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Advanced Waste Management: Fast Pyrolysis Technology with Solid Heat Carrier for Municipal Solid Waste Processing

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Abstract

Municipal solid waste (MSW) recycling is critical in addressing the environmental challenges posed by increasing urbanization and waste generation. This study explores the use of fast pyrolysis technology with solid heat carriers for efficient MSW processing. The technology, originally developed for oil shale processing, involves the thermal decomposition of waste in an oxygen-free environment using its own ash as a heat carrier. This method produces valuable outputs, including synthetic oil, gas, thermal and electrical energy, construction materials, and ferroalloys. The study conducts a comprehensive techno-economic analysis of fast pyrolysis plants with capacities of 150,000 tons/year (UTT-500) and 1,000,000 tons/year (UTT-3000), assessing their technical feasibility, economic viability, and environmental performance. Results indicate that this technology can significantly reduce harmful emissions compared to traditional incineration and offers greater versatility in processing various waste types. The findings support the potential of fast pyrolysis to enhance MSW management, aligning with circular economy principles and contributing to sustainable waste management practices. This research underscores the need for innovative solutions to improve recycling efficiency and reduce environmental impact, addressing the growing waste management challenges in urban settings.

Keywords: Fast pyrolysis; Solid heat carrier; Waste-to-energy; Techno-economic analysis.
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1. Introduction

The history of solid waste management is a reflection of the development of cities and technology. In ancient times, waste was most often incinerated or discarded outside city walls. In medieval Europe, household rubbish was simply piled up in the streets until sanitation became an important aspect of life. By the end of the nineteenth century, with population growth and urbanisation, the first incinerators and waste disposal systems began to be built.

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Municipal solid waste (MSW) recycling has become a critical component in waste management strategies worldwide, driven by increasing urbanization, population growth, and environmental concerns.[1–3] The process involves the collection, sorting, and transformation of recyclable materials from household and commercial waste streams into new products, thereby reducing the volume of waste sent to landfills or incineration facilities. Despite significant advancements in recycling technologies and increased public awareness, the global recycling rate remains relatively low, with only about 13.5% of MSW being recycled globally as of 2020.[4] This highlights the urgent need for improved recycling systems and policies to address the growing waste management challenges faced by municipalities and nations alike.

The effectiveness of MSW recycling programs is influenced by various factors, including public participation, technological capabilities, economic viability, and regulatory frameworks.[5–8] While some countries have made substantial progress in implementing comprehensive recycling initiatives, others struggle with inadequate infrastructure, limited resources, and a lack of public engagement. Furthermore, the complexity of modern consumer products, particularly in electronics and packaging, poses additional challenges to the recycling process.[9,10] As researchers and policymakers continue to seek innovative solutions to enhance MSW recycling efficiency and reduce environmental impact, there is a growing emphasis on adopting circular economy principles and developing more sustainable consumption patterns to address the root causes of waste generation.[11,12]

In the realm of MSW management, the concept of waste-to-energy has emerged as a highly efficient approach to waste utilization. This method transforms waste into a valuable alternative energy source, addressing both waste reduction and energy production challenges simultaneously.[13,14]

One such promising approach is fast pyrolysis using solid heat carriers, which offers a potential solution for processing various types of waste, including MSW. Unlike conventional pyrolysis methods, fast pyrolysis occurs within milliseconds in a specialized mixer, where the feedstock comes into contact with ash heated to 800 °C, rapidly increasing its temperature to 500-520 °C. This rapid thermal decomposition distinguishes it from slow pyrolysis, which typically takes several hours at lower temperatures (300-400 °C), and from standard pyrolysis, which occurs in minutes to hours at moderate heating rates. Following the initial stage in the mixer, the material enters a rotating drum reactor, where it undergoes further pyrolysis for 15-20 minutes, ensuring efficient conversion into valuable products.

Fast pyrolysis has been successfully implemented in various industrial applications, particularly in the processing of oil shale and lignite.[15] Several studies have demonstrated that this method significantly enhances thermal efficiency and product yield compared to traditional slow pyrolysis.[16] However, its application in MSW treatment remains relatively underexplored, making this study a crucial step toward adapting and optimizing fast pyrolysis for sustainable urban waste management.

Incineration, a widely adopted waste-to-energy technique globally, offers significant advantages. It can process unsorted or untreated waste, generating energy while dramatically reducing waste volume by up to 90%, thereby minimizing the need for landfills.[17,18] However, this process is not without drawbacks. The byproducts of incineration, including ash residue and gaseous emissions, often pose substantial environmental risks. To mitigate these hazards, state-of-the-art incineration facilities employ sophisticated multi-stage gas purification systems. Notably, the cost of these purification systems frequently exceeds that of the primary incineration equipment, highlighting the economic challenges of this approach.[19,20]

In contrast, thermal decomposition technologies, particularly pyrolysis, present a promising alternative to direct incineration for MSW treatment.[14,21-25] Pyrolytic methods offer several advantages in the thermal processing of solid waste. They significantly reduce harmful emissions, especially the highly toxic polychlorinated dibenzo-para-dioxins and dibenzofurans.[25–27] Furthermore, pyrolysis techniques are more versatile, capable of processing diverse waste compositions without requiring costly fuel preparation.[28–30] This flexibility and reduced environmental impact position pyrolysis as an increasingly attractive option in the evolving landscape of waste-to-energy technologies.

In light of these global challenges in MSW recycling, innovative technologies are crucial for improving recycling efficiency and reducing environmental impact. One such promising approach is fast pyrolysis using solid heat carriers, which offers a potential solution for processing various types of waste, including MSW. This study presents a techno-economic analysis of MSW processing using fast pyrolysis technology in plants with solid heat carriers, capable of processing 150,000 tons/year (UTT-500) and 1,000,000 tons/year (UTT-3000) of dry mass. This method, originally developed for oil shale processing, has been adapted for MSW treatment, potentially offering a more efficient and environmentally friendly alternative to traditional recycling and waste management techniques.

The proposed technology is based on the method of fast pyrolysis, developed by specialists at the G. M. Krzhizhanovsky Energy Institute (Moscow, Russia) in the 1940s.[31] This method involves the thermal decomposition of finely crushed raw material in a continuous, oxygen-free process using its own ash as a heat carrier. The process yields a vapor-gas mixture and a carbonaceous residue (semi-coke).[32] This versatile method is suitable for processing various low-potential raw materials, including oil shale, lignite, filter cakes, and MSW.[33]

The technology has been successfully implemented in several oil shale processing plants in the Baltic region. Notable examples include the Kiviõli Chemical Plant (Estonia) with two UTT-500 units, the "Oil Factory" at the Estonian Power Plant site with two UTT-3000 units, and VKG AS in Kohtla-Järve (Estonia) with three UTT-3000 units.[34] The total processing capacity of these UTT-type units exceeds 5.3 million metric tons per year, with operational lifespans ranging from 6-12 years (Kohtla-Järve) to 40 years ("Oil Factory").[35]

The long-term industrial application of this technology in oil shale processing demonstrates its reliability and efficiency, making it a promising candidate for MSW treatment. Our research aims to adapt and optimize this proven technology for the challenges specific to MSW processing, potentially offering significant advantages in terms of energy recovery and environmental impact compared to conventional waste management methods.

This comprehensive approach to waste processing not only addresses the pressing issue of MSW management but also offers a solution for various industrial waste streams. By transforming these waste materials into valuable resources, the technology aligns with circular economy principles and contributes to sustainable waste management practices.[36] The ability to process such a diverse range of waste materials while producing multiple valuable outputs underscores the versatility and potential economic benefits of this fast pyrolysis technology.

The objective of this study is to conduct a comprehensive techno-economic analysis of MSW processing using fast pyrolysis technology with solid heat carriers. Specifically, we aim to:

- Evaluate the technical feasibility and economic viability of fast pyrolysis plants with capacities of 150,000 tons/year (UTT-500) and 1,000,000 tons/year (UTT-3000) for processing dry MSW.
- Assess the potential for producing valuable outputs, including synthetic oil, gas, thermal and electrical energy, construction materials, and ferroalloys from the pyrolysis process.
- Explore the adaptability of this technology, originally developed for oil shale processing, to various types of low-potential raw materials, including MSW, lignite, and industrial wastes.

Through this analysis, we seek to contribute to the development of more efficient, economically viable, and environmentally friendly solutions for MSW management, addressing the growing challenges of waste disposal and resource recovery in urban environments.

2. Materials and methods

2.1 Sample preparation

The methodology for sample preparation of MSW was designed to ensure reliable analysis and quality assessment by following standardized protocols for sampling, processing, and storage. Depending on the storage conditions and state of the waste, different sampling methods were applied. Sampling from the material flow was the preferred method, as it minimized errors associated with material heterogeneity. Samples were collected from a moving conveyor belt, ensuring uniform distribution across the entire batch. Sampling from transport vehicles was conducted when waste was delivered in batches. Each batch required a specific number of spot samples taken from different levels of the vehicle (surface, middle, and bottom). Sampling from stationary material (stored waste) was performed if the waste was stockpiled in stacks or containers. In this case, samples were collected layer by layer to ensure uniform composition.

