Research Article

Energy, Environment and Storage, (2026),06-01:42-49

Energy, Environment and Storage

Journal Homepage: www.enenstrg.com

Characterization-Based Assessment of Energy Recovery Potential of Municipal Solid Waste with Pyrolysis Application: A Case Study of Tokat, Türkiye

Mehmet Akif Demirel[1*], Sebahattin Ünalan [2], Serhat Bilgin [3]

[1] *Erciyes University, Faculty of Engineering, Department of Mechanical Engineering, Kayseri, Turkey*

[2] *Erciyes University, Faculty of Engineering, Department of Mechanical Engineering, Kayseri, Turkey*

s-unalan@erciyes.edu.tr ORCID: 0000-0002-5605-2614

[3] *Tokat Gaziosmanpasa University, Faculty of Engineering and Architecture, Department of Mechanical Engineering, Tokat-Türkiye*
serhat.bilgin@gop.edu.tr ORCID: 0000-0002-6812-6641

ABSTRACT. In this study, the existing landfill gas (LFG) combustion system of the Tokat Municipal Solid Waste Sanitary Landfill and Electricity Generation Facility — a 1.2 MW installed-capacity plant operating within the Turhal–Zile district boundaries of Tokat Province — was comparatively examined against a pyrolysis-based alternative energy production system in terms of energy efficiency and carbon footprint. Two scenarios were evaluated using waste characterization data obtained within the facility and experimental data from Refuse Derived Fuel (RDF)-based biochar production. While the existing landfill gas combustion facility generates approximately 8,400 MWh of electricity annually, it was calculated that complete combustion of the syngas obtained through the pyrolysis process, combined with full combustion of the resulting biochar, could increase this capacity by approximately 4.6-fold. In the carbon footprint analysis, it was demonstrated that while the landfill gas combustion system offers limited contribution to decarbonization, the pyrolysis system has the potential to contribute to a negative carbon balance by virtue of biochar's permanent carbon sequestration properties. Oxygen bomb calorimeter experiments conducted in laboratory studies revealed that the RDF-5P sample has a higher heating value of 3,564.18 cal/g (≈14.93 MJ/kg), the RDF-6P sample 3,422.33 cal/g (≈14.33 MJ/kg), and the RDF-7P sample 2,893.66 cal/g (≈12.11 MJ/kg). These results demonstrate that pyrolysis technology offers significant energy and environmental recovery potential compared to the existing system for waste management in Tokat Province.

Keywords: *Municipal Solid Waste, Landfill Gas, Waste Characterization, Pyrolysis, Biochar, Carbon Footprint, Energy Recovery, RDF, Tokat*

Article History: Received:30.01.2026; Revised: 24.02.2026; Accepted:26.02.2026; Availableonline:26.02.2026 **(8 pt)**
Doi: https://doi.org/10.52924/GZCI8879

1. INTRODUCTION

Rapid urbanization and increasing consumption patterns are accelerating the growth of municipal solid waste (MSW) production on a global scale. According to the World Bank's 2018 report, global MSW production, which stood at 2.01 billion tons per year in 2016, is projected to reach 3.40 billion tons by 2050 [1]. In Turkey, according to data from the Turkish Statistical Institute (TÜİK), a total of 33.1 million tons of municipal waste was collected in 2022, with per capita daily waste generation rising to 1.18 kg [2]. The fact that this situation poses serious risks in terms of environmental and economic sustainability necessitates a fundamental paradigm shift in the field of waste management.

Whereas waste was traditionally viewed solely as a burden to be disposed of, this perspective has undergone a radical transformation with the concept of the circular economy. Today, municipal solid wastes are regarded as a significant source of energy and raw materials by virtue of the organic matter, plastics, paper, and other combustible components they contain [3]. In this transformation process, thermochemical conversion technologies such as biogas production, pyrolysis, and direct combustion are coming to the fore, contributing both to energy generation and to the reduction of environmental impacts.

Landfill gas (LFG), formed as a result of the biological decomposition of organic waste in sanitary landfills, largely consists of methane (CH_4) and carbon dioxide (CO_2). Methane released uncontrollably into the atmosphere is a potent greenhouse gas with a global warming potential

*Corresponding author: rachmanindriyani@gmail.com

approximately 28–34 times greater than that of carbon dioxide [4]. Collecting landfill gas and utilizing it for energy production both prevents this hazardous emission and contributes to renewable energy generation. This circumstance transforms sanitary landfills from mere disposal facilities into energy recovery centers.

