EMERG, Volume X, Issue 4/2025 ISSN 2668-7003, ISSN-L 2457-5011

ENERGY RECOVERY FROM BONE WASTE GASIFICATION

VALORIFICAREA ENERGETICĂ A DEȘEURILOR DE OASE PRIN GAZEIFICARE

Mircea Gabriel MACAVEI[1,*], Roxana PĂTRAȘCU[2], Gabriela IONESCU[3],
Cosmin MĂRCULESCU[4]

Abstract: *This study investigates the energy recovery potential of animal bone waste through pyrolysis and subsequent gasification of the resulting biochar using air and steam as gasifying agents. Experimental results show that steam gasification yields a hydrogen-rich syngas (H_2 = 45 vol.%) with higher heating value (10.2 MJ/Nm³) compared to air gasification (8.9 MJ/Nm³). When extrapolated to a population of 400000 inhabitants, the process could substitute up to 147000 Nm³ of natural gas annually, generating economic savings exceeding 120000 €. These findings demonstrate an efficient sustainable pathway for waste valorization, resulting in fossil fuel reduction, and environmental impact reduction.*

Keywords: bone waste; gasification; syngas; energy recovery; energy efficiency.

Rezumat: *Această lucrare investighează potențialul de valorificare energetică al deșeurilor osoase animale prin piroliză și gazeificarea ulterioară a biocharului rezultat, utilizând aer și abur ca agenți de gazeificare. Rezultatele*

---

[1] PhD student, Dept. of Power Engineering, National University of Science and Technology Politehnica Bucharest, 060042 Bucharest, Romania, e-mail: mircea.macavei@yahoo.com; *0000-0001-8547-4552*

[2] Prof., Dept. of Power Engineering, National University of Science and Technology Politehnica Bucharest, 060042 Bucharest, Romania, e-mail: op3003@yahoo.com; *0000-0002-8672-2930*

[3] Assoc. Prof., Dept. of Power Engineering, National University of Science and Technology Politehnica Bucharest, 060042 Bucharest, Romania, e-mail: gabriela_ionescu@ymail.com; *0000-0001-9072-2709*

[4] Prof., Dept. of Power Engineering, National University of Science and Technology Politehnica Bucharest, 060042 Bucharest, Romania, e-mail: cosminmarcul@yahoo.co.uk; *0000-0001-5426-4528*

* Corresponding author

experimentale arată că gazeificarea cu abur produce un gaz de sinteză bogat în hidrogen (H_2 = 45 vol.%) cu o putere calorifică inferioară (10,2 MJ/Nm^3) mai ridicată comparativ cu gazeificarea cu aer (8,9 MJ/Nm^3). Extrapolarea la o populație de 400000 de locuitori indică posibilitatea înlocuirii a până la 147000 Nm^3 de gaz natural anual, generând beneficii economice anuale de peste 120000 €. Rezultatele evidențiază o soluție eficientă de valorificare a deșeurilor, conducând la reducerea consumului de combustibili fosili și reducerea impactului asupra mediului.

Cuvinte cheie: deșeuri de oase; gazeificare; gaz de sinteză; valorificare energetică; eficiență energetică.

1. Introduction

The continuous growth in poultry demand across the European Union is producing large amounts of animal-derived waste, which, if improperly handled, can have negative effects on the environment and the economy. Approximately 30.2% of all meat produced in the EU in 2021 came from poultry, with chicken accounting for over 80% of this production [1]. Classical disposal methods, such as landfilling or incineration, are increasingly restricted under European waste-management policies due to their environmental impact and poor resource recovery efficiency [2], [3], [4]. As a result, in a circular economy framework, thermochemical conversion, such as pyrolysis and gasification, has become an option for turning waste into useful materials and alternatives resources to conventional fuels [5], [6], [7].