The minimum number of spot samples collected per batch was 24, based on the material's homogeneity and the need for representativeness. Once collected, the samples underwent preliminary processing, including grinding and homogenization to reduce particle size to <100 μm, preventing fractional separation and ensuring uniform composition. Drying under controlled conditions was performed if the sample moisture content exceeded 15%, in such cases, the material was stored at a temperature not exceeding +5 °C for no more than one week. If long-term storage was required, pre-drying was conducted before analysis. Prepared samples were stored in airtight containers in a dry environment to prevent moisture absorption and alterations in chemical properties. All information regarding sample origin, sampling method, and storage conditions was documented in a laboratory log. This sample preparation methodology ensured high accuracy in MSW composition analysis, enabling an objective assessment of its suitability for processing via rapid pyrolysis.

2.2 MSW pyrolysis process

The analysis of the yield of solid, liquid, and gaseous products from the thermal decomposition of MSW was conducted within the temperature range of 470-520 °C. The process was carried out in an aluminum retort, where the sample was heated for 80 minutes under an oxygen-free atmosphere. This setup allowed for the controlled decomposition of organic components, followed by the condensation and collection of volatile products. To ensure precise quantification, the experiment involved systematic separation and measurement of the resulting fractions.

The solid residue (char) remaining in the retort after pyrolysis was weighed to determine the yield of the carbonized fraction. The condensed phase, consisting of tar and pyrolytic water, was collected in a receiver cooled by a water bath. The mass of pyrolytic water was determined volumetrically using a toluene-based distillation method, while the yield of tar was calculated by subtracting the mass of pyrolytic water from the total mass of condensed products. The gaseous fraction was calculated as the difference between the initial mass of the sample and the sum of the masses of the char, tar, and pyrolysis water. To ensure the accuracy of the results, all mass measurements were performed with high-precision analytical balances.

The collected data were subsequently normalized to different reference states, including dry and analytical conditions, to facilitate comparative analysis. This methodology enabled a detailed assessment of the mass distribution of pyrolysis products, providing insights into the efficiency and feasibility of MSW conversion into valuable energy carriers. The experimental protocol was designed to minimize potential sources of error, ensuring reproducibility and reliability of the obtained results.

The main feature of the technology is that the crushed waste, after separation and sorting, is dried in a fluidized bed, and sand of 0-2 mm, heated in an air-fountain heater, is used as a solid heat carrier (SHC). The mixture of MSW and SHC with lime is then fed into a rotating drum pyrolysis reactor.

Fig. 1 shows a schematic diagram of the installation for MSW processing. The MSW processing method includes stages of sorting and classification, mixing with a solid heat carrier, pyrolysis in a drum-type reactor to produce a vapor-gas mixture of pyrolysis products, which is sent for condensation, and a solid carbon-containing residue, which is utilized in a heat recovery boiler to produce steam.

MSW and industrial waste are transported to the industrial site of the enterprise by truck or conveyor transport. In the preparatory department of MSW (1), the waste partially (in

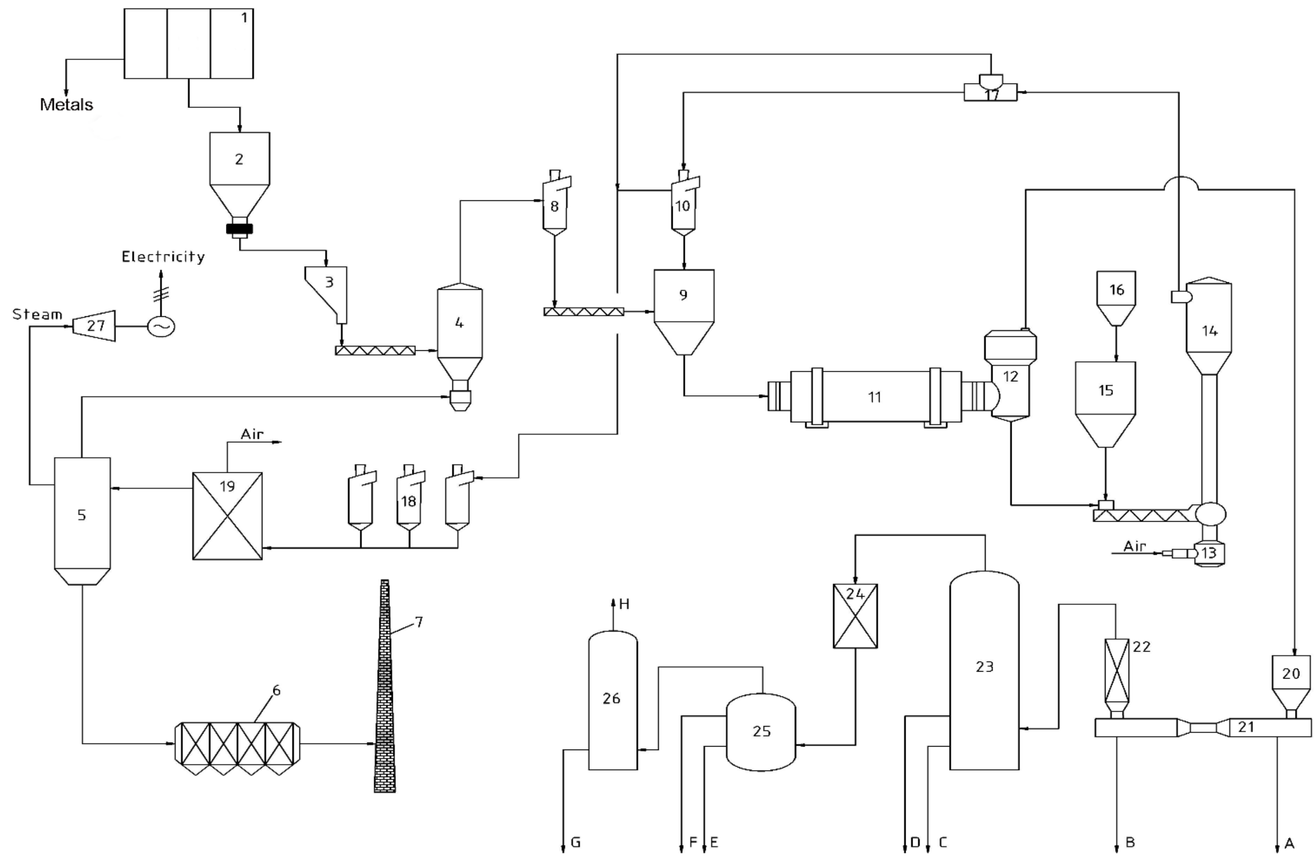

Fig. 1: The principal scheme of high temperature pyrolysis with solid heat carrier. 1 - preparatory unit, 2 - feeder, 3 - receiving hopper, 4 - air fountain dryer, 5 - heat recovery boiler, 6 - electrofilter, 7 - chimney, 8 - MSW cyclone, 9 - mixer, 10 - heat carrier cyclone, 11 - rotary kiln reactor, 12 - dust separation chamber, 13 - air fountain furnace, 14 - air fountain heater, 15 - sand hopper, 16 - lime hopper, 17 - heat carrier bypass, 18 - ash cyclones, 19 - ash heat exchanger, 20 - wet scrubber, 21 - gas-collecting main, 22, 24 - cooler, 23 - rectification column, 25 - separator, 26 - tower washer, 27 – steam turbine. Products: A - dirty oil for pyrolysis, B - heavy-medium fraction, C - medium oil, D - diesel fraction, E - phenolic water, F - gasoline fraction, G - water and gas condensate, H - semicoke gas to consumers.

portions) undergoes preliminary dosimetric control, separation by groups and sorting, for example, capturing metal particles or objects with electromagnetic separators, followed by pressing of ferrous metal (with possible manual removal of non-ferrous metal), crushing to a fraction of 0-25 mm, and classification of the inorganic part with removal of foreign objects.

The raw material prepared for processing is fed by a belt conveyor to the feeder (2). Then, the MSW passes through scales via conveyor and is fed into the receiving hopper (3) of the screw (auger conveyor) for raw materials, and further - by screw into the air fountain dryer (4). The screw is equipped with a sealing chamber to prevent gas flow from the mixer into the atmosphere.

The drying agent is flue gas from the heat recovery boiler (5) with a temperature of 150-350 °C. The spent drying agent is purified from volatile oxides in absorbers, and from dust in an electrostatic precipitator (6), and is discharged into the atmosphere through a chimney (7). Ferrous and non-ferrous metals are extracted from the dry crushed waste.

