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Heliothermal Conversion of Municipal Household Waste into Biogas: A Sustainable Approach for Environmental Protection and Resource Recovery

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Abstract:- The current global energy crisis and the growing threat of climate change necessitate significant innovation within the energy sector, as well as a swift transition to a green economy in both developed and developing nations. In this context, thermal power plants (TPPs) remain one of the main contributors to greenhouse gas emissions due to their dependence on fossil fuels, despite having traditionally formed the basis of electricity generation. Consequently, international and national energy strategies are focusing more and more on introducing technologies that reduce the environmental impact of TPPs, increase the efficiency of heat-to-energy systems, and cut emissions. Significant attention is being paid to adapting to climate-related challenges, decarbonising thermal energy infrastructure, and developing sustainable 'green growth' models that integrate renewable energy sources, waste-to-energy technologies, and advanced heat efficiency technologies into power generation systems. The depletion of traditional fossil fuel reserves, coupled with the environmental problems caused by their combustion, has led to a surge in global interest in environmentally friendly, waste-free energy technologies. At the same time, the world's population is growing rapidly and consumer production is expanding, leading to a significant increase in municipal solid waste generation and putting pressure on land and water ecosystems. This study aims to develop and evaluate a sustainable method of recovering waste gas from household solid waste through heliothermal (solar-assisted) anaerobic processing. The proposed system incorporates solar energy into the degradation process of waste, thereby reducing the need for conventional fossil fuels and minimising environmental emissions. A pilot-scale heliothermal reactor with a working volume of 1 m³ was designed. It features a dual-layer structure measuring 1.2 × 1.0 m, as well as a mechanical mixer, filter, gas holder and transparent top cover connected to a solar air heater (SAH). Experimental results under thermophilic conditions (50÷55°C) showed that 469 kg of household waste produced 95 m³ of waste gas and 365 kg of biogas. Introducing water and coal powder at a ratio of 3:1 increased waste gas generation efficiency by up to 138.9%. Furthermore, using previously fermented substrates as inoculum accelerated the onset of anaerobic digestion by 2–3 days. The

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developed heliothermal processing system offers a sustainable approach to waste treatment that reduces land pollution and enhances the recovery of renewable energy in municipal waste management.

***Keywords**: Heliothermal processing, anaerobic digestion, municipal solid waste, waste gas recovery, solar energy, biogas generation, environmental sustainability, renewable energy, waste management.*

1. Introduction

The accumulation and improper management of municipal solid waste (MSW) have emerged as significant challenges for environmental protection and the sustainable development of modern energy systems. In many developing countries, the steady rise in MSW generation caused by rapid population growth, industrialisation, agricultural expansion and increasing household energy consumption is putting additional pressure on land and water resources, and is having an indirect effect on the reliability and sustainability of energy infrastructures.

The uncontrolled disposal of solid waste results in the formation of leachates that contain organic pollutants, nutrients, heavy metals and pathogenic microorganisms. These substances can infiltrate soil layers and groundwater, which leads to the long-term degradation of natural resources and poses risks to energy-related facilities, water supply systems and agricultural production. Such environmental degradation reduces the resilience of ecosystems and increases the energy demand associated with water treatment, land restoration and safeguarding public health.

From a power system technology perspective, developing environmentally safe and energy-efficient waste treatment methods is particularly important. Advanced waste-to-energy approaches, such as heliothermal processing and anaerobic digestion, effectively integrate waste management with decentralised energy generation. These technologies mitigate the environmental impact of municipal solid waste (MSW) on land and water systems and enable the conversion of waste into useful energy carriers, such as biogas and thermal energy.

Integrating heliothermal-assisted anaerobic treatment systems into local energy networks improves energy efficiency, reduces dependence on fossil fuels and enhances energy security. Furthermore, these systems promote the adoption of circular economy principles by converting municipal waste from an environmental liability into a renewable energy source. This aligns waste management strategies with the objectives of sustainable power system development.

Fossil fuels — including natural gas, coal, shale and oil — currently form the basis of the world's traditional energy sources. These sources are becoming depleted every year due to processing and usage levels. The rational use of fuel and energy resources is one of the most important global issues. Successfully resolving this issue is crucial not only for the further development of the global community, but also for maintaining a sustainable environment. One promising approach to addressing this issue is to adopt new energy-efficient technologies that utilise renewable and alternative energy sources.

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In recent years, the depletion of traditional fossil fuel reserves and the environmental consequences of burning them have led to a significant increase in interest in waste-free technologies based on renewable energy sources in almost all developed countries worldwide. However, the world's rapidly growing population, coupled with improved living standards and increased consumption of consumer products, is leading to a sharp rise in solid household waste. This poses a global threat to human development and environmental sustainability. The Uzbek economy's main priorities are to increase the efficiency of energy resources, eliminate the impact of solid household waste on human health and environmental sustainability, and introduce waste-free, energy- and resource-efficient technologies to ensure the country's energy independence and preserve its export potential.