Previous studies have shown that pyrolysis of bone waste can generate mineral-rich biochar, high energy gas and valuable bio-oil compounds [8]. However, studies on the direct gasification of bone material remain limited [9], [10]. Gasification is a high-temperature process (typically 700–1200 °C) where carbonaceous materials react with a limited oxidant (air, oxygen, or steam) to produce synthetic gas (syngas), primarily composed of CO, H_2, CH_4, CO_2, and N_2 [11], [12]. Animal bones, particularly those from chicken, consist of approximately 65–70% inorganic matter (mainly calcium phosphate) and 30–35% organic compounds (predominantly collagen protein) [9], [13]. During gasification of bone waste, the organic fraction leads to the formation of a combustible gas, while the inorganic matter yields a solid fraction, rich in minerals (hydroxyapatite). The syngas can be used as fuel in gas turbines or integrated into combined heat and power systems, reducing the fossil fuels (natural gas) demands [14]. However, the syngas obtained from biomass sources often has a lower LHV (between 4–10 MJ/Nm^3), compared with the LHV of ~36 MJ/Nm^3 typical for natural gas [15]. Positively, due to the organic nature of the waste, the CO_2 emitted during gasification is generally considered biogenic, therefore carbon-neutral [16]. Additionally, the ash produced has multiple applications, such as fertilizers, soil amendments, catalyst supports, and biomedical materials [9], [17], [18]. Therefore, the gasification of animal bones could promote renewable energy generation, contribute to the reduction of greenhouse gases (GHG) and to the circular economy concept.

In this study the energy recovery potential of bone-derived biochar through gasification (air and steam as oxidizing medium) is investigated. The experimental results are further extrapolated to a representative population of 400000 inhabitants to quantify the potential renewable energy output, the equivalent natural gas substitution, and the associated economic and environmental benefits. The results contribute to sustainable waste-to-energy strategies, by proposing integration of animal bone waste into local energy systems.

2. Materials and methods

The experimental gasification of bone waste. The feedstock used in this work was obtained from the pyrolysis of chicken bone waste at 700 °C in an inert N_2 atmosphere, yielding a mineral-rich char [8] used for subsequent gasification. Two gasification configurations were then investigated: (i) air and (ii) steam gasification. Both processes were conducted under similar conditions, with variations limited to the gasifying medium (type and flow rate) and process temperature. Both thermochemical processes were performed in an electrically heated tubular batch furnace, Nabertherm model RO 60/750/13 [19], [20]. Both experiments used 3 g of biochar obtained from chicken bone pyrolysis at 700 °C, with a heating rate of 10 °C/min in N_2 atmosphere. The equivalence ratio (E.R.) represents the air-to-fuel ratio relative to stoichiometric combustion, while the steam-to-carbon (S/C) ratio indicates the molar ratio of steam to carbon in the feedstock. The air gasification was conducted at 700 °C, to ensure partial oxidation and char conversion [21]. On the other hand, the steam gasification was carried out at 900 °C, needing a higher temperature to initialize steam-reforming and water–gas shift reactions[22]. The parameters of the gasification process are presented in Table 1.

Table 1. **Summary of operating parameters for air and steam gasification experiments**

Gasification type	Air	Steam
Temperature (°C)	700	900
Biochar (g)	3	3
Retention time (min)	10	10
Gasification agent flow (mL/min)	0.4	0.7
E.R. (air) and S/C ratio (steam)	0.3	3

The generated syngas was collected throughout the gasification process and analyzed using an INFICON MicroGC Fusion gas analyzer. The obtained gas composition was normalized on a nitrogen-free basis, yielding the relative concentrations of H_2, O_2, CO, CH_2, CO_2, and hydrocarbons [8], [23].

The energy content of the produced syngas was determined from its LHV, calculated using the normalized volumetric fractions of each combustible component and the corresponding calorific constants reported in the literature [15]. The total annual syngas energy (MJ/year) is obtained by multiplying the syngas volume by its LHV. This value represents the chemical energy in the product gas available for conversion to electricity. For power generation, we assume the syngas is used in a gas turbine generator with a net electric efficiency of 40 %.

2.1. System boundaries

The experimental results were further extrapolated to an urban area of 400000 inhabitants. Based on Romania's average poultry meat consumption of 27.9 kg/capita/year [24] and estimating that 95 % of this amount corresponds to chicken [25] with an average bone content of approximately 25 wt.%, the annual bone waste generation per capita was estimated. It was further assumed that the entire quantity of this bone waste is collected and processed through pyrolysis. The experimental results yielded approximately 42 wt.% biochar [8]. This biochar fraction is then used as feedstock in the gasification processes (air and steam), enabling the recovery of energy in the form of syngas.

