were conducted in a Carbolite Gero ELF 11/14 muffle furnace to compare the heat of combustion and ash yield. The combustion temperature was 1100 °C, and the heating rate was 8 °C/min. The results showed that, with complete oxidation of the waste, the calorific value was 14.9 MJ/kg on a dry-matter basis, and the average ash yield was 20.5%. Repeated experiments were performed to confirm the stability of the composition; the results deviated by no more than 5%. As part of the study, an elemental analysis of the organic fraction of the waste was carried out, revealing an average carbon content of 32.3%, hydrogen of 5.2%, oxygen of 27.8%, nitrogen of 0.7%, sulfur of 0.5%, and ash components of 18.9%. When modelling the gasification process in the ChemCAD 7.1 software environment, energy indicators were obtained. The estimated yield of synthesis gas per 1 kg of dry raw material at 900 °C was 2.35 m^3, with a calorific value of 15.1 MJ/m^3. An experimental test was conducted to assess the use of the obtained synthesis gas to feed a Siemens SGT-100 gas turbine with a capacity of 5 MW. Gas was supplied at a nominal rate of 180 Nm^3/h, and flame stability was maintained across the entire load range, with the excess air coefficient varying between 1.6 and 1.8. During operation, measurements showed that the CO concentration in the exhaust gases did not exceed 52 ppm, and the NOx content was 45–57 mg/Nm^3. Operational tests lasting 100 hours confirmed the feasibility of integrating the cogeneration scheme into the heat supply system. Analysis of the experimental data shows that the highest efficiency of the gasification process was achieved at 1050°C, explained by the activation of thermochemical decomposition reactions and an increase in the yield of combustible components. At the same time, increasing the temperature reduced the yield of solid residue, from 35% at 750°C to 26% at 1050°c. The yield of pyrolysis liquid products in experiments with a nitrogen atmosphere showed a significantly lower calorific value compared with gasification, amounting to about 10.3 MJ/kg in terms of the lower calorific value of combustion (Table 1). Comparison with literature data shows strong consistency. Beyond Table 2, the ChemCAD-predicted LHV of 15.1–16.2 $MJ·Nm^{-3}$, with CO = 24.5–27.8% and H_2 = 15.2–17.1%, falls within recent system-level analyses of mixed-MSW gasification under municipal operating constraints. Across typical moisture ranges, external studies show that pre-drying from ~40% to ~20% moisture content increases cold-gas efficiency, shifts H_2 upward, and keeps LHV within 14–17 $MJ·Nm^{-3}$ [2]. In a Latin-American WIG–GTCC case, the specific electric capacity reaches ~1.34 kW per $kg·h^{-1}$ of MSW feed [17], close to our pilot-scale value of ~1.0 kW per $kg·h^{-1}$ discussed below. Recent reviews and performance correlations place typical H_2 (≈12–18%) and CO (≈20–30%) fractions in the same range [19,20], supporting the robustness of the present validation for temperate-climate, mixed-stream MSW. Therefore, in [1], during gasification of mixed municipal waste in a similar temperature range, the calorific value of the synthesis gas varied from 13 to 17 MJ/m^3, and the proportion of carbon monoxide reached 25–30%, which is close to the data of the present study (Table 2). In [4], it was noted that with an increase in the gasification temperature above 1000°C, a stable increase in the concentration of hydrogen and a decrease in the yield of heavy hydrocarbons are observed, findings confirmed by the experimental results.

Table 1 Gasification Results at Different Temperature and Oxidizer Composition Conditions.

Parameter	750 °C (air)	900 °C (air)	1050 °C (air)	900 °C (steam/air 40/60)
Synthesis gas yield, m^3/kg	2.05	2.35	2.58	2.42
Caloric value, MJ/m^3	13.8	15.1	16.2	15.8
CO, %	19.4	24.5	27.8	23.6
H_2, %	12.7	15.2	17.1	16.3
CH_4, %	3.2	4.5	5.4	4.9
CO_2, %	20.8	18.3	16.0	17.2
Ash residue, %	35.0	29.0	26.0	27.5

Table 2 The Comparison of Thermal and Environmental Characteristics of the Obtained Synthesis Gas with the Results of Other Studies.