Municipal solid waste (MSW) comprises solid waste generated from daily activities such as work, industrial processes, manufacturing, household activities, medical services and landscaping. It includes food and fruit and vegetable waste, paper, metals (both ferrous and non-ferrous), textiles, industrial products, glass, rubber, plastic, wood, plant waste and household items that have lost their useful properties. The morphological composition of municipal solid waste (MSW) depends on various factors, such as the level of a country's or region's development, the population's cultural level, population density, gross domestic product per capita, customs, seasonal changes, the region's meteorological and climatic characteristics, and the characteristics of industrial sectors. Packaging materials account for one third of MSW, and this proportion is constantly increasing. MSW is characterised by its heterogeneous, multicomponent composition, low density, and instability (decomposability).

According to its morphological composition, solid household waste includes paper, bulky materials, organic waste, plastics, metals, rubber, leather, textiles, glass, wood, plant residues and other types of waste.

Annual standards for the generation of household waste per capita are in place. In Uzbekistan, for example, this figure is 150÷250 kg per year, whereas in Russia it is 225÷250 kg per year, and in developed European countries it averages at 600 kg per year.

2. Objectives

In modern cities and multi-storey residential areas, solid household waste generated by daily activities is stored in waste collection areas before being taken away for disposal or recycling. Figure 1 shows the Urban Neighbourhood Meeting (NM) waste collection area located in the territories of the “Oidin” and “Gungon” NMs in the city of Karshi in the Kashkadarya region. Waste dumped in these areas provides an ideal environment for the development of microorganisms that cause infectious diseases. Therefore, failing to neutralise waste and promptly transport it to landfills or recycling facilities can result in widespread environmental pollution and the spread of diseases that negatively affect human health.

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Figure 1. Waste collection area in the territory of a) "Oidin" NM and b) "Gungon" NM in Karshi city (as of 2024)

Figure 1 illustrates examples of improper municipal solid waste management typically observed in urban residential areas. Image (a) shows mixed household waste accumulating on unprotected ground, indicating an absence of systematic waste collection and primary sorting. Image (b) shows an overflowing waste container due to insufficient collection frequency and inadequate waste management infrastructure. Such conditions promote the uncontrolled dispersion of solid waste, increasing the risk of soil and groundwater contamination and creating favourable environments for the development of pathogenic microorganisms. The visual evidence presented highlights the need to implement environmentally safe and energy-efficient waste treatment technologies, such as heliothermal and anaerobic processing, to reduce the negative impact of municipal solid waste on land and water ecosystems.

Due to its direct interaction with the environment, the temperature of municipal solid waste (MSW) in landfills rises to between 25 and 35 °C, prompting the onset of aerobic decomposition. At the same time, the upper layer of the waste pile dries out and becomes highly flammable. Anaerobic decomposition of MSW in the lower, highly humid (85÷90%) layers that lack oxygen leads to the release of various compounds that cause environmental pollution, ozone layer depletion, and the formation of greenhouse gases.

3. Methods

The issue of recycling and disposing of solid waste is one of the most urgent problems facing countries around the world. Various methods are employed to address this issue. This process requires different conditions and technologies. However, as these methods are expensive to implement on a large scale, cheap, inefficient methods of waste recycling are commonly used in practice.

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There are several general methods for disposing of solid waste and eliminating its harmful effects, including burying municipal solid waste (MSW) in special landfills, processing it to obtain cheap raw materials, and direct incineration.

One such method is biothermal composting. This thermal processing method removes large compounds, metals, glass, plastic, polyethylene compounds, ceramics and rubber from MSW. The remaining organic waste is placed in a special biothermal drum and processed by supplying hot air at 60 °C under natural conditions. The organic compounds in the drum are kept for 2÷3 days, resulting in the production of compost. This composted organic waste is then cleaned of metals, crushed and transferred to the next stage for use as biotechnological fuel or compost in agriculture.

The anaerobic processing method. This method uses less energy and involves microorganisms decomposing organic matter in an oxygen-free environment. This process converts organic materials into waste gas, namely methane (CH_4), carbon dioxide (CO_2) and other low-molecular-weight substances.

To achieve this, the municipal solid waste (MSW) is continuously heated in an oxygen-free environment (in a waste reactor, bioreactor, or other specialised structure) at a temperature ranging from 25 to 60 °C for between 10 and 15 days, or up to 60 days depending on the temperature regime. Anaerobic processing of MSW results in the production of waste gas and high-quality local biofertiliser.

In A. Nopharatana's studies, the anaerobic processing of waste generated by factories and enterprises processing fruit, vegetables, and melons was examined. The experimental process involved adding food waste to the wastewater produced by these enterprises in the required proportion.

Chinese scientists Ruihong Zhang and Zhiqin Zhang have also studied the anaerobic digestion of rice straw for biogas production. In their research, they added ammonia to the processing of the rice straw and used it as an additional nitrogen source. Anaerobic digestion of rice straw was carried out using various physical (mechanical), thermal and chemical (ammonia) treatment methods at mesophilic temperatures between 30 and 35 °C. The results showed that the highest amount of biogas was produced when the rice straw was 10 mm long and the temperature and ammonia treatment were both 110 °C. This increased biogas production efficiency by 17.5% compared to untreated rice straw.