2.2. Energy, Environmental and Economic analysis

To contextualize the energy potential of the produced syngas, the equivalent volume of natural gas required to generate the same amount of electricity was estimated. Assuming identical turbine efficiency of 40 % for both syngas and natural gas, the annual energy input from natural gas must equal the energy from syngas, E_{syngas} (MJ/year). Using a typical LHV of ~36 MJ/Nm^3 for natural gas [15], the energy requirement was converted into an equivalent natural gas volume:

$$V_{\mathrm{NG}} = \frac{E_{\mathrm{syngas}}}{36} \ (\mathrm{Nm}^3/\mathrm{year}) \tag{1}$$

where V_{NG} represents how much natural gas consumption is avoided by utilizing the bone waste syngas instead.

The main environmental indicator investigated in this study is the CO_2 emissions that are avoided by substituting natural gas with syngas produced via the gasification of animal-bone feedstock. The analysis estimates that the combustion 1 Nm^3 of natural gas emits 1.9 kg CO_2 [26]. This value is estimated based on LHV of the natural gas, its volumetric density and a factor of conversion of 0.205 $\mathrm{kg_{CO_2}}$/kWh (SR EN ISO 52000-1:2017).

In this study, the economic assessment integrates both energy and environmental dimensions, internalizing the benefits derived from fuel substitution, reduced waste disposal, and the mitigation of CO_2 emissions. For the fuel cost analysis, a natural gas price of 0.67 €/Nm^3 was adopted, consistent with recent average industrial natural gas prices in Romania [27]. The annual fuel cost saving was calculated as $V_{\mathrm{NG}} \times 0.67$, representing the avoided expense on natural gas that would otherwise be required to produce the same amount of energy. This value reflects the direct substitution of natural gas with the syngas generated from bone waste. Additionally, the gasification of bone waste provides increased economic benefits in waste management by eliminating the need for landfilling or incineration. In this analysis, a landfilling tax of 31.5 €/t of waste was applied [28], representing the avoided disposal costs. To assess the economic benefits associated with the carbon tax savings, two assumptions were considered: (i) a carbon tax rate of 79 €/$\mathrm{t_{CO_2}}$ [29], and (ii) the gasification of animal bone waste is considered carbon-neutral due to the biogenic origin of the feedstock. The calculations were based on the annual amount of bone waste generated within the defined system boundaries.

The total economic benefit of the process is determined by taking into account the fuel cost savings resulting from the substitution of natural gas with syngas, avoided CO_2 emission taxes, avoided landfilling costs, and specific electric consumption of the gasification system. This assessment (eq. 2) captures both the energy and environmental economic advantages of bone waste gasification and provides a more accurate estimate of the actual economic performance of the system.

$$Economic\ Benefit = \left(FCS + LCS + CO_{2,taxes}\right) - GEC\ (€/year) \tag{2}$$

where FCS –fuel cost savings (€/year), LCS –landfilling cost savings (€/year), $CO_{2,\ taxes}$ –avoided CO_2 emission taxes (€/year), and GEC –energy consumption cost of the gasification process (€/year). For the purposes of this study, the energy consumption of the gasification process was calculated as:

$$GEC = E_{spec} \times m_{bone\ waste} \times p_{el}\ (€/year) \tag{3}$$

where E_{spec} –specific energy consumption approximated at 0.5 kWh/kg, $m_{\text{bone waste}}$–annual mass of bone waste (kg/year), and p_{el} –electricity price of 0.14 €/kWh [30].

2.3. *Sensitivity analysis*

A sensitivity analysis was conducted to evaluate how variations in key techno-economic parameters affect the total annual economic benefit of the steam gasification of bone-derived biochar. The analysis considered six independently varied parameters: natural gas price (0.50–0.85 €/Nm³), CO_2 emission tax (70–120 €/t_{CO2}), landfill taxes (25–60 €/t), electricity price (0.12–0.18 €/kWh), and syngas LHV (8–15 MJ/Nm³). These values reflect economic conditions and experimental results, and the variation range was chosen to represent plausible fluctuations in market prices, policy incentives, and technical performance.

3. Results and discussion

3.1. *Gasification of bone waste*

Table 2 shows a clear influence of the gasifying agent on the gas composition. Air gasification yielded a CO-rich syngas (CO = 43.5 vol.%, CO_2 = 39.2 vol.%, H_2 = 14.0 vol.%), indicating predominant partial oxidation reactions and limited hydrogen formation. In contrast, steam gasification produced a hydrogen-rich syngas (H_2 = 45.0 vol.%, CO = 36.7 vol%, CO_2 = 14.3 vol.%), driven by steam–carbon and water–gas shift reactions [10], [20]. The higher H_2 and lower CO_2 contents confirm the enhanced reforming efficiency of steam gasification, making it more suitable for hydrogen-oriented energy applications.