After the drying stage, the MSW charge settles in a cyclone (8) and is fed by a sealing screw to the mixing stage in a shelf-type mixer (9), where, in addition to the raw material, the heat carrier - ash from processed raw materials with sand and lime at a temperature of 800-1000 °C - is fed through a cyclone (10). When mixing the raw material and the heat carrier, the mixture temperature is established at 470-520 °C, and the pyrolysis process begins in a rotating drum reactor (11). Pyrolysis is carried out with a solid heat carrier to MSW ratio in the range of 2-3.

From the reactor, pyrolysis products in the form of a vapor-gas mixture (a mixture of liquid fraction vapors and pyrolysis moisture), ash, and semi-coke enter the dust settling chamber (12) with built-in cyclones, where the flows are separated: the solid phase is directed to the semi-coke screw, while the vapor-gas mixture undergoes cyclone purification from mechanical impurities and enters the condensation equipment, where it is separated into fractions of liquid synthetic fuel (heavy, medium, and light), gas gasoline, pyrolysis water, and semi-coke gas as it cools.

The semi-coke screw, equipped with a sealing chamber, feeds the solid phase into the air fountain furnace (13), where residual carbon is burned off at a temperature of 780-800 °C. Blast air with a temperature of 300-400 °C is supplied for carbon burnout. The combustion temperature is regulated by the air flow rate (α<1). The air fountain heater (14) is connected to the sand bunker (15) and lime bunker (16) through a sealing screw and is connected to the air fountain furnace at the bottom.

From the air furnace, the ash-gas flow passes through the heat carrier bypass (17), where it is divided into two streams, one of which is directed to the heat carrier cyclones, and the other bypasses the cyclones. The cyclones separate the amount of heat carrier necessary for the pyrolysis process. Its flow rate is automatically regulated by changing the ash-gas mixture flow into the cyclone with a movable damper (gate) by an impulse from the temperature sensor in the reactor.

After the heat carrier cyclones, the ash-gas flows are combined and directed to the ash cyclones (18), installed in three stages. The ash captured in the cyclones flows by gravity into the ash heat exchanger (19), where it transfers its heat to the blast air for the air fountain furnace and the heat recovery boiler. The temperature of the heated air is 300-400 °C, and the temperature of the cooled ash is 90 °C.

The flue gas, cleaned of ash and at a temperature of 780 °C, is fed into the heat recovery boiler, where its potential and physical heat is used to produce steam with energy parameters (3.9 MPa, 440 °C). The boiler is also fed with semi-coke gas after all liquid fractions have been extracted from it, gas from melting furnaces (if present), and liquid fuel if necessary. The temperature of the exhaust gases behind the boiler is 150 °C. The gases are either subjected to final cleaning in an electrostatic precipitator and discharged into the atmosphere through a chimney, or fed to dry the raw material.

The electricity generation in UTT facilities is based on the utilization of chemical and physical heat from the pyrolysis process. In the air-fountain furnace, the temperature is regulated by adjusting the air supply. To maintain a temperature of 800 °C, the amount of air supplied is kept below the level required for complete carbon combustion in the semi-coke. As a result, the flue gas contains a high concentration of CO (incomplete combustion products). This CO-rich gas is subsequently combusted in the waste heat boiler after the removal of ash in cyclones. Additionally, the waste heat boiler receives semi-coke gas from the condensation unit and CO gas from the smelting shop. The chemical energy of these gases, combined with the physical heat of the flue gas and preheated blast air (which is heated in the ash heat exchanger during ash cooling), is utilized for generating high-energy steam. This steam is then directed to a turbine (27) for electricity generation.

The vapor-gas mixture from the dust chamber is directed for final cleaning to a 'wet' scrubber (20), after which it undergoes stepwise condensation to obtain a heavy fraction, medium fraction (possible extraction of diesel fraction), gasoline fractions, and pyrolysis moisture. The liquid fractions are sent to an intermediate liquid product storage, from where they are pumped to the commodity park, where various commercial products can be obtained by mixing them in different proportions (boiler and furnace fuel, turbine fuel, diesel fuel, components for bunkering marine fuel, analogues of fuel oils). Pyrolysis moisture is subjected to fire neutralization in the air fountain furnace. The high-calorie semi-coke gas is directed to the heat recovery boiler.

The process ash is used for the production of asphalt concrete based on bitumen obtained by oxidation of the heavy fraction of tar. Part of the ash can be directed to melting furnaces, where ferroalloys are obtained with the necessary additives to the charge (coal, quartzite, iron, manganese, limestone).

2.3 Technical characteristics of UTT-500 and UTT-3000 facilities

The UTT-500 and UTT-3000 facilities are innovative complexes designed for the processing of MSW using a fast pyrolysis method with a solid heat carrier. This technology, originally developed for oil shale processing, has been adapted for efficient MSW utilization, offering an environmentally friendly alternative to traditional waste management methods.

Thermal energy for heating production facilities and hot water supply is generated in the shell-and-tube ash heat exchanger during ash cooling. In the upper sections of the heat exchanger, ash is cooled from 800 °C to 400 °C by air, while in the lower sections, it is further cooled from 400 °C to 50-90 °C by water. The heated water, at a temperature of 90-110 °C, is supplied to consumers via the district heating network. Meanwhile, the air heated to 400 °C is directed to the air-fountain furnace and the waste heat recovery boiler.

The distinctive features of the UTT-500 and UTT-3000 facilities include:

(1) Processing capacity: UTT-500 can process up to 150,000 tons of waste per year (500 t/day), while UTT-3000 has a capacity of up to 1 million tons per year (3,330 t/day).

(2) Product output: During the processing, the facilities produce synthetic oil, gas, thermal and electrical energy, construction material components, and ferroalloys.

(3) Energy self-sufficiency: The complexes are capable of meeting their own electricity and heat requirements.

(4) Environmental performance: The technology is designed to minimize harmful emissions and ensure efficient resource utilization.

(5) Flexible location: The facilities can be situated at various sites, including operational or planned landfills, waste sorting plants, and industrial areas.

The UTT-3000 complex with a capacity of 1 million tons per year occupies an area of 16.4 hectares. The minimum permitted sanitary protection zone of the enterprise has a radius of 1 km from the fence. The total fenced area of the UTT-500 complex is 6.55 hectares. The minimum permitted sanitary protection zone of the enterprise has a radius of 1 km from the fence. When the moisture content of the raw material is up to 12% by mass, drying is not required. At higher moisture levels, the raw material undergoes preliminary drying, which increases the plant's raw material processing capacity by the volume of removed moisture.

The following energy resources are required for the operation of the facility:

- Power and electricity consumption: 6,237 kW and 42.9 GWh/year, respectively. The specific consumption is 40 kWh per 1 ton of raw material.
- Thermal energy for heating production facilities and hot water supply.
- Technical water to compensate for losses in the recirculating technical water supply system: 16.5 m³/h.
- The demand for the first two resources is met through the facility's own production.
- Thus, the facilities represent a comprehensive solution to the MSW utilization problem, combining efficient waste processing with valuable resource production, aligning with the principles of circular economy and sustainable development.
- Several components mentioned in the manuscript, such as the smelting shop, smoke gas, and pyrolysis water, play essential roles in the high-speed pyrolysis process and subsequent material utilization. Their functions within the technological workflow are as follows:
- Smelting Shop: The smelting shop is used for melting ash with additives such as sand, iron, and coal. This process enables the recovery of valuable materials, including ferroalloys, reducing waste generation and supporting circular economy principles. Additionally, carbon monoxide (CO) generated in the smelting process is directed into the waste heat boiler, contributing additional thermal energy to the system.
- Smoke Gas: This refers to the flue gas exiting the waste heat boiler, which passes through an electrostatic precipitator for particulate removal before being released through the chimney. Proper gas treatment ensures compliance with environmental regulations and minimizes atmospheric emissions.
- Pyrolysis water: This is the condensed water fraction collected in the condensation unit during the cooling of the vapor-gas mixture from the pyrolysis reactor. It primarily consists of moisture released from the waste material during thermal decomposition. The controlled removal of pyrolysis water helps optimize the efficiency of the pyrolysis.

2.4 Elemental analysis

Elemental analysis of solid and liquid samples was conducted using a Multi EA® 5100 universal analyzer (Analytik Jena, Germany). This instrument enables the determination of sulfur, chlorine, nitrogen, and carbon content in liquid, solid, paste-like, and gaseous samples of oil, petroleum products, and other organic matrices.

The sample mass did not exceed 10 mg. Solid samples were ground in a ball mill to a particle size of <100 μm. Liquid samples were homogenized by shaking for 5 minutes. Instrument calibration was performed using certified reference materials (CRMs) for each element to be determined. Calibration curves were constructed in the concentration range of 0.001% - 10% for sulfur, nitrogen, and chlorine, and 0.1% - 50% for carbon. Quality control was ensured through daily analysis of control samples. The relative standard deviation of the results did not exceed 2% for all elements determined. All measurements were carried out in triplicate. Statistical processing of the results was performed using OriginPro 2022 software (OriginLab Corporation, USA).