J. David studied the anaerobic digestion of cow dung and field crop residues. Under laboratory conditions, anaerobic digestion of a mixture of cow dung, barley straw, rice husks and straw was carried out over 18 months. The lignin-to-nitrogen and lignin-to-carbon ratios of the various feed mixtures given to the cows ranged from 12.3 to 40. Maximum efficiency occurred when the lignin-to-nitrogen ratio of these feed mixtures was between 25 and 32. Various factors

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affect the release of biogas, including the type and morphological composition of the MSW substrate, temperature, and mixing time. The most common indicator of anaerobic decomposition is the volume fraction of biological methane (CH_4), which characterises the maximum amount of methane gas that can be produced per unit mass of solids or volatile solids. Values for the methane produced by the anaerobic digestion of one tonne of solid household waste can be found in Appendix 1.6 of the dissertation. The average methane

H. Darimani and D.C. Pan proposed a technology for producing biogas through the anaerobic processing of a substrate made from a blend of food waste and plant and forest waste collected from Ghanaian pastures. During the research, laboratory-scale reactors were filled with various proportions of plant residues and food waste, totalling 8%. These were labelled R1 (100% food waste and 0% plant waste), R2 (75% food waste and 25% plant waste), R3 (50% food waste and 50% plant waste), R4 (25% food waste and 75% plant waste) and R5 (0% food waste and 100% plant waste). The temperature of the device was maintained at 35 ± 2 °C for 15÷20 days. The biogas output for R1, R2, R3, R4 and R5 was found to be 805 ml, 840 ml, 485 ml, 243 ml and 418 ml, respectively. Food waste produced 805 ml of biogas, while plant waste produced 418 ml. It was found that food waste produces 50% more biogas than grass.

Edwin Richard considered municipal solid waste (MSW) to be a raw material with a high organic and moisture content, noting that it is the best substrate for anaerobic fermentation. His research showed that the anaerobic digestion of MSW consists of four metabolic steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis. These metabolic steps have been found to be influenced by several factors, including the nature of the substrates, the accumulation of volatile fatty acids, and the proportion of ammonia.

Karamyan G.O. developed a solar biogas plant for a small pig farm and proposed a biogas plant with a heat supply using a flat solar water heating collector. A SOLAR-500 brand solar water heating collector with a useful surface area of 4.72 m^2 was selected for the heating system of the biogas plant. The developed bioreactor has a total volume of 20 m^3, a working volume of 14 m^3 (70% of the total) and a diameter of 2.6 m, with a height of 2.65 m and a substrate density of 1280 kg/m^3.

The following important conclusions were drawn during the research conducted within the framework of the research topic, based on a comparative analysis of the methods used in the processes of formation, collection, utilisation and processing of municipal solid waste (MSW), bioenergy, pyrolysis and combined solar biogas plants:

In countries around the world, and particularly in our own, leading scientists and specialists have conducted scientific, theoretical and practical research into the introduction of energy- and resource-saving devices that allow MSW to be processed and utilised using various methods, as well as into the selection of optimal thermal and technical parameters.

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Despite numerous scientific, theoretical and practical studies being carried out, taking into account the region's meteorological and climatic characteristics, including the high technical and economic potential of solar energy, insufficient research has been conducted on developing biogas plants with a heat supply system based on solar devices. This research should substantiate their thermal, heliotechnical, technical and economic parameters, reduce traditional fuel consumption in MSW processing and provide autonomous consumers and agricultural facilities with biogas (waste gas) and high-quality local fertiliser year-round.

Insufficient research has also been conducted into the selection of optimal parameters for solar air heating collectors and flat reflector waste reactors that enable heliothermal processing of municipal solid waste (MSW) through anaerobic fermentation. This would achieve energy and resource savings through the use of active and passive solar heating systems in waste reactors. The research would also identify interlayer heat and mass exchange processes in waste reactors and develop technical solutions for their implementation in practice. Furthermore, it would establish the technical and economic basis for solar air heating collectors and flat reflector waste reactors.

According to theoretical studies, energy consumption in all MSW processing methods is high, accounting for an average of 50–60% of the total energy balance of devices and technologies. A scientific and practical solution to this problem can be found by introducing active and passive solar heating systems to reduce the fuel and energy consumption of devices used for the thermal processing of MSW that has not been separated into useful components by anaerobic methods. This would ultimately achieve minimal heat losses.

Development trends in scientific, technical and practical solutions for energy-efficient anaerobic MSW processing devices and their implementation are primarily related to the development of MSW thermal processing devices with solar air collector heating systems. This involves selecting optimal thermal and technological parameters for these systems to ensure the device's heat load, studying interlayer heat exchange processes between the device material and waste, and investigating the properties of additives that maximise exhaust gas separation from MSW.

4. Results

The following important conclusions were drawn from the comparative analysis of the methods used in the formation, collection, utilisation and processing of municipal solid waste (MSW), bioenergy, pyrolysis and combined solar biogas plants, which was conducted within the framework of the research topic:

Leading scientists and specialists in countries around the world, including our own, have conducted scientific, theoretical and practical research into introducing energy- and resource-

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saving devices that allow MSW to be processed and utilised using various methods, as well as into selecting optimal thermal and technical parameters.

Despite numerous studies being carried out that take into account the region's meteorological and climatic characteristics, including the high technical and economic potential of solar energy, insufficient research has been conducted into developing biogas plants with a heat supply system based on solar devices. Such research would substantiate the thermal, heliotechnical, technical and economic parameters of these plants, reduce the consumption of traditional fuels in MSW processing, and provide autonomous consumers and agricultural facilities with biogas (waste gas) and high-quality local fertiliser year-round.