Table 2. **Syngas composition of the gasification of bone waste biochar and the calculated LHV (MJ/Nm^3)**

Gas component (vol. %)	**Air gasification**	**Steam gasification**
H_2	14.01	45.04
O_2	0	2.19
N_2	0	0
CO	43.53	36.66
CH_4	0.32	1.18
CO_2	39.20	14.32
Ethylene	0.151	0.02
Ethane	0.06	0.07
Propene	1.54	0.00003
Propane	1.16	0.49
Butane	0.00182	0
Pentane	0.0003	0.0004
Hexane	0.0008	0.0004
LHV (MJ/Nm^3)	8.9	10.2

The LHV of the syngas increased from 8.9 MJ/Nm^3 for air gasification to 10.2 MJ/Nm^3 for steam gasification. This improvement is due to the higher hydrogen content obtained with steam as the gasifying agent.

3.2. *System boundaries*

The extrapolated results highlight the potential energy recovery from chicken bone waste in a community of 400000 inhabitants. Based on national poultry consumption data and assuming 25 wt.% bone content, approximately 2650 t/year of bone waste could generate about 1113 t/year of biochar through pyrolysis. When used as gasification feedstock, this biochar yields between 436000 Nm^3 (air gasification) and 519000 Nm^3 (steam gasification) of syngas annually. The corresponding thermal energy potentials are 1.089 GWh$_t$/year and 1.472 GWh$_t$/year, respectively.

Assuming a 40 % gas turbine efficiency, the recoverable electrical energy would reach approximately 0.435 GWh$_e$/year for air gasification and 0.588 GWh$_e$/year for steam gasification. This demonstrates that steam gasification provides superior energy recovery, primarily due to its higher hydrogen yield and improved syngas heating value.

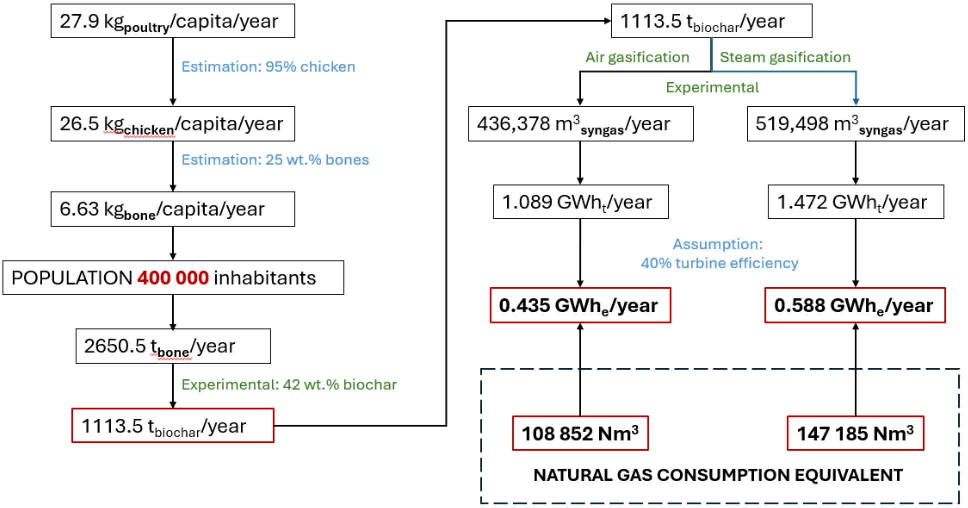

Fig 1. Extrapolation of experimental results to a local population of 400000 inhabitants.

3.3. *Energy, Environmental and Economic analysis*

To generate the same electrical output of 0.435 GWh$_e$ (air gasification) and 0.588 GWh$_e$ (steam gasification) in a gas turbine operating at 40 % efficiency, a natural gas installation of identical efficiency would require approximately 108852 Nm^3 and 147185 Nm^3 of natural gas per year, respectively. The equivalent fuel volumes were derived from the syngas energy content using eq (1). These results demonstrate that the syngas from bone waste can effectively substitute a significant fraction of fossil fuel in local energy systems. Notably, the volumetric energy density of the syngas is significantly lower than that of natural gas. Based on the measured heating values, approximately 4 Nm^3 of air-gasified syngas and 3.5 Nm^3 of steam-gasified syngas are required to deliver the same energy as 1 Nm^3 of natural gas. Therefore, a syngas-fueled turbine must operate with proportionally higher volumetric fuel flow rates to achieve equivalent power generation, which represents an important consideration for system design and overall process scaling.