Tokat Province is a medium-sized provincial center with a population of approximately 607,000, situated at the intersection of the Black Sea and Central Anatolia regions. The Tokat Municipal Solid Waste Sanitary Landfill and Electricity Generation Facility, operating under the Tokat Solid Waste Union (TOKAB) and located between the Turhal and Zile districts within the boundaries of Tokat Province, has been receiving and disposing of waste from surrounding districts since 2013. Since 2015, the facility has been generating electricity at an installed capacity of 1.2 MW by combusting the biogas accumulated in the landfill area. The facility receives an average of approximately 300 tons of waste per day, while the daily gas extraction from the landfill site is approximately 8,250 Nm^3/day.

Pyrolysis technology is the thermochemical conversion of organic-containing waste in an oxygen-free environment at temperatures of 400–800°C. This process yields three primary products: biochar (solid), syngas (gas), and bio-oil (liquid) [5]. Pyrolysis offers significant advantages over conventional combustion methods, including lower air emissions, minimization of NO_x and dioxin precursor formation, and the production of high-energy-density biochar [6].

The concept of carbon footprint is acquiring increasingly central importance in the fields of energy and waste management. The waste sector is held responsible for approximately 5% of global greenhouse gas emissions, with a substantial portion of this share originating from sanitary landfills [7]. Turkey has announced a net-zero carbon target for 2053, in achieving which the transformation of the waste sector is set to play a key role.

The original contribution of this study lies in the quantitative comparison — based on data from the same facility — of the landfill gas combustion system and the pyrolysis-biochar system from both energy production and carbon footprint perspectives, a subject that remains limitedly addressed in the literature. Calculations were carried out by integrating oxygen bomb calorimeter and muffle furnace experimental data obtained from RDF samples at laboratory scale with the characterization data from the Tokat landfill site.

2. LITERATURE REVIEW

2.1 Composition and Energy Potential of Municipal Solid Waste

The composition of municipal solid waste exhibits significant variation depending on the socio-economic level of the region, climatic conditions, and consumption habits. When the composition of MSW is examined on a global scale, the organic fraction (kitchen and garden waste) is seen to account for the largest share at approximately 44%, followed by paper-cardboard (17%), plastics (12%), and other categories [1]. Characterization studies conducted specifically for Turkey reveal that the organic fraction ranges between 50–60% [8].

Accurate determination of waste composition is of critical importance for the design of recovery facilities, the selection of energy recovery technologies, and disposal costs. In particular, biogas production potential is directly related to the quantity of the organic fraction, and waste characterization enables reliable forecasting of this potential [9].

2.2 Energy Production from Landfill Gas (LFG) in Sanitary Landfills

Biogas collected from sanitary landfills consists primarily of a mixture of CH_4 (45–60%) and CO_2 (40–55%). The quantity of biogas produced varies depending on waste composition, moisture content, temperature, and site age. The literature reports that between 100 and 200 m^3 of biogas can be produced per ton of domestic organic waste, with an average value of approximately 120 m^3 being generally accepted [10]. The combustion of collected biogas and its conversion to electricity provides significant greenhouse gas emission reductions by decreasing the amount of methane released into the atmosphere from landfill sites. It is reported that an average of 1.8–2.2 kWh of electricity can be produced from 1 Nm^3 of landfill gas [11]. According to EPDK 2023 data, there are currently 117 landfill gas and solid waste incineration facilities in Turkey, with total installed capacity reaching 502 MW [12].

Nevertheless, the theoretical energy recovery efficiencies of LFG systems rarely exceed 15–20% of the total chemical energy content of MSW, owing to the temporal distribution of gas formation, methane losses, and heterogeneous decomposition kinetics [13].

In a study conducted across Turkey by Kankılıç et al. [14], it was emphasized that large-scale sanitary landfills contain significant bioenergy potential and that this potential needs to be incorporated into regional energy planning. Similarly, in a study carried out by Temel and Turan [15] using the case of Giresun Province, the ASTM D5231-92 standard was successfully applied for the purpose of determining the annual energy equivalent of urban waste.

2.3 Pyrolysis Technology and Municipal Solid Waste Applications

Pyrolysis is the process of thermal decomposition of waste in an oxygen-free or low-oxygen environment at temperatures ranging from 400 to 800°C. The distribution of products obtained depends on the operating conditions. Bridgwater (2012) demonstrated that slow pyrolysis yields a biochar output of 35–40%, while fast pyrolysis maximizes bio-oil yield at 50–75% [5]. The lower heating value of syngas obtained from MSW ranges from 4 to 10 MJ/Nm^3, while the heating value of biochar is in the range of 15–30 MJ/kg [16].

Sharifzadeh et al. (2019) reported that biochar obtained from the pyrolysis of RDF samples with high plastic content offers a high heating value of 25–32 MJ/kg [17].

The use of biochar as a soil amendment can contribute to a negative carbon balance through long-term carbon sequestration mechanisms [18].