There has also been insufficient research into selecting optimal parameters for solar air heating collectors and flat reflector waste reactors to enable the heliothermal processing of municipal solid waste (MSW) through anaerobic fermentation. This would result in energy and resource savings by making use of active and passive solar heating systems in waste reactors. The research would also identify interlayer heat and mass exchange processes in waste reactors, developing technical solutions for their practical implementation. Furthermore, it would establish the technical and economic basis for solar air heating collectors and flat reflector waste reactors.

According to theoretical studies, energy consumption in all MSW processing methods is high, accounting for an average of 50÷60% of the total energy balance of devices and technologies. One solution to this problem is to introduce active and passive solar heating systems to reduce the fuel and energy consumption of devices used for the thermal processing of MSW that has not been separated into useful components by anaerobic methods. This would ultimately result in minimal heat loss.

Development trends in scientific, technical, and practical solutions for energy-efficient anaerobic MSW processing devices, and their implementation, are primarily related to the development of MSW thermal processing devices incorporating solar air collector heating systems. This involves selecting the optimal thermal and technological parameters for these systems to ensure the device’s heat load; studying the heat exchange processes between the device material and waste in the interlayer; and investigating additives that maximise the separation of exhaust gas from MSW.

The amount of solid household waste in local areas is currently increasing. In hot climates, this waste can lead to the formation of hazardous compounds such as methane and hydrogen sulfide. This research project has therefore developed a thermal scheme for a heliothermal processing device for household waste, presented in Figure 2.

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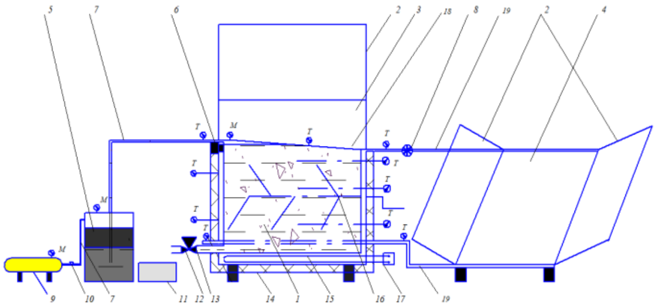

Figure 2. Thermal diagram of a heliothermal household waste recycling plant.

T – thermometer; M – manometer; 1 – waste reactor; 2 – flat reflector; 3 – transparent coating; 4 – flat reflector solar air heating collector with heat accumulator; 5 – filter; 6 – cap; 7 – pipe; 8 – fan; 9 – gas holder; 10, 13 – valve; 11 – bunker; 12 – MSW outlet pipe; 14 – insulation layer; 15 – air duct; 16 – mixer; 17 – electric heater; 18 – metal absorber; 19 – air pipe.

The proposed helithermal household waste treatment device operates as follows: Various types of household waste (including water) are loaded into the waste reactor (1) via a chute (6). A transparent triangular cover (3) acts as a passive solar heating system and is installed in the upper part of the waste reactor (1). Direct and scattered solar radiation passes through the transparent cover and is converted into thermal energy. This heats the metal absorber (18) and the waste in the reactor due to convective heat exchange. The temperature is recorded on a thermometer (T). To increase the energy efficiency of the waste reactor, a flat reflector is installed parallel to the rear of the reactor to refract incident solar radiation and increase the efficiency of the passive solar heating system. To constantly heat the household waste at a temperature of 30÷55 °C and minimise heat loss, the bottom and sides of the waste reactor are made in the form of air channels (15). A flat reflector solar air heating collector with a heat accumulator is connected to the upper part of the air channel via an air pipe. Hinged flat reflectors (2) and a heat accumulator are installed parallel to the side of the solar air heating collector with a heat accumulator (4), increasing the device's efficiency by enlarging its useful surface area. The solar air heating collector (4) with a heat accumulator heats the air to a temperature of 65÷75 °C using solar energy. The heated air is transferred to the air duct (15) of the waste reactor (1) via a fan (19) installed in the air duct, and the air inlet temperature is recorded on the thermometer (T).

Hot air moves along the air ducts (15), heating the waste mass via convective heat exchange through the bottom and side walls of the waste reactor (1). The waste mass is loaded into the reactor and heated anaerobically at a given temperature for 12–15 days, resulting in the release of a steam-gas mixture. Thermometers (T) and a monometer (M), installed at different points of the waste reactor (1), are used to determine the temperature and pressure of the waste mass in different layers. The vapour-gas mixture formed in the waste reactor moves along the pipe

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due to the pressure difference and enters the filter. We record the temperature of the vapour-gas mixture according to the thermometer indicator (T) installed in the pipe. The filter (5) consists of three parts: the lower part is made of water; the middle part is made of an adsorbent; and the upper part is made of hollow phases. The hydrogen sulfide and water vapour contained in the vapour-gas mixture entering the filter condense and remain in the aqueous phase. When the purified gas passes into the adsorbent phase, the moisture contained within it is absorbed by the adsorbent. Consequently, the waste gas passes into the hollow phase and its pressure is measured using a monometer (M). As the pressure of the waste gas builds up, it moves from the filter along the pipe and is collected in the gas holder connected to the pipe. Gas consumption is adjusted using the valve (10) installed in pipe (7).