The natural gas offsets of 108852 Nm^3/year (air gasification) and 147185 Nm^3/year (steam gasification) correspond to direct fuel cost savings of approximately 72930 €/year and 98614 €/year, respectively, based on a market price of 0.67 €/Nm^3. Regarding waste disposal cost savings, the 2650 t of bone waste generated annually would normally result in a landfilling tax of 83490 €/year. By applying a thermochemical process to this waste, the entire disposal tax is avoided, resulting in a direct economic benefit. The carbon tax avoided by using syngas for the air gasification is ~16339 €/year and ~22093 €/year for the steam gasification. These substantial annual savings show that bone waste can be valorized into a renewable and cost-effective energy source.

Table 3. **Energy, environmental, and economic analysis of air and steam gasification of bone-derived biochar**

			Air gasification	**Steam gasification**
Energy analysis		Natural gas economy (Nm^3/year)	436378.32	519498
		Energy consumption cost of the gasification process (kWh/year).	556605	
Environmental analysis		CO_2 emission avoided (t_{CO2}/year)	206.82	279.65
Economic analysis	Energy effect	Fuel cost savings (€/year)	72931	98614
		Energy consumption cost of the gasification process (€/year).	77924	
	Environmental effect	Landfilling cost savings (€/year)	83491	83491
		Avoided CO_2 emission taxes (€/year)	16339	22093
	Economic Benefit (€/year)		**94936**	**126273**

The comparative assessment presented in Table 3 and Figure 2 indicates that steam gasification outperforms air gasification in all evaluated categories. The process achieves a 19% higher natural gas offset and 35% greater CO_2 avoidance, leading to a total annual economic gain of approximately 126000 €. Steam gasification delivers significantly higher savings (~99000 €) than air gasification (~73000 €) due to its greater syngas yield and energy content. Both processes offer identical landfill savings (~83500 €/year), as they process the same amount of bone waste.

The results confirm that valorizing bone-derived biochar through steam gasification simultaneously enhances energy recovery, mitigates greenhouse gas emissions, and reduces waste management costs, proving a practical and sustainable pathway within circular economy principles.

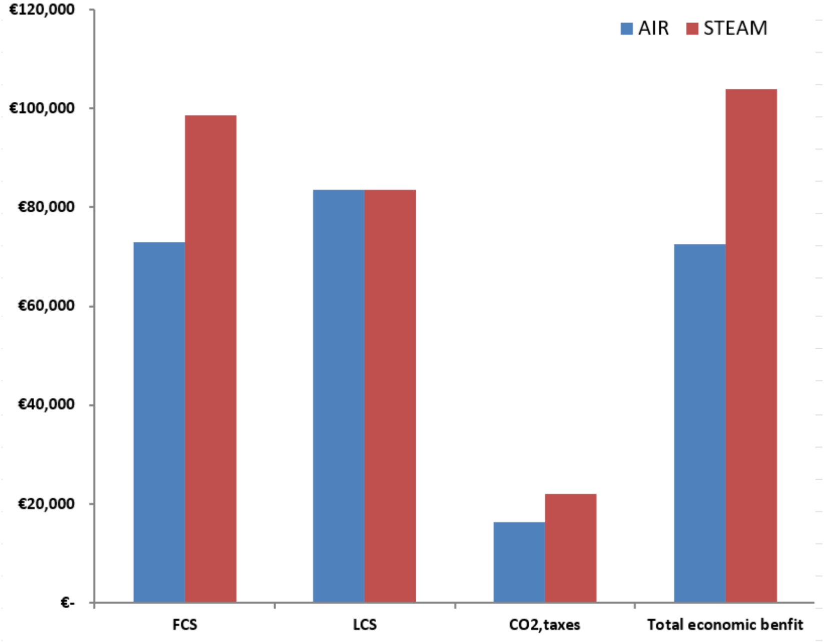

Fig 2. Economic analysis results of the two gasification experiments

3.4. Sensitivity analysis

Figure 3 presents the results, which highlight the influence of each factor on total economic performance. The landfill taxes exert the largest effect on profitability. Varying it between 25–60 €/t changes the total benefit by 109049 €/year to 201817 €/year. This underscores how waste management policies directly shape the economic attractiveness of bone waste gasification.