3. Results

3.1. MSW composition

For the purposes of this study, samples were taken from the landfills of Astana (Kazakhstan). The composition of MSW is given in Table 1.

Table 1: Composition of MSW before and after metal extraction (% by mass).

Component	Content before metal Extraction (% by mass)	Content after metal extraction (% by mass)
Paper	16.9	17.05
food waste	25.9	26.1
Bone	0.3	0.34
tard waste	3.5	3.56
Glass	9.2	9.26
Stone	0.8	0.84
Non-Ferrous metal	0.11	0.03
Ferrous metal	0.954	0.29
Plastic	7.2	7.22
Batteries	0.3	0.33
Leather, Rubber	2.3	2.36
textiles	4.6	4.59
Wood	2.7	2.73
Ceramics	1.0	1.07
Medical waste	0.02	0.02
Other	12.3	12.37
Screening (less than 16mm)	11.8	11.86
Total	100.0	100.0

The analysis reveals slight increases in the percentages of most components post-extraction, indicating the removal of metals. For instance, the proportion of paper increased from 16.9% to 17.05%, and food waste from 25.9% to 26.1%. Similar incremental changes are observed across other non-metal components such as bone (0.3% to 0.34%), yard waste (3.5% to 3.56%), and glass (9.2% to 9.26%).

On the contrary, the percentage of metals, both non-ferrous and ferrous, decreased significantly. Non-ferrous metals dropped from 0.11% to 0.03%, and ferrous metals from 0.954% to 0.29%, reflecting their successful extraction from the waste. Other components like leather, rubber, textiles, wood, ceramics, and miscellaneous items also showed minor increases, aligning with the overall trend.

Overall, the data demonstrate the effective separation of metals from the MSW, resulting in a slight increase in the relative proportion of non-metal components due to the reduction of the metal content. Analyses of the elemental composition of combustible shale from the Leningrad deposit and MSW from the landfills of Astana showed a significant correlation in their elemental composition. Table 2 presents the elemental compositions of MSW on a dry mass basis in % by mass.

Table 2: Elemental composition of MSW.

Element	Content in MSW (% by Mass)
Carbon	23.01
Hydrogen	2.92
Total sulfur	0.12
Oxygen	14.97
Nitrogen	0.53
Chlorine	0.1

The elemental composition analysis of combustible shale from the Leningrad deposit and MSW from the landfills of Astana reveals notable similarities and differences. Both materials have a comparable carbon content, with shale at 23.41% and MSW at 23.01%, indicating a similar potential for energy production through combustion. Hydrogen content is also nearly identical, with shale at 2.91% and MSW at 2.92%, further underscoring their similarities in organic composition.

However, the two materials differ significantly in their oxygen and sulfur content. MSW has a much higher oxygen content at 14.97% compared to shale's 3.48%, which could impact the combustion process and emissions profile. Conversely, shale contains a higher total sulfur content at 1.64%, whereas MSW has only 0.12%, which might influence the environmental impact regarding sulfur emissions. Nitrogen and chlorine levels are relatively low in both materials, but MSW has a higher nitrogen content at 0.53% compared to shale's 0.15%, while chlorine levels are identical at 0.1%. These variations highlight important considerations for the management and utilization of these materials as energy sources.

Based on the similarity in the elemental composition of these two raw materials, it can be concluded that the technology used for processing shale can also be successfully applied to MSW, including waste from the landfills of Astana. This opens up opportunities for more efficient and environmentally friendly waste management solutions.

The similarity in the elemental composition of the organic matter in MSW and oil shale indicates a comparable decomposition process during pyrolysis and the subsequent formation of a vapor-gas mixture. Upon cooling in the condensation unit, this mixture separates into liquid fractions of synthetic oil, semi-coke gas, and pyrolytic moisture. This behavior has been confirmed through extensive experiments conducted using both a Fischer retort and a laboratory-scale setup simulating the heating process with a solid heat carrier.

3.2 Recycling products

The waste management process not only involves the safe disposal of MSW but also the conversion of waste into valuable products. The main products generated from the recycling and disposal processes of incoming waste include:

- Synthetic liquid fuel: 300-400 tons/day for UTT-3000 (50-70 tons/day for UTT-500) - heavy, medium, and gasoline fractions, which can be mixed in various proportions to produce different types of commercial fuels such as boiler, furnace, and other fuels.
- Electric power: 50-90 MW, including 6.5 MW for internal needs (for UTT-500, 6.7 times less). The electricity can be supplied to the grid or used for ash melting.
- Thermal energy: 70 Gcal/h, 1650 Gcal/day for UTT-3000 (for UTT-500 - 6.7 times less).
- Ash: 1400-2000 tons/day, depending on the ash content (with low ash content, sand or limestone can be added as a heat carrier), used for the production of asphalt, concrete mixtures, and ferroalloys. When stored after moisture addition, it hardens into an inert material.
- Sorted metals: Non-ferrous metals (0.03%) and ferrous metals (0.3%).

In the absence of ash utilization, its volume constitutes 20-45% of the working mass of MSW or 600-1500 tons/day (100-240 t/day for UTT-500). The ash is inert and hardens upon moisture addition and compaction.

3.3 Technological calculations

The resulting composition of the raw material mixture is derived from the calculation of annual receipts by types of waste on the basis of their processing in the facility with solid heat carrier UTT-500, which has a capacity of 500 tons per day per dry mass of waste.

Table 3 presents the composition of raw material mixtures from MSW sorting, their elemental composition, and the yield of pyrolysis products. It shows that the total raw materials amount to 216,932 tons per year with a moisture content of 30.9%, resulting in 150,000 tons of dry mass. Paper, cardboard, and textiles constitute the largest portions, contributing significantly to the mixture's dry mass. The elemental composition reveals a high carbon content in materials like plastic and oiled sleepers, indicating a substantial potential for energy recovery through pyrolysis.

The pyrolysis product yield varies across different materials. For instance, plastic produces a high yield of oil at 90% dry weight, whereas glass yields no oil but remains inert in the process. Textiles and food waste also show significant oil yields at 47% and 48%, respectively. The total additive mixture contributes to 35% of the overall raw materials, with a substantial ash content of 7.5%, influencing the final composition and product yield.

Overall, the analysis indicates that the mixture of MSW and ash slag, with a 50/50 ratio, has a considerable ash content of 49.1%, affecting the pyrolysis process. The diverse composition of raw materials results in varying yields of oil,

Table 3: Composition of the raw material mixture and pyrolysis products yield.

Raw material composition	Operating weight, t/year	Moisture, %	Dry mass, t/year	Content in mixture, %	Elemental composition of organic matter and ash content of component, % dry weight						Pyrolysis product yield, % dry weight.		
					C	H	O	N	S	Ash*	Oil	Gas	Semi-coke
Tailings from MSW sorting													
Paper, cardboard	12 369	35.0	8 040	5.4	43.6	5.8	44.4	0.3	0.2	5.7	16.62	16.16	36
Glass	6 023	-	6 023	4.0						100.0			
Wood	2 126	43.0	1 212	0.8	49.1	5.9	41.0	0.2	0.1	3.9	16.62	16.16	36
Plastic	4 464	10.0	4 018	2.7	59.3	8.3	19.3	1.0	0.4	10.2	90	6.5	3
Aluminium	722	-	722	0.5						100.0			
Textiles	32 176	30.0	22 523	15.0	53.5	6.5	30.7	4.6	0.1	4.6	47	19	30
Food Waste	8 929	80.0	1 786	1.2	44.9	5.4	25.8	3.8	0.1	20.0	48	20	29
Oiled sleepers	3 400	22.0	2 652	1.8	52.7	6.3	37.3	0.2	0.1	3.4	30	17	34
Oil sludge	7 500	25.8	5 569	3.7	51.40	8.68	1.93	0.56	0	37.4	34.1	9.3	43.3
Total additives	77 708	-	52 543	35.0	15.7	2.1	8.9	0.8	0.0	7.5	12.9	4.9	9.4
MSW and ash slag mixture (50/50 ratio)	139 224	30.0	97 457	65.0	10.9	1.4	3.3	0.2	0.1	49.1	4.6	5.2	54.6
Total raw materials	216 932	30.9	150 000	100.0	26.62	3.44	12.22	0.96	0.18	56.5	17.50	10.14	64.00

Table 4: Yields of semi-coking products and heat distribution from thermal decomposition of 1 ton of dry raw material mixture.