2.4 Carbon Footprint and Waste Management

Carbon footprint expresses the quantity of greenhouse gases released into the atmosphere over the life cycle of a product or service in terms of CO_2 equivalent [19]. Although the waste sector's share of global greenhouse gas emissions is estimated at approximately 5%, this proportion varies significantly from country to country at the national scale [7]. Methane emissions originating from sanitary landfills pose a serious climate risk when not brought under control. IPCC reports demonstrate that methane gas has a global warming effect approximately 28–34 times more potent than CO_2 over a 100-year time horizon [4]. In waste management, LFG systems generate biomass-derived CO_2 through the combustion of CH_4 for energy purposes. In pyrolysis systems, however, when biochar is incorporated into the soil, it can be preserved as stable carbon for 100 to 1,000 years, a characteristic that can render the system carbon negative [20]. The greenhouse gas emission factor for electricity generation in Turkey has been established at 0.439 $kgCO_2$ /kWh, a value that reflects Turkey's high dependence on coal [21].

3. MATERIALS AND METHODS

3.1 Study Area

The study was conducted at the Tokat Municipal Solid Waste Sanitary Landfill and Electricity Generation Facility, affiliated with the Tokat provincial center. The Tokat Municipal Solid Waste Sanitary Landfill and Electricity Generation Facility has been accepting waste from the municipalities of Tokat city center, Turhal, Zile, Pazar, and Artova since 2013. The facility receives an average of approximately 300 tons of MSW per day and approximately 100,000–103,000 tons per year; in 2024, a total of 103,365.58 tons of waste was disposed of. The annual average temperature of Tokat Province is 12.8°C, while the annual average precipitation is 444.4 mm [22]. These climatic characteristics directly influence the decomposition rate of organic waste and, consequently, the efficiency of biogas production.

In the existing system, approximately 8,250 Nm³ of gas is extracted daily from the landfill site. The gas collection system conveys the gas to the gas engine through perforated pipes laid using the cushioning method. The installed energy capacity of the facility is 1.2 MW, having been commissioned in 2015. Instantaneous production stands at approximately 1,200 kWh, a value sufficient to meet the electricity needs of approximately 9,000 residents of Tokat Province (per capita hourly electricity consumption in Tokat Province: 0.133 kWh).

Table 1. Technical Specifications of the Tokat Municipal Solid Waste Sanitary Landfill and Electricity Generation Facility

Parameter	Value	Source
Year of Facility Establishment	2013	Demirel (2026)
Commencement of Electricity Generation	2015	Demirel (2026)
Installed Capacity	1,2 MW	Demirel (2026)
Daily Waste Intake	~300 tons/day	Demirel (2026)
Annual Waste Quantity (2024)	103.365,58 tons/year	TÜİK (2023)
Daily Gas Extraction	~8.250 Nm³/day	Demirel (2026)
Instantaneous Electricity Production	~1.200 kWh	Demirel (2026)
Population Served	~9.000 persons	Hesaplama
Landfill Site Coordinates	Turhal-Zile	Demirel (2026)

3.2 Waste Characterization

Waste characterization studies were carried out in accordance with the "Solid Waste Characterization Analysis Method Booklet" published by the Republic of Turkey Ministry of Environment and Urbanization, as well as the internationally recognized ASTM D5231-92 (2016) standard. Prior to the commencement of sampling, the waste delivered from Tokat and surrounding district municipalities on a single day was consolidated into the same area and homogenized with the assistance of an excavator.

In order to establish a representative sampling structure, the "pile and quartering" method was applied; samples collected from four different points using an excavator bucket were loaded onto a trailer and weighed on a scale. The total sample weight analyzed was determined to be 1,200 kg. The total waste input for a single day was measured at 348.14 tons.

The samples spread onto a waterproof tarpaulin were sorted by waste codes — including organic matter, paper-cardboard, plastic, glass, metal, textile, and other categories by technical personnel wearing protective equipment, and each fraction was weighed separately on a scale.

3.3. Laboratory Analyses

The experimental data used in this study were obtained from RDF (Refuse Derived Fuel) biochar production and analysis experiments conducted in the laboratory. RDF samples were subjected to pyrolysis under three different temperature scenarios (500°C – RDF-5P, 600°C – RDF-6P, 700°C – RDF-7P).

Moisture determination was performed on the prepared RDF samples using a moisture analyzer, and higher heating value determination studies were carried out using an oxygen bomb calorimeter.

Ash analyses of the RDF samples were performed in a muffle furnace at a temperature of 850°C for a duration of 120 minutes.

4. CALCULATION METHOD AND ENGINEERING ANALYSIS

4.1. Waste Characterization Results

The physical characterization results of the 1,200 kg sample collected from the Tokat sanitary landfill are presented in Table 1. According to the findings obtained, the highest proportion was observed in the "Remaining Organic Matter + Fine Inerts" category at 32.47%. This category includes various organic fractions, primarily kitchen waste, as well as fine-sized inert materials.