Similarly, improving syngas quality (higher LHV) increases net benefits by reducing external electricity purchases, which highlights the technical importance of optimizing the gasification process performance. The natural gas price also influences the annual economic benefits by approximately 25002 €/year and 26515 €/year respectively, highlighting the effect of market prices volatility. Moreover, the climatic policies reflected in the carbon tax show how small changes in the $CO_{2,tax}$ results in increasing overall savings by applying the thermochemical solution. Therefore, these results highlight the opportunity of the gasification of bone-derived biochar become competitive with conventional resources of energy production.

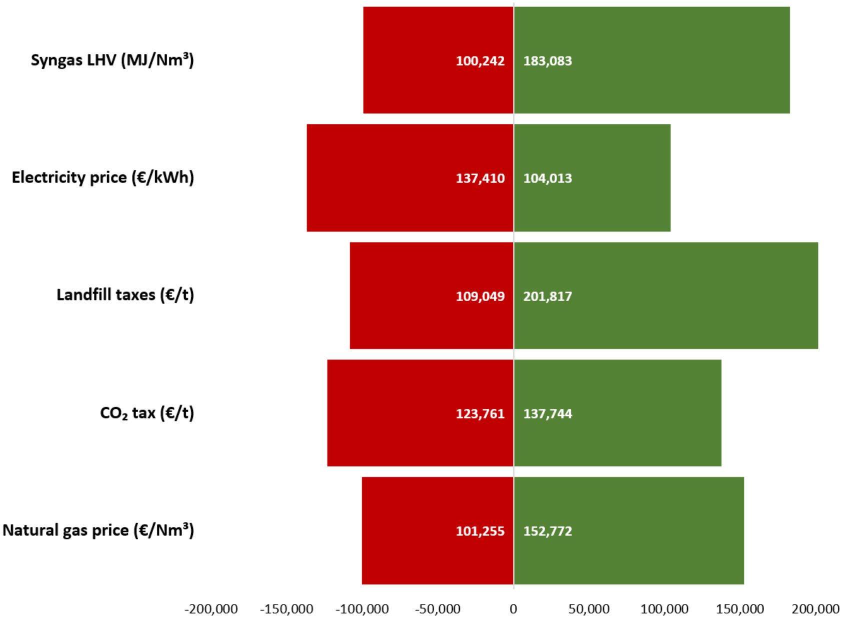

Fig 3. Sensitivity analysis results for the gasification of animal-derived biochar (baseline 126273 €/year)

4. Conclusions

This study demonstrates the technical and economic feasibility of valorizing bone waste through pyrolysis and subsequent gasification of the resulting biochar. The experimental campaign showed that the gasifying agent strongly influences syngas composition and energy quality. Air gasification produced CO predominant syngas (CO = 43.5 vol.%, H_2 = 14.0 vol.%), while steam gasification yielded a hydrogen-rich gas (H_2 = 45.0 vol.%, CO = 36.7 vol.%), with the syngas heating value increasing from 8.9 MJ/Nm^3 to 10.2 MJ/Nm^3.

When extrapolated to a population of 400000 inhabitants, the process could valorize approximately 2650 t/year of bone waste by producing 1113 t/year of biochar and generating 0.435 GWh$_e$/year (air gasification) and 0.588 GWh$_e$/year (steam gasification) of electricity. These outputs correspond to an annual fuel cost savings of 72921 € and 98614 € at current Romanian prices (0.67 €/m^3).

The findings highlight that steam gasification is the more efficient route for hydrogen-rich syngas generation and higher energy recovery, while both processes offer a sustainable pathway for reducing fossil fuel consumption, cutting CO_2 emissions, and eliminating bone waste disposal costs. Overall, bone waste gasification presents a viable renewable energy solution, capable of turning an environmental liability into a valuable local energy resource aligned with circular economy and sustainable development objectives.

The sensitivity analysis demonstrated that the positive economic impact of steam gasification of bone waste is most strongly governed by market factors like fuel and waste disposal prices technical performance parameters (syngas calorific value). External economic conditions, such as high natural gas prices or increased landfill taxes, can favor the implementation of the process, whereas low fossil fuel prices could reduce the economic benefits. Overall, the process proves to be economically robust under a range of plausible variations, with steam gasification yielding a net positive annual benefit in all tested cases, thereby reinforcing its potential as a sustainable waste-to-energy solution.