The pressure of the collected exhaust gas in the gas holder is controlled by the monometer (M). An electric heater (17) is installed in the lower air channel (15) of the waste reactor (1) for use in winter. The lower side of the air channel (15) of the waste reactor (1) is connected to a flat reflector solar heating collector (4) with a heat accumulator via a pipe (19). The temperature of the air at the air channel outlet is measured using a thermometer (T). Air moves along the air channel due to the pressure created by the fan (8), giving up its heat as it moves through the air channel and the pipe (19) from the bottom of the flat reflector solar heating collector with a heat accumulator. The outer walls of the waste reactor are insulated to reduce heat loss in the air channel. Since the temperature of the waste mass loaded into the waste reactor (1) is lower than the air duct temperature (15), there is no heat loss to the environment. At the end of the cycle, the waste is discharged into the bunker (11) by opening the valve (13) in the household waste discharge pipe (12). The cycle then continues.

The design parameters of the Helithermal household waste recycling device can be found in Table 1.

Parameter name	To be determined	Unit	Amount
Waste reactor height	h	m	1,05
Waste reactor working volume	$V_{w.r.}$	m^3	1
Amount of waste mass to be loaded into the waste reactor	m_{MSW}	kg	300÷400
Waste reactor temperature regime and temperature range	t, Mesophile Thermophilic	°C	30÷35 50÷55
Transparent cover height	$h_{c.h.}$	m	0,3
Transparent cover surface	$F_{c.s.}$	m^2	1,0
Width of waste reactor	a	m	1,10

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Length of waste reactor	L	m	1,10
Width of waste reactor air duct	$a_{a.d.}$	m	0,05
Height of waste reactor air duct	$h_{a.d.}$	m	1,0
Waste reactor flat reflector surface	F_{Ref}	m^2	1,0
Useful surface of solar air heating collector	F_{col}	m^2	1,8
Surface of solar air heating collector flat reflectors	$F_{f.ref}$	m^2	1,8
Floor area occupied by the device	F	m^2	4,0
Thickness of waste reactor metal absorber	δ_{ab}	m	0,002
Thickness of waste reactor wall	δ_{wall}	m	0,004
Thickness of waste reactor insulation material	δ_{in}	m	0,06

In order to study the anaerobic heliothermal processing of household waste using solar energy, a pilot model of a heliothermal processing plant for household waste was created at the “Solar and Bioenergetic Devices” laboratory, which is part of the “Alternative Energy Sources” educational and scientific centre. The polygon is part of the “Energy Efficiency and Alternative Energy Sources” research and development centre within the “Energy Engineering” department at the Faculty of Energy Engineering at Karshi State Technical University (see Figure 3). Thermal-technical, experimental and research tests were then conducted.

Figure 3. Experimental setup of a heliothermal household waste treatment plant.

1-waste reactor; 2-solar air heating collector with flat reflector and heat accumulator; 3,4-flat reflector; 5-passive solar heating system, filter.

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The HW thermal treatment plant comprises the following systems:

- A solar air heating collector and a flat reflector waste reactor, which are designed in a parallelepiped shape measuring 1.2 x 1.0 m, in two layers. They are equipped with a mechanical mixer, a filter, and a gas holder. A transparent cover sits on top, and the systems are connected to the solar air heater (SAH) on the side. These systems enable the anaerobic treatment of solid household waste using the heliothermal method.

The side and bottom parts of the waste reactor consist of air channels and are connected to a flat reflector solar air heating collector with a heat accumulator and a useful surface area of 1.8 m^2. To increase the energy efficiency of the solar air heating collector, flat reflectors with a surface area of 1.8 m^2 are installed in parallel. Water and transformer oil are used as heat accumulators. Consequently, the solar air heating collector with a flat reflector and heat accumulator serves as an active solar heating system, processing solid household waste in the waste reactor at temperatures ranging from 30 to 35 °C and 50 to 55 °C.

A transparent triangular cover is installed on top of the waste reactor to act as a passive solar heating system. To increase the efficiency of this passive system, a flat reflector measuring 1.2 x 1.0 m is installed in parallel with the waste reactor on its back.

Experimental research methodology. This study involves conducting experiments to produce waste gas and local fertiliser (digestate) from household waste, as shown in Figure 1. The heat required for anaerobic fermentation-based heliothermal waste processing is provided by the active and passive solar heating systems of the waste reactor.

The experimental model of the thermal processing device for solid household waste consists of three parts:

1. The waste reactor is shaped like a parallelepiped to enable the production of waste gas and high-quality local fertiliser (digestate) through the anaerobic fermentation of household waste.

2. The passive solar heating system, whereby the upper part of the waste reactor is covered with transparent glass to act as a passive solar heating system. Flat reflectors installed parallel to the waste reactor increase the system's efficiency.

3. The active solar heating system connects the waste reactor in series to a flat reflector solar air heating collector. This has an air duct installed on the side and bottom, as well as a heat accumulator. This setup acts as an active solar heating system.