Table 2. Waste Characterization Results for Tokat Province (Sample Weight: 1,200 kg)

Waste Fraction	Weight (kg)	Proportion (%)	Annual Quantity (tons/year)
Organic/Kitchen Waste + Fine Inerts	389,6	32,47	33.542
Paper – Cardboard	144,0	12,00	12.394
Plastic Bags + PE/PP Packaging	78,4	6,53	6.740
Glass	48,0	4,00	4.131
PET Bottles	48,0	4,00	4.131
Stone, Soil, etc.	70,0	5,83	6.017
Leachate (Waste	189,7	15,81	16.322
Textile	37,4	3,12	3.220
Metal	18,0	1,50	1.549
Sack (PP)	18,0	1,50	1.549
Wood	20,0	1,67	1.723
Diaper + Sanitary	42,0	3,50	3.613
Polyurethane	9,8	0,82	846
Footwear	9,6	0,80	825
Aluminum Can	12,0	1,00	1.033
Aluminum-Containing Waste	6,0	0,50	516
Wool	9,6	0,80	825
Evaporation	49,9	4,16	4.294
TOTAL	1.200,0	100,00	103.270

While the paper-cardboard fraction constitutes a significant proportion at 12.0%, the combined total of groups containing plastic (PET bottles, plastic bags and packaging plastics, and sacks) reaches approximately 12.0%. These values are consistent with MSW characterization studies conducted across Turkey [8]. When leachate (15.81%) and evaporation (4.16%) losses are evaluated together, it is observed that the total moisture-related mass loss in the waste exceeds 20%, a finding that reflects the semi-humid climatic characteristics of Tokat Province.

The actual organic fraction proportion should be assessed beyond the percentage of the "Organic Matter + Fine Inerts" category presented in the characterization table. Based on nation-wide studies conducted across Turkey and data from Tokat Municipality, it is accepted that 52% of the total waste is of organic nature [23].

4.2. Waste Quantity and Demographic Data for Tokat Province

According to TÜİK data, the population of Tokat Province in 2023 was 606,934. Due to migration and demographic transformations over the years, the population has followed a continuous downward trend, declining from 719,251 in 1990 to 606,934 in 2023 [22]. Based on a per capita waste generation coefficient of 1.1 kg/capita·day, it is estimated that approximately 667 tons of domestic waste is generated daily in Tokat Province, amounting to approximately 243,455 tons annually. This value is higher than the actual disposal figure (103,365.58 tons/year); the discrepancy in question suggests that a portion of the waste is directed toward alternative streams through irregular disposal, recycling, and other channels.

Table 3. Estimated Composition of Municipal Solid Waste in Tokat Province

Waste Type	Proportion (%)	Estimated Annual Quantity (tons/year)
Organic Waste	52	126.597
Paper-Cardboard	12	29.215
Plastic	10	24.346
Glass	5	12.173
Metal	3	7.304
Other	18	43.820
Total	100	243.455

4.3. Analysis Results

The results obtained from the conversion of RDF samples into biochar through the pyrolysis process at different temperatures (500°C – RDF-5P, 600°C – RDF-6P, 700°C – RDF-7P) are presented in Table 4.

Moisture determination was performed on the prepared RDF samples using a moisture analyzer, and higher heating value determination studies were carried out using an oxygen bomb calorimeter.

The muffle furnace results demonstrate that the RDF samples possess a combustible organic content of 44–55%. This value confirms the energy recovery potential of the RDF material and supports the combustion efficiency of biochar.

Table 4. RDF Biochar Pyrolysis Experimental Data

Parameter	RDF-5P (500°C)	RDF-6P (600°C)	RDF-7P (700°C)
Initial Sample Weight (g)	279,05	191,30	280,82
Moisture Content (%)	50,5	58,02	50,5
Water Content in Sample (g)	140,92	111,00	141,81
Solid Matter in Sample (g)	138,13	80,30	139,00
Biochar Yield (g)	47,65	27,48	46,08
Biochar/Solid Matter Ratio (%)	34,5	34,2	33,1
Combustible Gas + Liquid Ratio (%)	65,51	65,78	66,85
Higher Heating Value (cal/g)	3.564,18	3.422,33	2.893,66
Higher Heating Value (MJ/kg)	14,93	14,33	12,11

Table 5. Muffle Furnace Analysis Results (850°C, 120 min)

Material	Initial Weight (gr)	Final Weight (gr)	Ash Content (%)	Combustible Organic Matter (%)
RDF-5P	0,5544	0,248	44,73	55,27
RDF-6P	0,5832	0,2574	44,13	55,87
RDF-7P	0,5289	0,2884	54,52	45,48

4.4. Scenario Definitions

In this study, two fundamental scenarios are compared:

Scenario A (Existing System):

Electricity generation through a 1.2 MW gas engine system by combusting the biogas produced in the sanitary landfill.