REFERENCES

[1] "Poultry statistics - Statistics Explained - Eurostat." Accessed: Oct. 27, 2025. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php

[2] "Diversion of waste from landfill in Europe | Indicators | European Environment Agency (EEA)." Accessed: Oct. 27, 2025. [Online]. Available: https://www.eea.europa.eu/en/analysis/indicators/diversion-of-waste-from-landfill

[3] M. Ragazzi, V. Torretta, G. Ionescu, and I. A. Istrate, "Maintenance Strategies And Local Impact Of MSW Incinerators," *WIT Transactions on Ecology and the Environment*, vol. 176, pp. 3–13, Jun. 2013, doi: 10.2495/ESUS130201.

[4] M. Ragazzi, G. Ionescu, and S. I. Cioranu, "Assessment of environmental impact from renewable and non-renewable energy sources," *International Journal of Energy Production and Management*, vol. 2, no. 1, pp. 8–16, Jan. 2017, doi: 10.2495/EQ-V2-N1-8-16.

[5] C. Marculescu and C. Stan, "Pyrolysis treatment of poultry processing industry waste for energy potential recovery as quality derived fuels," *Fuel*, vol. 116, pp. 588–594, Jan. 2014, doi: 10.1016/J.FUEL.2013.08.039.

[6] C. Marculescu and F. Alexe, "Assessing the Power Generation Solution by Thermal-chemical Conversion of Meat Processing Industry Waste," *Energy Procedia*, vol. 50, pp. 738–743, Jan. 2014, doi: 10.1016/J.EGYPRO.2014.06.091.

[7] G. Ionescu, C. Bulmau, and C. Marculescu, "Bio-Gaseous Fuels from Agricultural Waste Pyrolysis (Part I)," *MATEC Web of Conferences*, vol. 290, p. 11004, Aug. 2019, doi: 10.1051/MATECCONF/201929011004.

[8] G. Ionescu *et al.*, "New integrated processing of chicken bone waste using an enzymatic pretreatment and slow pyrolysis to produce green chemicals," *Energy Convers Manag*, vol. 323, p. 119281, Jan. 2025, doi: 10.1016/J.ENCONMAN.2024.119281.

[9] M. G. Macavei *et al.*, “Thermochemical Conversion of Animal-Derived Waste: A Mini-Review with a Focus on Chicken Bone Waste,” *Processes 2024, Vol. 12, Page 358*, vol. 12, no. 2, p. 358, Feb. 2024, doi: 10.3390/PR12020358.

[10] A. Mlonka-Mędrala *et al.*, “Energy and material recovery from bone waste: Steam gasification for biochar and syngas production in a circular economy framework,” *Energy*, vol. 325, p. 136179, Jun. 2025, doi: 10.1016/J.ENERGY.2025.136179.

[11] C. Marculescu, “Comparative Analysis on Waste to Energy Conversion Chains Using Thermal-chemical Processes,” *Energy Procedia*, vol. 18, pp. 604–611, Jan. 2012, doi: 10.1016/J.EGYPRO.2012.05.073.

[12] G. Ionescu, C. Mărculescu, and A. Badea, “ALTERNATIVE SOLUTIONS FOR MSW TO ENERGY CONVERSION,” *U.P.B. Sci. Bull., Series C*, vol. 73, no. 3, 2011.

[13] N. C. Rath, G. R. Huff, W. E. Huff, and J. M. Balog, “Factors Regulating Bone Maturity and Strength in Poultry 1”.

[14] F. Califano, C. Mongiello, and C. Freda, “Combined Heat and Power Production from Meat and Bone Meal via Gasification and Gas Turbine: Technical and Economic Analysis,” *Waste Biomass Valorization*, vol. 8, no. 3, pp. 975–986, Apr. 2017, doi: 10.1007/S12649-016-9628-8.

[15] “Higher Calorific Values of Common Fuels: Reference & Data.” Accessed: Oct. 08, 2025. [Online]. Available: https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

[16] “Framework for Assessing Biogenic CO 2 Emissions from Stationary Sources,” 2014.