To conduct our experimental study, we load the household waste produced by the student cafeteria at the Faculty of Energy Engineering into the waste reactor via a loading bunker. We then add water at a ratio of 3:1 to the waste to ensure anaerobic fermentation and secure the bunker.

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A mechanical mixing device inside the waste reactor mixes the waste mass four to five times a day. To maintain the temperature regime required for anaerobic fermentation of the waste loaded into the reactor, a triangular glass panel is installed at a 45° angle in the upper part of the reactor. Solar radiation passes through the glass and is converted into thermal energy, which is absorbed by the absorber and used to heat the waste via thermal conductivity. To increase the passive solar heating system's efficiency, a flat reflector is installed parallel to the back of the waste reactor. The reflector refracts solar radiation falling on its grey surface, returning it to the glass and doubling the energy of the incoming radiation. This increases the energy efficiency of the passive solar heating system. In passive solar heating systems, temperature is recorded using an installed thermometer.

In an active solar heating system, a flat reflector solar air collector with a heat accumulator connected in series to the air duct of the waste reactor is used (SAH). The waste reactor is connected to a pipeline network, with a fan installed inside. The fan forcibly moves the air heated by solar energy in the SAH. We record the temperature of the hot air at the inlet to the waste reactor air duct using a thermometer. The hot air moving in the waste reactor air duct heats the mass loaded into the waste reactor due to convective heat exchange. The outlet of the waste reactor air duct is connected to the SAH via a pipeline network, and the temperature of the air at the outlet is recorded using a thermometer.

We measure the temperature of the waste material loaded into the waste reactor using thermometers installed at various points within the reactor, as well as a manometer located at the top. The steam-gas mixture formed during anaerobic digestion is cleaned of water and hydrogen sulfide by passing it through a filter. The resulting waste gas is then collected in a gas holder and directed for consumption.

From 14 to 28 May 2022, experimental studies of the anaerobic processing of household waste in one operating cycle of a flat reflector waste reactor with a solar air heating collector were carried out in the city of Karshi’s natural climatic conditions.

The results showed that adding water at a ratio of 1:3 to household waste with different morphological compositions at a specified thermophilic temperature regime (50–55 °C) produced different amounts of waste gas and local biogas through heliothermal processing. The results obtained are presented in Table 2.

The experimental process was carried out for 15 days, after which the remaining waste mass (local fertiliser) in the waste reactor was discharged using a discharge bunker.

Thus, the cycle continues.

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Table 2.

Experimental results

No	Hausehold waste, kg	Temperature regime, °C	Amount of waste gas, m^3	Local biofertilizer, kg,
1	466	50÷55	68	396
2	466	50÷55	70	393
3	466	50÷55	69	395
4	466	50÷55	62	398
5	466	50÷55	65	399

The distribution of the main gaseous components was analysed in order to evaluate the quality and energy potential of the waste gas produced during heliothermal anaerobic digestion.

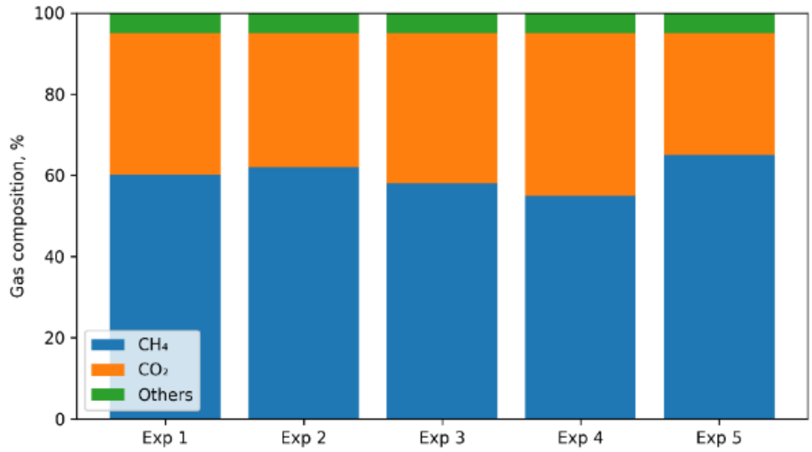

Figure 4. Chemical composition of waste gas generated during heliothermal anaerobic processing of municipal solid waste and its implications for energy recovery under thermophilic conditions (50÷55 °C).

Figure 4 illustrates the composition of waste gas produced by heliothermal-assisted anaerobic digestion of municipal solid waste under thermophilic conditions (50÷55 °C). The stacked bar chart illustrates the proportions of methane (CH_4), carbon dioxide (CO_2) and other gaseous components in the waste gas produced in five experimental runs.

The results demonstrate that methane is the dominant component of the waste gas produced, with concentrations ranging from approximately 55% to 65%. This high methane content confirms the effective performance of the anaerobic digestion process under thermophilic

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conditions and demonstrates the strong energy potential of the generated gas. The consistently high CH_4 content across all experiments indicates stable methanogenic activity and favourable process conditions.

Carbon dioxide is the second most abundant component, accounting for around 30÷40% of the total gas composition. The presence of CO_2 is associated with the acidogenesis and acetogenesis stages of anaerobic digestion, during which complex organic compounds are converted into intermediate products. The moderate and relatively stable CO_2 fraction indicates balanced microbial conversion and the absence of process inhibition.