№	Products	Heat of product combustion, kJ/kg		Weight yield of products, kg/t	Potential heat, MJ per 1 ton of dry raw material			
					Highest		Lowest	
		Highest	Lowest		MJ/t	%	MJ/t	%
1	Oil	38 064.56	35 848.97	175.00	6 661.30	55.32	6 273.57	55.69
2	Gas	39 385.04	35 871.75	101.40	3 993.64	33.16	3 637.40	32.29
3	Pyrolysis water	-	2 512.00	7.10	-	-	17.84	0.16
	Total volatiles	-		283.50	10 654.94	88.48	9 928.80	88.14
4	Coke residue	1 893.42	1 871.23	716.50	1 356.64	11.27	1 340.73	11.90
	Total			1 000.00	12 041.96	99.75%	11 264.25	100.05%

gas, and semi-coke, highlighting the potential for optimizing the pyrolysis process to maximize energy recovery and minimize waste.

For the resultant mixture, the yields of semi-coking products and heat distribution during thermal decomposition of 1 ton of dry raw material mixture were determined (Table 4)

Table 4 outlines the yields of semi-coking products and the heat distribution from the thermal decomposition of one ton of dry raw material mixture. It shows that the combustion heat of the products, particularly oil and gas, is substantial, with the highest values reaching around 38,065 kJ/kg for oil and 39,385 kJ/kg for gas. The weight yield of oil is 175 kg per ton, contributing to a potential heat of 6,661.30 MJ/t at the highest value, accounting for over half of the total energy yield. Gas also significantly contributes to the energy output with a yield of 101.40 kg per ton, translating to 3,993.64 MJ/t, making up about one-third of the total heat potential.

Pyrolysis water, although minimal in weight yield at 7.10 kg/t, has a negligible impact on the overall heat distribution. The coke residue, with a weight yield of 716.50 kg/t, provides the least potential heat per ton, contributing 1,356.64 MJ/t at its highest. The total volatiles, including oil and gas, constitute 283.50 kg/t and account for 88.48% of the total potential heat,

Table 5: Distribution of chemical elements in pyrolysis products from 1 ton of dry raw material mixture.

Component	Dry raw material		Oil		Gas		Semi-coke		Moisture	
	kg	%	kg	%	kg	%	kg	%	kg	%
Ash A	565.40	56.54	-	-	-	-	565.40	78.91	-	-
Sulphur S	2.20	0.22	0.09	0.05	-	-	2.11	0.29	-	-
Carbon C	266.20	26.62	138.67	79.24	65.78	64.87	61.75	8.62	-	-
Hydrogen H	34.40	3.44	17.15	9.80	15.76	15.54	0.70	0.10	0.79	11.11
Nitrogen N	9.60	0.96	1.05	0.60	-	-	8.55	1.19	-	-
Oxygen O	122.20	12.22	18.04	10.31	19.86	19.59	77.98	10.88	6.31	88.89
Total:	1 000.00	100.00	175.00	100.00	101.40	100.00	716.50	100.00	7.10	100.00

highlighting their critical role in the energy recovery process from the raw material mixture. Overall, the table indicates that the thermal decomposition process is highly efficient in converting raw materials into energy, with the majority of the heat derived from oil and gas production, emphasizing their importance in the semi-coking process. The distribution of chemical elements of organic matter by pyrolysis products was determined for the resulting mixture per 1 ton of dry mass (Table 5).

The majority of the ash content, 565.40 kg, is found in the semi-coke, which accounts for 78.91% of the semi-coke's total mass. Sulfur, although present in small quantities, is mainly found in the semi-coke (2.11 kg) and minimally in oil (0.09 kg). Carbon distribution shows a significant portion allocated to oil (138.67 kg) and gas (65.78 kg), comprising 79.24% and 64.87% of their respective masses, indicating their primary role as carbon carriers in the pyrolysis process.

Hydrogen is predominantly distributed in oil and gas, with oil containing 17.15 kg (9.80%) and gas 15.76 kg (15.54%). Nitrogen is mainly retained in the semi-coke (8.55 kg), contributing 1.19% of its mass. Oxygen content is notably higher in gas (19.86 kg) and semi-coke (77.98 kg), making up 19.59% and 10.88% of their masses, respectively. The moisture content is almost entirely comprised of oxygen (88.89%) and hydrogen (11.11%), reflecting its elemental composition.

Overall, the analysis highlights the significant retention of ash and sulfur in the semi-coke, while oil and gas predominantly contain carbon and hydrogen, which are essential for their energy potential. The distribution of elements underscores the efficiency of the pyrolysis process in concentrating valuable energy components in oil and gas while managing by-products like ash and sulfur in the semi-coke.

The heat of combustion of the raw materials and pyrolysis products was determined through a series of controlled experiments (Table 6). The highest heat of combustion for oil and gas is remarkably high, with oil reaching 38,065 kJ/kg and gas at 39,385 kJ/kg, compared to the raw material's 12,042 kJ/kg and semi-coke's 1,893 kJ/kg. Even the lowest heat values for oil and gas are substantially higher than those of the raw material and semi-coke. This indicates that the pyrolysis process effectively concentrates energy in the oil and gas products, making them highly efficient for energy recovery. The data underscores the superior energy potential of pyrolysis products, particularly oil and gas, over the original raw material and the resultant semi-coke. Raw material composition and heat of combustion under different conditions on different bases were determined (Table 7). The material and heat balance for 1 ton of raw material dried to 21% moisture content in a covered, ventilated, and average warehouse is presented in Table 8.

Table 6: Heat of combustion of the raw materials and pyrolysis products.

Heating value type	Dry raw material	Oil	Gas	Semi-coke
Highest heat of combustion Q_h, kJ/kg	12 042	38 065	39 385	1 893
Lowest heat of combustion Q_l, kJ/kg	11 264	35 849	35 872	1 871
Highest heat of combustion Q_h, kcal/kg	2 876	9 092	9 407	452
Lowest heat of combustion Q_l, kcal/kg	2 690	8 562	8 568	447

Table 8 provides a detailed breakdown of the material and heat balance per one ton of raw materials, showing the input and output in terms of weight, physical heat, chemical heat, total heat, and heat consumption. The inputs include air, raw materials with 21% moisture, water, and CO gas from the smelting shop, summing up to a total weight of 4.656 kg. The total heat input is 11.19 GJ, with the majority contributed by the chemical heat of the raw materials (9.515 GJ). Water also adds a significant amount of physical heat (0.615 GJ).

On the output side, the products of the pyrolysis process include Pyrolysis water, smoke gas, ash, steam, and oil. The total weight of the outputs matches the inputs, indicating a balanced process. The total heat output is 9.595 GJ, with steam contributing the largest share (4.727 GJ of physical heat).

Table 7: Raw material composition and heat of combustion.

Component / Parameter	Per working mass, %	Per analytical mass, %	Per dry mass, %	Per combustible mass, %	In organic matter (per dry ash-free base), %
Water W	20.98	2.2	-	-	-
Ash A	44.68	55.30	56.54	-	-
Sulphur S	0.17	0.22	0.22	0.51	-
Carbon C	21.03	26.03	26.62	61.25	61.56
Hydrogen H	2.72	3.36	3.44	7.92	7.96
Nitrogen N	0.76	0.94	0.96	2.21	2.22
Oxygen O	9.66	11.95	12.22	28.12	28.26
Total	100.00	100.00	100.00	100.00	100.00
Highest heat of combustion Q_h, kJ/kg	9 515	11 777	12 042	27 708	27 794
Lowest heat of combustion Q_l, kJ/kg	8 374	10 961	11 264	25 919	25 995
Highest heat of combustion Q_h, kcal/kg	2 273	2 813	2 876	6 618	6 638
Lowest heat of combustion Q_l, kcal/kg	2 000	2 618	2 690	6 191	6 209

Table 8: Material and heat balance per 1 ton of raw materials.

Material flow	Weight, kg	Physical heat, GJ	Chemical heat, GJ	Total heat, GJ	Heat consumption, GJ
		Input			
Air	2 160	0.181			
Raw materials (21% moisture)	1 000	0.015	9.515		
Water	1 429	0.615			
CO gas from the smelting shop	68	0.04	0.82		
Total	4 656	0.85	10.34	11.19	-
Output					
Pyrolysis water	6	0.019			
Smoke gas	2 669	0.918			
Ash	444	0.038			
Steam	1 429	4.727			
Oil	108	0.011	3.882		
Total	4 656	5.713	3.882	9.595	1.59
	100.00%	51.08%	34.70%	85.78%	14.22%

Smoke gas also contributes a notable amount of heat (0.918 GJ of physical heat). The total heat efficiency of the process is high, with 85.78% of the heat from the inputs being utilized in the outputs, while 14.22% accounts for heat consumption, reflecting the overall energy efficiency of the pyrolysis process. This balance suggests an effective conversion of raw materials into valuable by-products while efficiently materials into valuable by-products while efficiently managing the energy consumption.