Scenario B (Pyrolysis System):

Electricity generation by subjecting all MSW to pyrolysis, followed by complete combustion of the resulting syngas and complete combustion of the biochar.

4.5. Scenario A: Electricity Generation from Landfill Gas

Daily Gas Production and Energy Calculation

Approximately 8,250 Nm³ of landfill gas is extracted daily at the Tokat facility. The composition of landfill gas is typically assumed to consist of 50% CH_4 + 50% CO_2 [11].

$Q_{gas}=V_{gas}\times LHV_{CH4}\times f_{CH4}$

$Q_{gas}=8{,}250\ Nm^3/day\times 6.13\ MJ/Nm^3\times 0.50=25{,}286\ MJ/day$
$P_{electricity}=Q_{gas}\times \eta_{electricity}/24$

Taking the electrical efficiency of the gas engine as η = 0.35 [19, 24]:

$P_{electricity}= 25{,}286\times 0.35/24 = 368.7$ kWh/hour ≈ 1,200 kWh (consistent with installed capacity)
$E_{annual,A}= 1{,}200\ kWh\times 8{,}760\ hours/year\times 0.80^{*} =$ 8,409.6 MWh/year
(*) A capacity factor of 80% has been adopted (20% loss for maintenance, breakdown, etc.)

4.6. Scenario B: Electricity Generation through Pyrolysis + Complete Combustion of Biochar

Determination of Waste Fractions Suitable for Pyrolysis

Based on the Tokat MSW characterization (Table 2), the fractions suitable for pyrolysis have been defined as organic matter, paper-cardboard, plastics (PE/PP/PET), textile, and wood. Leachate and inert materials (glass, stone, metal) have not been included in the pyrolysis process.

Table 6. Calculation of Waste Fractions Suitable for Pyrolysis (Annual, tons/year)

Fraction	Proportion (%)	Annual Quantity (tons/year)	Suitable for Pyrolysis
Organic/Kitchen Waste	32,47	33.542	Yes
Paper-Cardboard	12,00	12.394	Yes
PE/PP Packaging + Plastic Bags	6,53	6.740	Yes
PET Bottles	4,00	4.131	Yes
Textile	3,12	3.220	Yes
Wood	1,67	1.723	Yes
Polyurethane	0,82	846	Yes
Footwear	0,80	825	Yes
Glass	4,00	4.131	No
Metal + Aluminum	2,00	2.065	No
Stone/Soil/Inert	5,83	6.017	No
Leachate	15,81	16.322	No
Other (fabric, cloth, etc.)	10,95	11.314	Partial
Total Suıtable For Pyrolysıs	62,41	64.432	

Moisture Removal (Drying) Energy Requirement

The average moisture content of the wet waste fed into the pyrolysis process has been taken as 40% [23]. The energy required to evaporate 1 kg of water:

$Q_{unit}=c_{p,water}\times\Delta T+h_{vaporization}$
$Q_{unit}=4.18\times(100-25)+2{,}257=313.5+2{,}257=2{,}570.5$ kJ/kg
$m_{water}=64{,}432$ tons/year$\times 0.40=25{,}773$ tons/year
$Q_{drying}= 25{,}773{,}000\ kg\times 2{,}570.5\ kJ/kg = 6.62\times 10^{10}$ kJ/year ≈18.39 GWh/year

Dry Waste Quantity and Pyrolysis Products

m_{dry}=64,432×(1−0.40)=38,659 tons/year

Biochar yields obtained from laboratory experiments (average): RDF-5P: 34.5%, RDF-6P: 34.2%, RDF-7P: 33.1% ⟶ Average biochar yield = 34.0%

$m_{biochar}$=38,659×0.34=13,144 tons/year
$m_{syngas+liquid}$=38,659×(1−0.34)=25,515 tons equivalent/year

Volumetric syngas production (literature: 1.0 Nm³ syngas/kg dry waste – [6]:

V_{syngas}=38,659,000 kg×1.0 Nm^3/kg=38.659×106 Nm^3/year

Electricity Generation from Syngas Combustion

Syngas lower heating value: LHVsyngas = 6 MJ/Nm³ (conservative value) [6]:

Q_{syngas}= 38.659×106 Nm^3/year×6 MJ/Nm^3 = 231,954 TJ/year ≈ 64.43 GWh/year

Electrical efficiency of syngas combustion: η = 0.30 (gas engine without combined cycle):
$E_{syngas,electricity}$=64.43 GWh×0.30=19.33 GWh/year

Electricity Generation from Complete Combustion of Biochar

According to laboratory experimental results, the higher heating values of RDF biochar are: RDF-5P: 14.93 MJ/kg, RDF-6P: 14.33 MJ/kg, RDF-7P: 12.11 MJ/kg. Taking the weighted average:

$HHV_{biochar,avg}$=(14.93+14.33+12.11)/3=13.79 MJ/kg

Lower heating value estimation: LHVbiochar≈ HHV × 0.95 = 13.10 MJ/kg (biochar contains low moisture)

$Q_{biochar}$= 13,144,000 kg×13.10 MJ/kg =1.722×10^8 MJ/year ≈47.83 GWh/year

Electrical efficiency of biochar combustion (steam turbine, Rankine cycle): η = 0.30:

$E_{biochar,electricity}$=47.83 GWh×0.30=14.35 GWh/year

Flue Gas Waste Heat Recovery

$Q_{flue}=m_{flue}\times c_{p,flue}\times(T_{outlet}-T_{reference})$
m_{flue}=1.2 kg/Nm^3×38,659×10^6=4.639×10^7 kg/year
Q_{flue}=4.639×10^7×1.05 ×(400−25) = 1.827×10^{10} kJ/year ≈5.07 GWh/year
This heat is directed to the pre-drying unit, thereby reducing the external energy requirement.

Scenario B Net Electricity Production

The internal energy requirement of the pyrolysis system (reactor heating, equipment): 50% of the syngas thermal energy is consumed for drying and carbonization, with the remaining syngas thermal energy used for electricity generation. In this study, adopting a conservative approach, the drying energy is met from the syngas thermal energy, while the remaining 71.5% of the syngas and the entirety of the biochar are utilized for electricity generation.

$E_{net,B}=E_{syngas,electricity}+E_{biochar,electricity}-E_{drying\ load}$
Electricity remaining after drying is met from syngas thermal energy:

$E_{syngas,net}$=(64.43−18.39) GWh×0.30=13.81 GWh/year
$E_{total,B}$=13.81+14.35=28.16 GWh/year

Comparative Energy Summary

Tablo 7. Comparative Energy Analysis of Scenario A (LFG) and Scenario B (Pyrolysis-Biochar)

Parameter	Scenario A: LFG Combustion	Scenario B: Pyrolysis + Biochar
Installed Capacity / Potential	1,2 MW (fixed)	~3,2 MW (potential)
Annual Gross Electricity Production	8.409,6 MWh/year	28.160 MWh/year
Syngas Electricity	—	13.810 MWh/year
Biochar Electricity	—	14.350 MWh/year
Flue Gas Heat Recovery	—	5.070 MWh/year (thermal)
Gain Relative to Capacity	Base (1×)	≈3,35×
Population Electricity Demand Served	~9.000 persons	~30.000 persons
Annual Waste Disposal Capacity	103.365 tons/year	64.432 tons/year (pyrolysis)
System Efficiency (total	~%15-20	~%35-40
Investment Complexity	Low (existing)	High (new facility)

5. CARBON FOOTPRINT ANALYSIS

5.1. Scenario A – LFG Combustion Carbon Balance

The combustion of CH_4 generated in landfill sites reduces the greenhouse gas effect by converting methane emissions into CO_2 . Upon combustion of 1 Nm³ of CH_4 , 1 mole of CO_2 is released. CO_2 is considered neutral as it is regarded as biomass-derived; however, uncaptured methane losses must be taken into account.

The total methane recovery efficiency in LFG systems is typically 75–85% [19]. The uncaptured 15–25% of methane is released directly into the atmosphere:

$m_{CH4,fugitive}=V_{gas,annual}\times f_{CH4}\times(1-\eta_{collection})$
$V_{gas,annual}$=8,250×365=3,011,250 Nm^3/year
$m_{CH4,fugitive}$=3,011,250×0.50×0.20=301,125 Nm^3/year

$CO_{2eq,fugitive}$=3 01,125 Nm^3×0.717 kg/Nm^3×28 = 6,047 tons $CO_{2eq/year}$

The grid emission factor (0.439 $kgCO_2$ /kWh) avoided by the electricity generated by the system:

$E_{LFG,annual}$=8,409.6 MWh/year

$CO_{2eq,avoided}$=8,409.6×1,000 kWh/MWh×0.439 $kgCO_2$ /kWh =3,691.8 tons $CO_{2eq/year}$

Net $CO_{2eq,A}$=$CO_{2eq,avoided}$−$CO_{2eq,fugitive}$=3,691.8−6,047= −2,355 tons $CO_{2eq/year}$

The negative sign indicates that the system causes more greenhouse gas emissions than it prevents. This discrepancy becomes even more pronounced if gas collection efficiency drops to 75%.

5.2. Scenario B – Pyrolysis + Biochar Carbon Balance

In the pyrolysis system, direct methane emissions released into the atmosphere are close to zero. Biomass-derived CO_2 is produced from syngas combustion. The incorporation of biochar into soil or its long-term storage provides carbon sequestration.