Minor gaseous components, including hydrogen sulfide (H_2S), ammonia (NH_3) and trace compounds, collectively remain below 5%. Their low concentration reflects controlled anaerobic conditions, which contribute to improved gas quality and reduced downstream gas purification requirements.

Overall, the observed gas composition demonstrates that heliothermal pretreatment combined with thermophilic anaerobic digestion increases methane production while ensuring consistent biogas quality. These results support the feasibility of the proposed system for decentralised energy generation and confirm its applicability for waste-to-energy integration within sustainable power systems.

The resulting residual mass is shown in Figure 4 below.

Figure 4. Local biofertilizer appearance

Figure 4 shows what the local biofertiliser looks like. It is produced as a by-product of heliothermal processing combined with the anaerobic digestion of household waste. As the experimental results demonstrate, the texture, homogeneity and moisture content of the biofertiliser depend on the morphological composition and granulometric characteristics of the processed municipal solid waste.

The presence of finely shredded organic matter promotes more uniform degradation, resulting in a darker, more homogeneous biofertiliser with improved structural consistency. Conversely, coarse or poorly sorted waste fractions hinder the biodegradation process, resulting in incomplete stabilisation and the formation of heterogeneous residues. These results confirm

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that particle size distribution and organic content play a critical role in the efficiency of anaerobic digestion and the subsequent quality of the biofertiliser.

Additionally, heliothermal pretreatment enhances microbial activity by raising the temperature of the substrate, thereby accelerating the hydrolysis and acidogenesis stages of anaerobic digestion. Consequently, the decomposition of complex organic compounds intensifies, leading to increased biogas production and improved nutrient availability (e.g. nitrogen and phosphorus compounds) in the residual biofertiliser.

According to the experimental results, the quantity and quality of waste gas and local biofertiliser produced during heliothermal processing of household waste depend heavily on the morphological composition and granulometric characteristics of the waste. These factors affect the rate of anaerobic degradation, the stability of the fermentation process, and the efficiency of energy recovery.

The experiments demonstrated that anaerobic digestion occurs more quickly at thermophilic temperatures (50÷55°C) than at mesophilic temperatures (30÷40 °C). Operating in the thermophilic regime increased waste gas production by 45÷50%, but this was accompanied by higher thermal energy consumption. This trade-off highlights the importance of optimising the operating temperature to balance energy input and biogas output.

Furthermore, it was established that introducing previously fermented material as an inoculum into the waste reactor prior to heliothermal treatment could accelerate the initial stage of anaerobic fermentation by two to three days. Using inoculum enhances microbial activity and reduces the lag phase of the digestion process.

Tables 3

Annual waste gas and biofertilizer production rates obtained in a 1 m^3 waste reactor

Waste type	**Waste+water +coal residue, kg**	**Exhaust gas, m^3**	**Biofertilizer, kg**	**Annual waste gas, m^3**	**Annual amount of biofertilizer, kg**
Household waste	469	95,9	365	2877	10 950
Paper waste	242	55	185	1650	5550
Leaves	283	53,2	226,8	1596	6804

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Additionally, the experimental results confirmed that introducing coenzymes intensifies anaerobic fermentation, thereby increasing the volume and methane content of the generated waste gas. This approach promotes the complete degradation of organic matter and improves process stability.

Using a co-fermenter increased the efficiency of waste gas production during the thermal processing of solid household waste. In this study, coal residue was added to the co-fermentation process. First, a mixture of household organic waste, paper waste and leaves was loaded into the waste reactor. Then, 1% coal residue was added. Water was then added to the waste mass at a ratio of 3:1 to ensure optimal moisture conditions. Table 3 summarises the improvements in waste gas yield and biofertiliser quality resulting from this process.

Based on the experimental data, the annual waste gas and local biofertiliser production rates obtained from a 1 m³ waste reactor demonstrate the practical potential of heliothermal-assisted anaerobic processing for decentralised waste-to-energy applications.

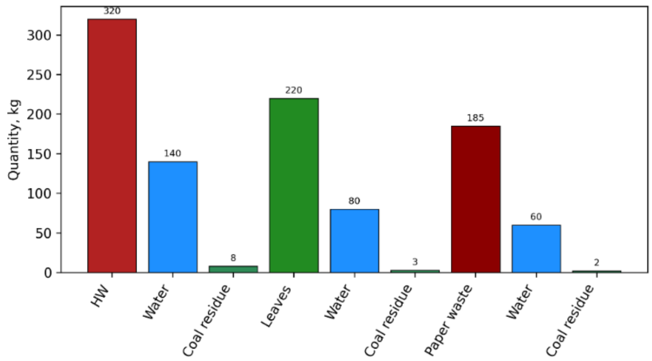

Figure 5. Material balance of thermal processing of municipal waste.