Table 9 presents the process efficiency of the pyrolysis system, focusing on the product yield in terms of steam, oil, and electricity. The majority of the heat produced comes from steam and oil, with steam contributing 4.727 GJ and oil 3.882 GJ, making up 45.7% and 37.6% of the total share, respectively. Electricity, generated from 393.9 kg of raw material, contributes 1.418 GJ, representing 13.7% of the total heat share. The combined heat yield from steam and oil is 8.609 GJ, which accounts for 83.29% of the total potential heat.

The table also highlights several efficiency metrics, with the chemical efficiency of oil at 37.56% and the energy efficiency of the UTT system for steam and oil at 83%. The turbine generator efficiency, which converts steam to power, stands at 30%. These figures indicate a robust conversion process, effectively transforming raw materials into valuable energy products with a relatively high efficiency.

3.4 Economic indicators of the UTT-500 operation.

Table 10 provides a comprehensive overview of the economic indicators associated with the operation of the UTT-500 pyrolysis system. The calculated data reveal the significant investment requirement of over 33 million USD per year, with the majority allocated to the UTT and power plant costs. Daily costs are substantial, encompassing expenses for extraction, processing, smelting, and raw material purchases. Despite these high costs, the revenue generated from various sources such as oil production, tariff placements, and electricity sales

Table 9: Calculation of process efficiency.

Product yield	Weight, kg	Heat, GJ	Share, %
Steam	1 428.5	4.727	45.7%
Oil	108.3	3.882	37.6%
Electricity, kWh	393.9	1.418	13.7%
Total (steam, oil)		8.609	83.29%
Chemical efficiency (oil)			37.56%
Energy efficiency of UTT (steam, oil)			83%
Turbine generator efficiency (power to steam)			30%

Table 10: Economic indicators of the UTT-500 operation.

Economic parameter	Quantity, per day	Cost, USD per unit	Amount, USD/day	Quantity, t/year	UTT-500, USD/year
Investments, USD total, incl:					33 607 310
UTT					25 000 000
Power plant					3 282 652
Preparation of raw materials					1 900 000
Smelting shop					3 424 658
Costs total, incl:			13 341		4 002 247
Extraction, preparation, tons	723	5.00	3 616	216 932	1 084 659
Processing, tons	723	7.00	5 060	216 932	1 518 523
Smelting, transshipment, t	321	3.00	964	96 355	289 065
Purchase of coal, quartzite, iron	1	3 700.00	3 700	300	1 110 000
Amortization			6 138		1 841 496
Total revenue, incl:			102 936		30 880 738
Oil, t	70	455.00	32 063	21 140	9 618 908
Tariff for placement, t	723	17.81	12 877	216 932	3 863 171
Power Plant Capacity, MW				11.9	
including for sale, MW				5.0	
Electricity, sale of kWh	119 152	0.05	5 958	35 745 476	1 787 274
Average annual heat supply, Gcal	190	24.66	4 685	57 000	1 405 479
Ferroalloy, t	36	959.57	34 545	10 800	10 363 377
Asphalt, t	302	42.47	12 808	90 485	3 842 529
Profit			89 595		26 878 491
Profit before taxation			83 457		25 036 994
Profit after tax			66 765		20 029 595
Cash, per day			72 904		21 871 092
Payback, years after start-up			1.54		1.54
Return on investment, % per year		65%			
Revenue per 1 ton of raw materials, USD/t		115			

is substantial, amounting to over 30 million USD annually. This indicates a robust revenue stream capable of covering operational costs and yielding profits.

Profitability is highlighted by the profit before taxation, which stands at 89,595 USD daily, translating to a significant annual figure. After accounting for taxes, the profit remains strong, showcasing the financial viability of the UTT-500 operation. The payback period of 1.54 years demonstrates the efficiency and quick return on investment. Additionally, the return on investment is impressive at 65% per year, indicating that the UTT-500 is not only a financially sound venture but also a highly lucrative one. Overall, the calculated economic indicators underscore the economic strength and profitability of the UTT-500 system, with strong revenue streams and a r apid payback period, making it a compelling investment.

3.5 Economic indicators of the UTT-3000 operation

Table 11 provides a comprehensive overview of the economic indicators associated with the operation of the UTT-3000 pyrolysis system. For UTT-3000, the total annual investment

Table 11: Economic indicators of the UTT-3000 operation.

Parameter	Quantity, per day	Cost, USD per unit	Quantity, t/year	UTT-3000, USD/year
Investments, USD total, incl:				118 227 708
UTT				70 000 000
Power plant				21 862 463
Preparation of raw materials				7 600 000
Smelting shop				18 765 245
Costs total, incl:				26 654 968
Extraction, preparation, tons	4 821	5.00	1 446 212	7 223 832
Processing, tons	4 821	7.00	1 446 212	10 113 365
Smelting, transshipment, t	2 141	3.00	642 366	1 925 171
Purchase of coal, quartzite, and iron	7	3 700.00	2 000	7 392 600
Amortization				
Total revenue, incl:				205 665 716
Oil, t	470	455.00	140 936	64 061 929
Tariff for placement, t	4 821	17.81	1 446 212	25 728 717
Power Plant Capacity, MW	0	0	79.0	
including for sale, MW			33.1	
Electricity, sale of kWh	794 344	0.05	238 303 149	11 903 243
Average annual heat supply, Gcal	1 267	24.66	380 000	9 360 493
Ferroalloy, t	240	959.57	72 000	69 020 093
Asphalt, t	2 011	42.47	603 236	25 591 240
Profit				179 010 748
Profit before taxation				171 128 901
Profit after tax				136 903 121
Cash, per day				144 784 968
Payback, years after start-up				0.82
Return on investment, % per year		122%		
Revenue per 1 ton of raw materials, USD/t		171		

required amounts to approximately 118 million USD, with the largest share going towards the UTT itself, followed by the power plant and preparation of raw materials. These substantial investments are necessary to support the extensive daily operations, which include the extraction, processing, smelting, and transshipment of materials, as well as the purchase of essential raw materials like coal, quartzite, and iron.

On the revenue side, the UTT-3000 operation generates impressive income streams from various sources. Oil production alone accounts for a significant portion of the revenue, with additional substantial contributions from tariffs for placement and the sale of electricity. The total annual revenue from all sources exceeds 205 million USD, indicating a strong financial performance. This robust revenue stream allows the operation to achieve a profit before taxation of 179 million USD annually. Even after accounting for taxes, the profit remains substantial, underscoring the financial viability and profitability of the UTT-3000. The operation boasts a return on investment of 122% per year, reflecting its efficiency and lucrative potential. Additionally, the payback period is relatively short at 0.82 years, further emphasizing the financial attractiveness of the UTT-3000 operation.

4. Discussion

Comparing the economic efficiency between the UTT-500 and UTT-3000 facilities reveals significant differences in scale, investment, and financial performance. The UTT-3000 requires a substantially higher investment, approximately 118 million USD per year, compared to the UTT-500, which demands around 33.6 million USD annually. This higher investment for the UTT-3000 is primarily due to its larger capacity and the extensive infrastructure required to support its operations, including costs for the power plant, preparation of raw materials, and smelting shop.

Despite the higher investment, the UTT-3000 generates significantly more revenue than the UTT-500. The annual revenue for the UTT-3000 exceeds 205 million USD, whereas the UTT-500 generates around 30.9 million USD. This substantial difference in revenue reflects the larger scale and higher production capacity of the UTT-3000. Consequently, the UTT-3000 achieves a higher profit before taxation, 179 million USD compared to 26.9 million USD for the UTT-500. Even after taxes, the UTT-3000 maintains a significantly higher profit, underscoring its superior financial performance. The return on investment (ROI) is also notably higher for the UTT-3000, at 122% per year, compared to 65% for the UTT-

500. This indicates that the UTT-3000 is more economically efficient, providing a greater return on the capital invested. Furthermore, the payback period for the UTT-3000 is shorter at 0.82 years, compared to 1.54 years for the UTT-500, highlighting the faster recovery of the initial investment in the larger facility. Overall, the UTT-3000 demonstrates superior economic efficiency, with higher revenue, greater profits, and a more attractive ROI and payback period compared to the UTT-500.

The pyrolysis process inherently prevents the formation of dioxins (tetrachlorodibenzo-p-dioxins), unlike direct waste incineration. This significantly reduces capital investment requirements. In waste incineration, chlorine, oxygen, and benzene coexist in a single combustion chamber, leading to the formation of dioxins, highly toxic compounds. The EU Waste Incineration Directive mandates that flue gases must be retained at a temperature of at least 1200°C for no less than 2 seconds to ensure dioxin decomposition. Following this, an advanced gas separation and purification system is required, along with cooling of the separated gases.

For example, at a flue gas velocity of 50–100 m/s, an incinerator would need to be 100–200 meters long, requiring additional fuel and air supply. Moreover, the internal surfaces of the incinerator and gas separation system must be lined with high-cost refractory materials, contributing to substantial capital expenditures. A conventional waste incineration plant with a capacity of 150,000 tons per year costs approximately $200 million.

