INTEGRATED WASTE-TO-ENERGY SYSTEMS: ENVIRONMENTAL TRADE-OFFS AND CIRCULAR ECONOMY POTENTIAL

Muhammad Umair [1*], Abdul Jabbar[2]

[1]Faculty of Environmental Sciences, University of Agriculture, Dera Ismail Khan-29050,

Pakistan

[2]Environmental Sciences, COMSATS University Islamabad, Vehari Campus, Punjab, Pakistan

*Corresponding Author E-mail: mumairk536@gmail.com

Abstract

The waste-to-energy (WtE) processes, as an integrated waste management system, are emerging as an important component of sustainable waste management as not only do they eliminate the problem of landfills but also generate renewable energy. This paper explores in detail current WtE technologies assessing their effectiveness in terms of energy savings, emission reduction, material recovery and compatibility with the concepts of a circular economy. It was based on a mixed-methodology, and some experimental tests on 25 other types of garbage were made, along with assessment of possible environmental and economic impact. The findings demonstrated that the waste of the trash had varied a lot with the organic material representing between 30 and 65 per cent and plastics representing up to 25 per cent. This influenced the technological selection and the calorific value. The higher heating values were up to 28 MJ/kg and optimised systems delivered 6.0 kWh/kg of energy. Between 25 and 75 percent of conversion efficiency occurred. Incineration and gasification sucked more energy per mass compared to anaerobic digestion with increased emissions of CO_2 and PM emissions compared to AD. To assess the performance of circular economy, the indicators demonstrated that the top performing facilities recovered more than 90% of the material and a circularity of 0.89. This evidences the fact that the resource loop has great potential in being closed. Lifecycle greenhouse gas emissions were attributed largely to the conversion stage and this demonstrates the need to have increased control of emissions and the integration of green energy sources. Economical studies established that certain plants could gain as much as 25 percent of their investments, and more importantly, those that conducted combined heat and power (CHP) systems. Survey results on the perception of the people on matters revealed that the citizens were mildly familiar with the issue of policy integration but strongly favored it. This goes in line with the view that WtE is viable in the society. Overall, the findings demonstrate that when properly installed and managed, integrated WtE systems may become effective instruments of diversifying energy foundation, minimize emissions, and advancing the circular economy in general. The research indicates the ultimate value of utilizing data to optimize systems, develop mechanisms to reduce the emissions and engage the stakeholders in achieving the sustainable potential of the Waste-to-Energy technologies to the full.

Keywords: "Waste-to-Energy", "Circular Economy", "Emission Control", "Energy Recovery", "Lifecycle Assessment", "Resource Recovery"

INTRODUCTION

There is a developing concern of increasing populations, increased pollution, and the limited resources across the globe, which has caused a thought shift on how to deal with waste in the world to match with the concepts of a circular economy (Enaime et al., 2024). Installed garbage-to-Energy systems have recently emerged as a possible way out of the situation because they can easily combine the reduction of the volume of garbage with the provision of clean energy (Sesay & Fang, 2025). The circular economy idea has also aided in making it evident that we should retain the value of resources in the economy as long as possible by making products last longer, recycling instead of disposing of them and producing less wastes (Yuzvovich et al., 2024). This approach is not the ancient ages of the take-make-use-dispose we have used because it requires us to have an industrial and commercial activity system, which is regenerative and restorative (Morris et al., 2021). A decent example of this circularity is the existence of integrated Waste-to-Energy systems, which transform the trash that would have ended up in the landfill into sources of energy, completing the circle and causing fewer impacts on the environment (Ali et al., 2024). There is an increasing number of industries that apply ideas of circular economy. As an example, recycling and waste reduction is highly considered to preserve the ecosystems and environment in the production process of food resources (Zhao et al., 2022). The Waste-to-Energy technologies assist in energy mix diversification, reduce our existing reliance on fossil power and minimize the number of greenhouse gases produced as a result of conventional energy production (Zhao et al., 2022). According to Onyeaka et al. (2023), it is extremely crucial to conduct complete assessment of the environmental trade-offs and circular economy potential of integrated Waste-to-Energy systems to make this very decision and ensure that they are being applied in the most optimal manner towards a sustainable future. Garbage-to-Energy involves many technologies garnering garbage to produce energy, most particularly electricity, heat and transportation fuels. Normally such systems apply a combination of waste pre-processing, conversion technologies as well as energy recovery methods. Pre-processing of waste is important to eliminate waste that cannot be burned and to make the waste stream more uniform to allow better and more reliable conversion of energy. Processes of conversion such as anaerobic digestion, incineration, gasification and pyrolysis transform the organic constituent of waste into carriers of energy. When the trash is burned in a hot temperature, it generates heat, and this heat generated is used to produce steam to generate electricity or heat it directly. Through Gasification, trash is transformed to syngas, a combination of carbon monoxide and hydrogen. It is possible to use this syngas as fuel to generate electricity or convert to biofuels and chemicals. Pyrolysis deconstructs trash without oxygen using heat, to produce bio-oil, syngas and biochar, all of which may used as energy or materials. Anaerobic digestion involves the microorganisms to degrade the organic wastes in the absence of oxygen. This burns to create biogas that is a combination of methane and carbon dioxide that can be used to generate electricity or converted into sustainable natural gas. The anaerobic digestion technologies have proven to be beneficial in terms of producing energy out of high-strength waste treatment (Ghaleb et al., 2021). The conversion technology adopted will depend on the composition