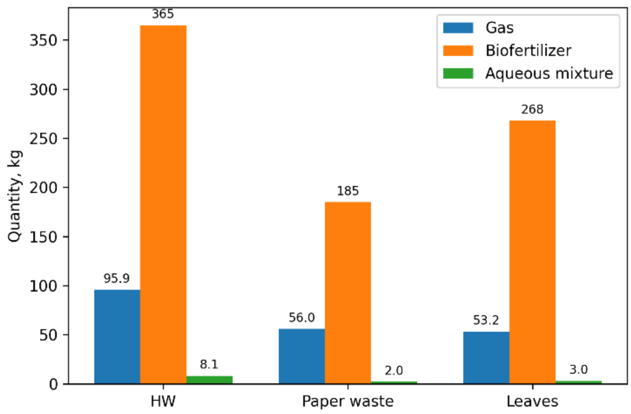

Figure 6. Material balance of products obtained from helithermal processing of household waste.

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The experimental results indicate that the 1 m^3 waste reactor was loaded with 350 kg of mixed household waste, 180 kg of paper waste, and 210 kg of tree leaves, all of which had varying densities. To initiate the anaerobic fermentation process, the mixture was supplemented with water and 1% coal powder by mass, at a ratio of 3:1.

5. Discussion

Under these operating conditions, a significant improvement in waste gas recovery efficiency was observed. Compared to the baseline process without additives, the efficiency of separating waste gas increased by 138.9% for household waste, 127.9% for paper waste and 133% for tree leaves. These results confirm the positive effects of moisture regulation and the use of coal powder as a co-fermenting additive in intensifying anaerobic digestion.

The enhanced gas separation efficiency can be attributed to improved mass transfer conditions, stabilisation of the microbial environment, and promotion of methanogenic activity within the reactor. Overall, the results demonstrate the effectiveness of the process configuration for increasing biogas yield from heterogeneous organic waste streams.

The figure below shows a quantitative comparison of the main products obtained from the heliothermal-assisted anaerobic digestion of various organic waste materials, such as household waste, paper waste, and tree leaves. The results clearly show how yields of gas, biofertiliser, and the aqueous mixture vary depending on the feedstock type.

Household waste exhibits the highest overall productivity, generating 95.9 kg of waste gas and 365 kg of biofertiliser. This can be attributed to its heterogeneous morphological composition and higher content of readily biodegradable organic matter. The high biofertiliser yield indicates effective stabilisation of the organic components and favourable nutrient retention conditions in the digestate. Compared to other types of waste, paper waste shows comparatively lower gas yields (56.0 kg) and moderate biofertiliser production (185 kg). This behaviour is associated with its higher cellulose content and the lower availability of easily degradable compounds, both of which limit microbial activity during anaerobic digestion. Consequently, the fermentation process proceeds at a slower rate, resulting in reduced biogas formation.

Tree leaves demonstrate intermediate performance, producing 53.2 kg of waste gas and 268 kg of biofertiliser. The relatively high biofertiliser output reflects the significant lignocellulosic fraction of leaves, which contributes to solid residue formation whilst enabling partial biodegradation under heliothermal conditions.

The yield of the aqueous mixture remains minimal across all waste types (2÷8.1 kg), indicating effective phase separation and confirming that the applied process parameters favour the conversion of organic matter into gaseous and solid products rather than liquid by-products. Overall, the results confirm that heliothermal-assisted anaerobic processing efficiently recovers resources from heterogeneous household waste streams. The highest energy and material

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recovery is achieved for mixed household waste. These results demonstrate the potential of the proposed approach for integrated waste-to-energy and biofertiliser production systems.

6. Conclusions

Based on the results of the conducted experimental studies, it can be concluded that heliothermal processing of municipal solid waste (MSW) under controlled thermophilic conditions (50÷55 °C) is an effective and energy-efficient approach to simultaneously treating waste and producing renewable energy. The experimental results showed that the heliothermal treatment of household waste with varying morphological compositions yielded up to 469 kg of processed material, with an average production of 95.9 m³ of waste gas and 365 kg of local biofertiliser.

Comparative analysis of temperature regimes confirmed that household waste decomposes significantly faster under thermophilic conditions (50÷55 °C) than under mesophilic conditions (30÷35 °C). Operating in the thermophilic regime increased waste gas generation by 45÷50%, indicating enhanced microbial activity and improved conversion efficiency of organic matter, despite the higher thermal energy demand.

Furthermore, the experimental findings revealed that introducing previously fermented material as an inoculum prior to heliothermal treatment accelerates the initiation of the anaerobic digestion process by 2÷3 days. This reduces the lag phase, improves process stability, and increases energy yields during fermentation.

Integrating anaerobic digestion with heliothermal pretreatment enables the organic fraction of municipal solid waste (MSW) to be converted into valuable energy carriers, including waste gas, biogas, and nutrient-rich biofertiliser suitable for agricultural use. The resulting biofertiliser can effectively improve soil fertility, while the generated waste gas provides an alternative, renewable energy source.

From an environmental perspective, the proposed technology significantly mitigates the harmful impact of unmanaged household waste on land and water ecosystems. It prevents groundwater contamination, mitigates soil degradation, and limits the spread of pathogenic microorganisms. Furthermore, using renewable solar thermal energy alongside anaerobic fermentation reduces greenhouse gas emissions and promotes sustainable waste management practices.

Overall, heliothermal-assisted anaerobic processing of municipal solid waste is a cost-effective, eco-efficient solution that combines renewable energy with sustainable land and water resource management. This approach aligns with the principles of the circular economy and will support Uzbekistan’s transition to a decentralised, low-carbon, environmentally resilient energy system.

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