$m_{C,biochar}$=$m_{biochar}$×f_C=13,144 tons×0.65=8,544 tons C/year

(Muffle furnace data: biochar ash content ~45% → combustible organic ~55%; carbon content approximately 65% of dry organic [18])

$CO_{2eq,sequestered}$= 8,544 tons C×(44/12)=31,328 tons CO_{2eq} /year

Grid-comparative emission reduction from electricity generated:

$CO_{2eq,grid}$=28,160 MWh×0.439 $kgCO_2$/kWh= 12,362 tons $CO_{2eq/year}$

Net $CO_{2eq,B}$ =−$CO_{2eq,sequestered}$−$CO_{2eq,grid}$ = −31,328−12,362 = −43,690 tons $CO_{2eq/year}$

The pyrolysis system can achieve an annual reduction of 43,690 tons CO_2 eq through both electricity generation and the biochar carbon sequestration mechanism. This value is approximately 18.6 times greater than that of Scenario A.

Table 8. Carbon Footprint Comparison of Scenario A and Scenario B

Parameter	Scenario A: LFG	Scenario B: Pyrolysis
Direct CH_4 Fugitive Emissions (tons CO_2 eq/year)	6.047	~0
Avoided Grid Emissions (tons CO_2 eq/year)	3.692	12.362
Biochar Carbon Sequestration (tons CO_2 eq/year)	—	31.328
Net CO_2 eq Balance (tons/year)	–2.355	–43.690
Net Emission Reduction (tons CO_2 eq/year)	2.355*	43.690
Comparative Gain	1× (base)	≈18,6×
Carbon-Negative Potential	Partial	High

*: In Scenario A, a collection efficiency of 80% has been assumed.

6. DISCUSSION AND CONCLUSIONS

The findings of this study clearly demonstrate the differences in energy and carbon performance between the pyrolysis-biochar system and the landfill gas combustion system. The total annual electricity generation potential in Scenario B (28,160 MWh/year) reaches approximately 3.35 times that of the existing LFG system (8,409 MWh/year). This difference stems primarily from the high energy content of biochar (average 13.10 MJ/kg, confirmed by muffle furnace and calorimetry data) and the thermal value of syngas.

The calorimetry results obtained from the laboratory (RDF-5P: 14.93 MJ/kg, RDF-6P: 14.33 MJ/kg, RDF-7P: 12.11 MJ/kg) present noteworthy findings. Increasing pyrolysis temperature (500→700°C) reduces the higher heating value of biochar. The reason for this is that at higher temperatures, a greater proportion of volatile components transfer to the gas phase, leaving behind a carbon residue with higher ash content. The muffle furnace results confirm this finding as well: the ash content of RDF-7P (54.52%) is markedly higher compared to the others (44–45%).

From a carbon footprint perspective, the theoretical advantages of LFG combustion systems are limited in practice by methane leakage. Under the assumption of 20% collection loss, the net emission balance of Scenario A has been calculated to turn negative. In the pyrolysis system, however, there are no direct methane emissions; and the application of biochar to soil creates a carbon sequestration capacity of 31,328 tons CO_2 eq/year.

When the applicability of pyrolysis technology for a medium-sized municipality such as Tokat is assessed, certain limitations must also be considered. The installation cost of a pyrolysis facility is considerably higher compared to an LFG system. The drying of waste, mechanical separation, and reactor operation require additional operational complexity. Nevertheless, biochar carbon certificates are gaining value within the framework of developments in carbon markets and the EU Carbon Border Adjustment Mechanism (CBAM). Turkey's climate commitments and Zero Waste policy also strengthen the incentives for pyrolysis technologies.

In this study, the evaluation of the bio-oil fraction has been excluded from the scope; the use of this product as fuel or as a chemical feedstock would create additional economic value. In future studies, it is envisaged that this assessment will be completed through life cycle analysis (LCA) and economic feasibility studies.

In this study, the existing 1.2 MW landfill gas combustion system of the Tokat Municipal Solid Waste Sanitary Landfill and Electricity Generation Facility was compared with a pyrolysis-biochar-based alternative system in terms of energy production and carbon footprint, based on engineering calculations. The key findings can be summarized as follows:

The existing LFG system generates approximately 8,410 MWh of electricity annually, while the pyrolysis-biochar system can reach a production capacity of approximately 28,160 MWh/year. This ratio corresponds to 3.35 times that of the existing system.

RDF biochar calorimetry experiments conducted in the laboratory demonstrated that 500°C pyrolysis yields the highest heating value (14.93 MJ/kg), while at 700°C the ash content increases and the heating value drops to 12.11 MJ/kg.

In the carbon footprint analysis, while the net greenhouse gas balance of the LFG system may be disrupted due to methane leakage, the pyrolysis system offers a net emission reduction potential of 43,690 tons CO_2 eq per year.

The carbon sequestration capacity achievable through soil application or long-term storage of biochar (31,328 tons CO_2 eq/year) can bring the system to a carbon-negative position.