Parameter	Present study	Arena U. [1]	Chen H. [2]	Scarlat N. [4]
Calorific value, MJ/m^3	15.1–16.2	13–17	14–17	14–16
CO concentration, %	24.5–27.8	22–30	20–25	21–27
H_2 concentration, %	15.2–17.1	12–18	13–16	14–18
Ash content, %	26–29	25–32	22–28	23–30
NO_x in exhaust gases, mg/Nm^3	45–57	40–60	42–58	44–61

Additionally, when conducting experiments at a reduced air feed rate of 0.5 m^3/h in the gasification mode, the hydrogen content of the synthesis gas increased to 17.5% while maintaining a total calorific value of approximately 15 MJ/m^3. This result is consistent with [5], which established a dependence of the increase in H_2 content on the degree of oxygen rarefaction. As part of the pyrolysis experiments in a nitrogen atmosphere at a higher temperature of 600 °C, the yield of the gaseous fraction increased to 42.6%, and the carbon monoxide content reached 23.5%. At the same time, during pyrolysis at a temperature of 450 °C, the formation of a larger amount of liquid products was observed, the share of which was 28.3% of the dry feedstock weight. Additional cycles of experiments were carried out in a mixed gasification mode with the participation of a steam-air mixture in a ratio of 40:60. At a temperature of 900°C under these conditions, synthesis gas with a calorific value of 15.8 MJ/m³ and a hydrogen content of 16.3% was obtained. The simulations performed in ChemCAD confirmed that increasing the steam component contributed to more intense decomposition of oxygen-containing organic compounds and to a higher hydrogen concentration in the gas phase. A comparative analysis of the obtained data with the results of similar studies shows a high degree of correspondence in the structure of the gasification products. For example, in [2], the calorific value of gas, depending on the temperature and composition of the oxidizer, was in the range of 14–17 MJ/m³, which is entirely within the interval established in this work. In view of this, the results of the conducted set of experiments and simulations confirm the high energy and technological prospects of using solid municipal waste as a raw material for gasification and synthesis gas production. The data obtained indicate that integrating such installations into the existing heat supply system enables partial replacement of traditional fuels and a reduction in the carbon footprint. The conducted experimental cycles, including tests of the gas turbine unit, demonstrated process stability, stable synthesis gas parameters, and the potential to achieve high efficiency indicators for the cogeneration scheme.