[17] E. Cascarosa, A. Boldrin, and T. Astrup, “Pyrolysis and gasification of meat-and-bone-meal: Energy balance and GHG accounting,” *Waste Management*, vol. 33, no. 11, pp. 2501–2508, Nov. 2013, doi: 10.1016/J.WASMAN.2013.07.014.

[18] G. Petcu *et al.*, “Synthesis of hydroxyapatite – containing catalysts from bone waste – conventional route versus microwaves,” *Catal Today*, vol. 462, p. 115538, Feb. 2026, doi: 10.1016/J.CATTOD.2025.115538.

[19] C. Marculescu and C. Stan, “Poultry processing industry waste to energy conversion,” *Energy Procedia*, vol. 6, pp. 550–557, Jan. 2011, doi: 10.1016/J.EGYPRO.2011.05.063.

[20] C. Mărculescu, R. N. Tîrţea, L. Khachatryan, and D. Boldor, “Investigation of gasification kinetics of multi-component waste mixtures in a novel thermo-gravimetric flow reactor via gas analysis,” *Bioresour Technol*, vol. 343, p. 126044, Jan. 2022, doi: 10.1016/J.BIORTECH.2021.126044.

[21] D. Glushkov, G. Nyashina, A. Shvets, A. Pereira, and A. Ramanathan, “Current Status of the Pyrolysis and Gasification Mechanism of Biomass,” *Energies 2021, Vol. 14, Page 7541*, vol. 14, no. 22, p. 7541, Nov. 2021, doi: 10.3390/EN14227541.

[22] D. Cvetinović *et al.*, “Thermodynamic equilibrium modeling of biomass gasification: Effects of operating conditions on gasifier performance,” *J King Saud Univ Sci*, vol. 36, no. 9, p. 103370, Oct. 2024, doi: 10.1016/J.JKSUS.2024.103370.

[23] M. Gabriel Macavei *et al.*, “Bio-based material as microwave susceptor and catalyst support for plastic waste microwave-assisted pyrolysis,” *Clean Technologies and Environmental Policy 2025*, pp. 1–15, Aug. 2025, doi: 10.1007/S10098-025-03275-W.

[24] A. Popescu, M. Stanciu, O. Drăghici, H. N. Ciocan, V. Serban, and L. Blaga, "MEAT PRODUCTION, TRADE, CONSUMPTION AND SELF-SUFFICIENCY RATE IN ROMANIA IN THE PERIOD 2014-2022," *Scientific Papers Series Management, Economic Engineering in Agriculture and Rural Development*, vol. 24, p. 2024.

[25] R. Aniela, I. (Gheorghe, D. Tapaloaga, C. Sonea, L. I. Ilie, and P.-R. Tapaloaga, "CHICKEN MEAT PRODUCTION TRENDS IN ROMANIA-A TWELVE-YEAR FORECAST", doi: 10.2478/AGR-2023-0002.

[26] "Conversion Guidelines-Greenhouse gas emissions".

[27] "Oferta ENGIE România: prețuri, oferte și detalii de contact | economisi.ro." Accessed: Oct. 27, 2025. [Online]. Available: https://economisi.ro/energie/furnizori/engie

[28] "ADMINISTRATIA FONDULUI PENTRU MEDIU - CALENDAR FISCAL." Accessed: Oct. 28, 2025. [Online]. Available: https://www.afm.ro/taxe_calendar_fiscal.php

[29] "Live Carbon Prices Today, Carbon Price Charts • Carbon Credits." Accessed: Oct. 28, 2025. [Online]. Available: https://carboncredits.com/carbon-prices-today/

[30] "PZU: Raport PIP si Volum Tranzactionat." Accessed: Oct. 28, 2025. [Online]. Available: https://www.opcom.ro/grafice-ip-raportPIP-si-volumTranzactionat/ro

Acknowledgements

This study was funded by Romania's National Recovery and Resilience Plan, Pillar III "Smart, sustainable and inclusive growth, including economic cohesion, jobs, productivity, competitiveness, research, development, and innovation, and a well-functioning internal market with strong small and medium-sized enterprises (SMEs)," Component C9. Support for the private sector, research, development, and innovation, I8 "Development of a program to attract highly specialized human resources from abroad in research, development and innovation activities''. The project is: "Green Chemistry and Thermochemical Processing, a Convergent Approach towards biobased Chemicals and Hydrogen Synthesis—ConverGreen", ID: CF 86/15.11.2022, cod 86. No. 760094.