In contrast, the UTT-500 plant with the same processing capacity (150,000 tons/year) has an estimated cost of only $30 million. The UTT process completely eliminates the formation of tetrachlorodibenzo-p-dioxins. While chlorine and benzene are present in the pyrolysis reactor, oxygen is absent, preventing dioxin synthesis. Benzene is removed from the reactor along with the pyrolysis vapor-gas mixture. Subsequently, semi-coke is fed into the air-fountain furnace, where chlorine and oxygen are present, but benzene is absent. In the air-fountain furnace, chlorine binds with calcium to form the harmless salt calcium chloride ($CaCl_2$), which is then removed with the ash. Consequently, there is no need for expensive equipment to decompose dioxins.

This technology has the following advantages over other technologies of solid waste neutralization: High unit capacity (from 200 thousand to 1.5 million tons per year on a raw basis). It is possible to process a wide range of both previously stored and newly arriving MSW, industrial waste, sludge, and sludge residues in various mixtures and proportions. The entire volume of waste can be recycled (the technology is waste-free). Sorting of MSW before processing is not required. Only ferrous and non-ferrous metals are separated. Organization of the pyrolysis process excludes the formation of dioxins (tetrachlorodibenzodioxins), unlike direct incineration of waste. It reduces the volume of capital investments many times. The technological process does not require third-party energy carriers. Own needs of the process are covered by the potential heat of waste.

Table 12 schematically illustrates the full cycle of waste processing implemented in this technology from raw material preparation and metal separation to feeding into the pyrolysis reactor. This visual representation demonstrates the integration of a covered averaging warehouse, crushing/grinding systems, electromagnetic and eddy current separators, and the final mixing stage with hot ash and limestone, highlighting the closed-loop and energy-autonomous nature of the system, as well as its adaptability to different types of waste.

The raw material feeding system includes a covered averaging warehouse, crushing/grinding of the feedstock, removal of ferrous metals using an electromagnetic separator, separation of non-ferrous metals via an eddy current separator, and feeding the processed waste, along with added limestone, into a mixer with hot ash.

Ecological indicators of production comply with EU requirements (for example, 3 units of UTT-3000 are located within the city limits of Kohtla-Järve, 2 units of UTT-500 operate in Kiviili in Estonia). Viru Keemia Grupp AS operates three Petroter units in Kohtla-Järve, Estonia. These facilities comply with EU environmental regulations and the reference document "Best Available Techniques for Oil Shale Processing in Estonia" (BAT).[37]

Table 12: Annual direct atmospheric emissions from a single petrochemical plant.

Emission	Weighted Average Concentration in Flue Gases, mg/nm^3
PM	4,0
NO_2	186,1
CO	179,8
CO_2	208 826
SO_2	691,7

The technology is waste-free - all pyrolysis products are either marketable (liquid fuel, electric and thermal energy, ash) or used in the technological process (pyrolysis gas, excess heat of the pyrolysis process). The generated ash is inert and can be used for the production of building materials, asphalts, fertilizers, and when smelting, ferroalloys and calcium carbide.

Special attention should be paid to the possibilities of utilization of industrial and MSW in Astana (Kazakhstan), where tens of millions of tons of solid waste, as well as "tailings" after sorting of solid waste, are placed. The developed technological schemes provide high flexibility of plant operation and response to seasonal changes in consumption of heat and electricity, liquid boiler fuel, and changes in demand for ash processing products (building materials, ferroalloys, asphalt mixtures, paving slabs, *etc*.). Construction of such plants in municipal areas (500 t/day) will help to meet the demand for heat and electricity at the expense of a renewable inexhaustible source of energy ("waste to energy"), thus reducing the cost of procurement and storage of fuel for the heating season and reducing the cost of energy.

The use of waste to cover energy needs frees up natural gas, coal, and liquid fuels. Surplus heat energy can be used to develop greenhouse farms for growing fruits and vegetables, and for entrepreneurship. Destruction of previously accumulated industrial and MSW at existing and closed landfills will help to free the land occupied by waste and sanitary protection zones, clean and neutralize the soil under the former landfills, and bring these lands back into economic turnover.

All the necessary equipment for the operation of the UTT units can be manufactured in Kazakhstan. The establishment of UTT facilities in Kazakhstan, utilising locally manufactured equipment, presents a range of economic and strategic benefits for the country. Firstly, collaboration between local manufacturers enables a reduction in transportation costs and customs duties, thereby enhancing the economic viability of the project. The reduction in logistics costs that results from the location of UTT facilities in Kazakhstan has a favourable impact on the overall cost of the project. Secondly, the utilisation of Kazakhstani equipment serves to reinforce economic ties between disparate regions within Kazakhstan. Such collaboration may result in mutual investments, technological exchange, and the creation of new employment opportunities in Kazakhstan. Such projects contribute to the development of local industry and may stimulate the creation of joint ventures, thereby contributing to the diversification of Kazakhstan's economy.

In conclusion, the capacity to manufacture equipment enables Kazakhstan to expeditiously and effectively initiate projects to establish UTT facilities. The country possesses the requisite experience and technology to produce superior-quality equipment, thereby guaranteeing the reliability and efficiency of the plants. This, in turn, contributes to enhancing Kazakhstan's energy independence and developing its industrial potential, which is of paramount strategic importance for the country.

Construction and operation of the UTT units reduce environmental damage from landfills, greenhouse gas, and landfill gas emissions into the atmosphere, and groundwater pollution. UTT technology is absolutely compatible with other technologies used to reduce gas emissions, does not exclude covering landfills with geo-films to collect landfill gases, reclamation, and covering landfills with layers of limestone and soil to eliminate odors. Plants for waste processing on the basis of UTT have high economic efficiency. Development of a network of such plants in Kazakhstan can be carried out at the expense of cash flows generated by already built plants on the principles of project financing.

5. Conclusion

In conclusion, fast pyrolysis technology with solid heat carriers represents a promising and sustainable alternative for MSW processing. Its ability to produce multiple valuable products and align with circular economy principles makes it a viable solution for modern waste management systems. Future research and development should focus on optimizing this technology further and exploring its application to other types of waste to enhance overall waste management efficiency and environmental sustainability.

(1) Potential of fast pyrolysis technology for MSW management: This study highlights the significant potential of fast pyrolysis technology with solid heat carriers for improving MSW management. A comprehensive techno-economic analysis demonstrates that this method offers several advantages over traditional incineration, including reduced harmful emissions and greater flexibility in processing diverse waste types. The fast pyrolysis process efficiently converts waste into valuable products such as synthetic oil, gas, thermal and electrical energy, construction materials, and ferroalloys, contributing to resource recovery and energy production.

(2) Operational performance and environmental benefits: The operational performance of UTT-500 and UTT-3000 plants indicates that these facilities can meet their own energy needs while minimizing environmental impact. These results emphasize the importance of adopting advanced waste processing technologies to address the growing challenges of urban waste management.

(3) Future prospects and research directions: Fast pyrolysis technology with solid heat carriers represents a promising and sustainable alternative for MSW processing. Its ability to produce multiple valuable products and align with circular economy principles makes it a viable solution for modern waste management systems. Future research and development should focus on optimizing this technology further and exploring its application to other types of waste to enhance overall waste management efficiency and environmental sustainability.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

References

[1] J. Ma, K. W. Hipel, Exploring social dimensions of municipal solid waste management around the globe-A systematic literature