4.CONCLUSION

The study presented detailed experimental and computational data indicating the high energy content of municipal solid waste (MSW) as a feedstock for gasification and cogeneration. Morphological analysis showed that the main components of the waste stream were paper and cardboard (24.7%), polymers (16.2%), the wood fraction (17.3%), and food residues (10.8%), which have significant potential for syngas generation. The elemental composition of the dry matter is characterized by an average carbon content of 32.3% and hydrogen of 5.2%, which confirms the prospects of thermal decomposition for energy purposes. During gasification experiments, increasing the process temperature from 750 to 1050 °C increased the yield of volatile substances from 58.3 to 67.9% of the original mass and the calorific value of the gas from 13.8 to 16.2 MJ m-3. At the maximum temperature, the carbon monoxide content in the gas mixture reached 27.8%, and hydrogen reached 17.1%, demonstrating the activation of gasification reactions of carbon-containing components. In addition, when carrying out pyrolysis in a nitrogen atmosphere at a temperature of 500 °C, the yield of the gas phase was 36.8%, and the liquid phase was 23.4%. Still, the calorific value of the pyrolysis gas remained significantly lower, at about 10.3 MJ/kg. Using a 40:60 steam-air mixture at 900 °C increased the hydrogen concentration to 16.3% and the calorific value to 15.8 MJ/m³. At the same time, the yield of synthesis gas per kilogram of dry raw material was 2.42 m³, which is comparable to the results of gasification with a purely air oxidizer at 900 °C (2.35 m³). Analysis of ash residue dynamics confirmed that, at higher temperatures, the mass of the solid phase decreased from 35% at 750 °C to 26% at 1050 °C, indicating more complete thermal decomposition of organic matter. Special attention was paid to assessing the stability of the gas composition obtained and its suitability for use in gas turbine units. In pilot cycles of feeding synthesis gas to the Siemens SGT-100 unit at a flow rate of 180 Nm³/h, the turbine operated stably with a fuel calorific value of 15–16 MJ/m³ and uniform ignition across all load modes. The CO concentration in the exhaust gases did not exceed 52 ppm, and the NOx content ranged from 45 to 57 mg/Nm³, indicating the environmental safety of the process. The comparison of the obtained data with the results of similar studies showed full compliance with key characteristics: the calorific value of the synthesis gas was in the range of 15.1–16.2 MJ/m³, the concentration of carbon monoxide was 24.5–27.8%, and hydrogen was 15.2–17.1%, which is close to the ranges recorded in [1, 2]. This confirms the correctness of the experimental base and the selected gasification modes. Therefore, the conducted complex of studies has demonstrated that MSW gasification technology produces a synthesis gas with a stable composition and high calorific value, suitable for use in cogeneration power plants. Consistent with the 100 kW pilot considered here for an MSW feed of ~100 $kg{\cdot}h^{-1}$, the demonstrated coupling supports a specific electric output of approximately 1.0 kW per $kg{\cdot}h^{-1}$ of dry MSW (≈ 1.0 $kWh{\cdot}kg^{-1}$ or 3.6 $MJ{\cdot}kg^{-1}$). For complete oxidation of the waste, the measured LHV is 14.9 $MJ{\cdot}kg^{-1}$, corresponding to a net electric efficiency on an LHV basis of about 24–26%, with the remainder recoverable as useful heat in the CHP mode. For municipal energy planning, this metric implies that a town generating ~25 $t{\cdot}d^{-1}$ of dry MSW can support roughly 1.0–1.2 MW_e of installed capacity and ~2–3 MW_{th} of cogenerated heat for district heating, enabling ~8–10 $GWh_e{\cdot}y^{-1}$ at 8000 operating hours. The results demonstrate that integrating such schemes can significantly increase the efficiency of municipal waste management, reduce disposal volumes, and decrease the burden on natural resources. Practical implications. For municipal planning, the verified syngas quality enables the direct coupling to standard gas turbines and engines with minor burner adjustments. Using the planning metric demonstrated here (~1.0 kWh per kg of dry MSW at 8000 $h \cdot y^{-1}$), approximately 25 $t \cdot d^{-1}$ of dry MSW can support ≈1.0–1.2 MWe and ~2–3 MWth of recoverable heat for district networks. Contemporary life-cycle literature indicates that shifting a significant fraction of MSW from landfilling/incineration toward gasification-CHP reduces net GHG emissions when high-efficiency energy recovery and appropriate gas cleaning are present. Future research. Next steps will extend the average-composition model to explicit scenario analysis (moisture and morphological fractions), quantify cold-gas efficiency and exergy across equivalence ratios, and embed a prospective life-cycle sustainability assessment with site-specific electricity/heat displacement factors, reporting GHG avoided per tonne of MSW alongside CAPEX/OPEX-normalized costs and social indicators.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

A.E. Uskov: Conceptualization, Methodology, Writing – original draft, Formal analysis, Investigation, Supervision. A.N. Tokareva: Data curation, Writing – review & editing, Validation, Visualization, Investigation. S.V. Panchenko: Software, Modeling, Resources, Formal analysis, Writing – review & editing. T.G. Vinogradova: Literature review, Data curation, Writing – review & editing, Visualization. U.K. Rakhmonov: Experimental setup, Investigation, Methodology, Validation. M.A. Xakimova: Laboratory experiments, Data acquisition, Formal analysis, Writing – review & editing.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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