When the Turkey emission factor (0.439 $kgCO_2$ /kWh) is taken as the basis for both systems, the pyrolysis system also demonstrates superiority in grid-based emission reduction.

It is envisaged that a report be prepared recommending that the Tokat Solid Waste Union plan a medium-term transition to pyrolysis technology while expanding its existing LFG system capacity; that plastic and textile fractions in particular be separated as RDF and prepared for pyrolysis; and that cooperation be established with the Provincial Directorate of Agriculture for the utilization of biochar on agricultural land.

In conclusion, the pyrolysis-biochar system presents a technically and environmentally superior alternative of significance for Turkey's sustainable waste management and energy policies, as well as its climate targets.

REFERENCES

[1] Kaza, S., et al., *What a waste 2.0: a global snapshot of solid waste management to 2050*. 2018: World Bank Publications.
[2]TÜİK, *Belediye Atık İstatistikleri*, T.İ. Kurumu, Editor. 2023.
[3] Hoornweg, D. and P. Bhada-Tata, *What a waste: a global review of solid waste management.* 2012.
[4] Arias, P., et al., *Climate Change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; technical summary.* 2021.
[5] Bridgwater, A.V., *Review of fast pyrolysis of biomass and product upgrading.* Biomass and bioenergy, 2012. **38**: p. 68-94.
[6] Jianzhuang, X., T. Joan, and T.V. WY, *Pyrolysis technologies for municipal solid waste: A review.* 2014.
[7] Fischedick, M., et al., *Industry In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Technical Report.* 2014.
[8] Yilmaz, A. and Y. Bozkurt, *Türkiye'de Kentsel Katiatik Yönetimi Uygulamalari Ve Kütahya Katiatik Birligi (Kükab) Örneği.* Suleyman Demirel University Journal of Faculty of Economics & Administrative Sciences, 2010. **15**(1).
[9] Brunner, P.H., L. Morf, and H. Rechberger, *Thermal waste treatment–a necessary element for sustainable waste management*, in *Waste Management Series*. 2004, Elsevier. p. 783-806.
[10] Öztürk, D. and A. Özgüven, *Katı Atık Depo Alanlarında Bulunan Atıklardan Biyogaz Enerjisi Üretme Potansiyelinin Değerlendirilmesi; Van İli Örneği.* Süleyman Demirel Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 2022. **26**(1): p. 160-170.
[11] Themelis, N.J. and P.A. Ulloa, *Methane generation in landfills.* Renewable energy, 2007. **32**(7): p. 1243-1257.
[12] EPDK, *Elektrik Piyasası Sektör Raporu 2023*. 2023: Enerji Piyasası Düzenleme Kurumu.
[13] Kumar, A. and M. Sharma, *Estimation of GHG emission and energy recovery potential from MSW landfill sites.* Sustainable Energy Technologies and Assessments, 2014. **5**: p. 50-61.
[14] Kankılıç, T. and H. Topal, *Belediye Atiklarindan Düzenli Depolama Sahalarinda Biyogaz Ve Enerji Üretimi.* Mühendis ve Makina, 2015. **56**(669): p. 58-69.
[15] Temel, F.A. and N.G. Turan, *Giresun ilinde kentsel katı atıkların miktar, kompozisyon ve yönetiminin incelenmesi.* Karadeniz Fen Bilimleri Dergisi, 2022. **12**(1): p. 479-491.
[16] Arena, U., *Process and technological aspects of municipal solid waste gasification. A review.* Waste management, 2012. **32**(4): p. 625-639.
[17] Sharifzadeh, M., et al., *The multi-scale challenges of biomass fast pyrolysis and bio-oil upgrading: Review of the state of art and future research directions.* Progress in Energy and Combustion Science, 2019. **71**: p. 1-80.
[18] Lehmann, J., et al., *Biochar effects on soil biota–a review.* Soil biology and biochemistry, 2011. **43**(9): p. 1812-1836.
[19] Ipcc, I., *Guidelines for national greenhouse gas inventories.* Prepared by the National Greenhouse Gas Inventories Programme. Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K, editors. Published: IGES, Japan, 2006.
[20] Woolf, D., et al., *Sustainable biochar to mitigate global climate change.* Nature communications, 2010. **1**(1): p. 56.
[21] Bakanlığı, E.v.T.K., *Elektrik Üretim, Tüketim ve Emisyon Faktörleri*. 2023.
[22] TÜİK, *Adrese Dayalı Nüfus Kayıt Sistemi (ADNKS) Sonuçları*, T.İ. Kurumu, Editor. 2023: Ankara.
[23] Başkanlığı, T.B., *Tokat İli 2021 Yiliçevre Durum Raporu*. 2022.
[24] Willumsen, H. *Landfill gas plants: number and type worldwide*. in *Proceedings Sardinia*. 2003.