review, *Waste Management*, 2016, **56**, 3-12, doi: 10.1016/j.wasman.2016.06.041.
[2] D. Guan, J. Zhao, Y. Wang, Z. Fu, D. Zhang, H. Zhang, J. Xie, Y. Sun, J. Zhu, D. Wang, A critical review on sustainable management and resource utilization of digestate, *Process Safety and Environmental Protection*, 2024, **183**, 339-354, doi: 10.1016/j.psep.2024.01.029.
[3] V. Vanchurin, Y. I. Wolf, M. I. Katsnelson, E.V. Koonin, Toward a theory of evolution as multilevel learning, *Proceedings of the National Academy of Sciences of the United States of America*, 2022, **119**, 3-11, doi: 10.1073/pnas.2120037119.
[4] S. Kaza, L. Yao, P. Bhada-Tata, F. Van Woerden, Waste and society, What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050, The World Bank, 2018, 115-140, ISBN: 978-1-4648-1329-0.
[5] N. Vukovic, E. Makogon, Waste-to-energy generation: complex efficiency analysis of modern technologies, *Sustainability*, 2022, **14**, 13814, doi: 10.3390/su142113814.
[6] Z. Ren, G. Zuo, Challenges of implementing municipal solid waste separation policy in China, *Sustainability*, 2024, **16**, 8081, doi: 10.3390/su16188081.
[7] R. Kumar, S. Sharma, A. Kumar, R. Singh, F. A. Awwad, M. I. Khan, E. A. A. Ismail, Sustainable energy recovery from municipal solid wastes: An in-depth analysis of waste-to-energy technologies and their environmental implications in India, *Energy Exploration & Exploitation*, 2025, **43**, 3-28, doi: 10.1177/01445987231210323.
[8] T. Louzizi, E. Chakir, Z. Sadoune, A comprehensive review on solid waste management in Morocco: assessment, challenges and potential transition to a circular economy, *Euro-Mediterranean Journal for Environmental Integration*, 2024, **1**, 1-16, doi: 10.1007/s41207-024-00662-5.
[9] M. Farzadkia, A. H. Mahvi, A. Norouzian Baghani, A. Sorooshian, M. Delikhoon, R. Sheikhi, Q. Ashournejad, Municipal solid waste recycling: Impacts on energy savings and air pollution, *Journal of the Air & Waste Management Association*, 2021, **71**, 737-753, doi: 10.1080/10962247.2021.1883770.
[10] M. N. Nassajfar, M. Abdulkareem, M. Horttanainen, End-of-life options for printed electronics in municipal solid waste streams: a review of the challenges, opportunities, and sustainability implications, *Flexible and Printed Electronics*, 2024, **9**, 033002, doi: 10.1088/2058-8585/ad699b.
[11] M. Asif, M. Laghari, A. M. Abubakar, A. Et, Review on municipal solid waste, challenges and management policy in Pakistan, *Portugaliae Electrochimica Acta*, 2025, **43**, 249-258, doi: 10.4152/pea.2025430404.
[12] Z. Kowalski, A. Makara, J. Kulczycka, A. Generowicz, P. Kwaśnicki, J. Ciuła, A. Gronba-Chyła, Conversion of sewage sludge into biofuels *via* different pathways and their use in agriculture: a comprehensive review, *Energies*, 2024, **17**, 1383, doi: 10.3390/en17061383.
[13] J. Liu, H. W. Kua, C.-H. Wang, Y. W. Tong, J. Zhang, Y. Peng, Improving urban ecosystem holistic sustainability of municipal solid waste-to-energy strategy using extended exergy accounting analysis, *Science of the Total Environment*, 2023, **904**, 166730, doi: 10.1016/j.scitotenv.2023.166730.
[14] S. Kasiński, M. Dębowski, Municipal solid waste as a renewable energy source: advances in thermochemical conversion technologies and environmental impacts, *Energies*, 2024, **17**, 4704, doi: 10.3390/en17184704.
[15] M. Asadullah, N. S. Ab Rasid, S. A. S. A. Kadir, A. Azdarpour, Production and detailed characterization of bio-oil from fast pyrolysis of palm kernel shell, *Biomass and Bioenergy*, 2013, **59**, 316-324, doi: 10.1016/j.biombioe.2013.08.037.
[16] S. Yorgun, D. Yıldız, Slow pyrolysis of paulownia wood: effects of pyrolysis parameters on product yields and bio-oil characterization, *Journal of Analytical and Applied Pyrolysis*, 2015, **114**, 68-78, doi: 10.1016/j.jaap.2015.05.003.
[17] A. Assi, F. Bilo, A. Zanoletti, J. Ponti, A. Valsesia, R. La Spina, A. Zacco, E. Bontempi, Zero-waste approach in municipal solid waste incineration: Reuse of bottom ash to stabilize fly ash, *Journal of Cleaner Production*, 2020, **245**, 118779, doi: 10.1016/j.jclepro.2019.118779.
[18] W. Zhou, J. Chai, Z. Xu, Y. Qin, J. Cao, P. Zhang, A review of existing methods for predicting leachate production from municipal solid waste landfills, *Environmental Science and Pollution Research*, 2024, **31**, 16131-16149, doi: 10.1007/s11356-024-32289-y.
[19] Y. Zhang, L. Wang, L. Chen, B. Ma, Y. Zhang, W. Ni, D. C. W. Tsang, Treatment of municipal solid waste incineration fly ash: State-of-the-art technologies and future perspectives, *Journal of Hazardous Materials*, 2021, **411**, 125132, doi: 10.1016/j.jhazmat.2021.125132.
[20] P. Sharma, A. Bano, S. P. Singh, S. Varjani, Y. W. Tong, Sustainable organic waste management and future directions for environmental protection and techno-economic perspectives, *Current Pollution Reports*, 2024, **10**, 459-477, doi: 10.1007/s40726-024-00317-7.
[21] D. Chen, L. Yin, H. Wang, P. He, Pyrolysis technologies for municipal solid waste: a review, *Waste Management*, 2014, **34**, 2466-2486, doi: 10.1016/j.wasman.2014.08.004.
[22] T. R. Sarker, D. Z. Ethen, H. H. Asha, S. Islam, M. R. Ali, Transformation of municipal solid waste to biofuel and bio-chemicals–a review, *International Journal of Environmental Science and Technology*, 2025, **22**, 3811-3832, doi: 10.1007/s13762-024-05975-0.
[23] S. A. Razzak, Municipal solid and plastic waste co-pyrolysis towards sustainable renewable fuel and carbon materials: a comprehensive review, *Chemistry - An Asian Journal*, 2024, **19**, e202400307, doi: 10.1002/asia.202400307.
[24] R. Rauch, Y. Kiros, K. Engvall, E. Kantarelis, P. Brito, C. Nobre, S. M. Santos, P. A. Graefe, Hydrogen from waste gasification, *Hydrogen*, 2024, **5**, 70-101, doi: 10.3390/hydrogen5010006.
[25] W. Cui, Y. Wei, N. Ji, Global trends of waste-to-energy (WtE) technologies in carbon neutral perspective: Bibliometric analysis, *Ecotoxicology and Environmental Safety*, 2024, **270**, 115913, doi: 10.1016/j.ecoenv.2023.115913.
[26] L. Traven, Sustainable energy generation from municipal

solid waste: A brief overview of existing technologies, *Case Studies in Chemical and Environmental Engineering*, 2023, **8**, 100491, doi: 10.1016/j.cscee.2023.100491.

[27] Y. Liang, D. Xu, P. Feng, B. Hao, Y. Guo, S. Wang, Municipal sewage sludge incineration and its air pollution control, *Journal of Cleaner Production*, 2021, **295**, 126456, doi: 10.1016/j.jclepro.2021.126456.

[28] R. Narayana Sarma, R. Vinu, An assessment of sustainability metrics for waste-to-liquid fuel pathways for a low carbon circular economy, *Energy Nexus*, 2023, **12**, 100254, doi: 10.1016/j.nexus.2023.100254.

[29] J. Wang, S. Wang, Preparation, modification and environmental application of biochar: A review, *Journal of Cleaner Production*, 2019, **227**, 1002-1022, doi: 10.1016/j.jclepro.2019.04.282.

[30] N. Li, M. He, X. Lu, B. Yan, X. Duan, G. Chen, S. Wang, L.-A. Hou, Municipal solid waste derived biochars for wastewater treatment: Production, properties and applications, *Resources, Conservation and Recycling*, 2022, **177**, 106003, doi: 10.1016/j.resconrec.2021.106003.

[31] O. P. Potapov, V. V. Khaskhachikh, G. Ya Gerasimov, State-of-the-art technologies of oil shale thermal processing, *Journal of Physics: Conference Series*, 2017, **891**, 012236, doi: 10.1088/1742-6596/891/1/012236.

[32] E. P. Volkov, G. F. Stelmahh, The stages of research on creating commercial units for processing oil shale fines. development of the "galoter" process in 1944-1999, *Oil Shale*, 1999, **16**, 161, doi: 10.3176/oil.1999.2.08.

[33] G. Gerasimov, V. Khaskhachikh, O. Potapov, G. Dvoskin, V. Kornileva, L. Dudkina, Pyrolysis of sewage sludge by solid heat carrier, *Waste Management*, 2019, **87**, 218-227, doi: 10.1016/j.wasman.2019.02.016.

[34] A. N. Tugov, A. Ots, A. Siirde, V. T. Sidorkin, G. A. Ryabov, Development of measures to improve technologies of energy recovery from gaseous wastes of oil shale processing, *Thermal Engineering*, 2016, **63**, 430-438, doi: 10.1134/s0040601516060082.

[35] O. P. Potapov, Experience and prospects of oil shale utilization for power production in Russia, *Thermal Engineering*, 2016, **63**, 643-647, doi: 10.1134/s0040601516080097.

[36] R. Moradi, M. Yazdi, A. Haghighi, A. Nedjati, Sustainable resilient E-waste management in London: a circular economy perspective, *Heliyon*, 2024, **10**, e34071, doi: 10.1016/j.heliyon.2024.e34071

[37] A. Molis, C. Palazzo, K. Ainsalu, Mitigating risks of hybrid war: search for an effective energy strategy in the Baltic states, *Journal on Baltic Security*, 2018, **4**, 23-32, doi: 10.2478/jobs-2018-0009.