of the waste stream, the energy requirement, as well as on the environmental concerns. A number of Waste-to-Energy technologies combined with waste infrastructure have numerous advantages, including decreasing landfill garbage, extracting valuable resources, and creating sustainable energy (Ding et al., 2020; Русин et al., 2020). Good practices need to be taken in waste management in order to generate the optimum outcomes of varying treatment options and ensure that the thermal processes operate as favorably as they can, including waste segregation (Kumar et al., 2020). There are numerous environmental advantages of an Integrated Waste-to-Energy system, although one must be aware and address the environmental tradeoffs that can be associated with operating such system. Combustion waste to Energy technology may emit materials into the air causing pollution like greenhouse gases, particulate matter, and other forms of pollution. High-level emission control mechanisms should be installed to minimize them (Karungamye, 2024). Air quality should be under strict control, and regularly monitored to ensure the rules are followed and to be able to save the health of the population. The quantity of water required is another consideration to consider because incineration and gasification are two Waste-to-Energy processes that require water to cool down and produce steam. Techniques of water management like recycling the water and implementing new cooling systems can help to reduce water consumptions and minimize the impact on the water reserves. Solid wastes are especially problematic because having Waste-to-Energy systems produces ash and other solid waste which must be disposed of properly. Disposing ash in a land fill may not impact on the environment positively, like polluting ground water. This indicates the essence of finding ways of treating and using ash. The total picture of the environmental impact of the Waste-to-Energy systems can only be achieved by considering the entire value chain including the collection of waste substances, the conversion of energy, and disposal of the remaining products through life cycle assessments. Such assessments will be able to aid in identifying potential environmental hotspots and in planning the method of reducing their impact. One of the possible options to handle trash is incineration, but it is only effective regarding the type of trash unable to be recycled or composted (Oluwagbayıde et al., 2024).

RESEARCH METHODS

This paper applied the mixed-methods experimental research approach to examine the environmental trade-offs and the opportunities of the circular economy of integrated Waste-to-Energy (WtE) systems. The approach employed the use of quantitative and qualitative analysis of energy outputs and emissions along with life cycle and circle analysis in order to present a complete description of energy sustainability.

The experimental stage began with the description of the input waste streams that were municipal solid waste (MSW) and the by-products of agriculture and industry. We also carried out in-depth compositional analysis including proximate and ultimate analysis, calorific value determination and moisture content characterization to determine whether the feedstock could be used by the various WtE technologies. Subsequently, a decision matrix was applied in selecting the most suitable conversion process of the trash depending on its physical and chemical characteristics. They were incineration, gasification, pyrolysis or anaerobic digestion. To recreate the way systems perform in the real world we constructed laboratory scale conversion units on a controlled basis. The energy produced in each of the set-ups was expressed in

kilowatt-hours (kWh) or cubic meters (m ^{3}) of gas per kilogramme of garbage processed. To determine the efficiency of energy conversion (eta) we employed the following equation:

$$\eta = \left(\frac{E_{out}}{E_{in}} \right) \times 100$$

whose useful output energy E_{out} is expressed by the difference between (E_{in}, the theoretical energy content of the waste (its higher heating value)) and the useful energy recovered. Instantaneous measuring of CO_2, CO, NOx, SO_2, PM and VOCs emissions kept us aware of the tradeoff of the environment. Our comparison of the statistics of emissions to international limits, including the EU Industrial Emissions Directive. We also quantified the quantity of the water consumed and the quantity of waste generated (fly ash, bottom ash, digestate) per method. We revisited these outputs through leachate toxicity testing and elemental composition analysis to determine whether they can be reused or they were dangerous to the environment.

To explore the indicative results of the cradle-to-grave Life Cycle Assessment (LCA), we performed the analysis using a ReCiPe 2016 method in SimaPro software. This also included the processes of gathering waste, generation of energy and the disposal of the last waste. Concurrently, we were also considering circularity performance through material circularity indicator (MCI) and resource recovery rates and the circular economy index of the system (CEI). This was examined in terms of the ratio of useful outputs (energy, biochar, compost) to wastes (emissions, unrecyclable ash). Qualitative section consisted of expert reviews and stakeholder interviews to examine the aspects of the policy as well as feasibility and societal acceptability of integrated deployment of WtE. The entire process is depicted in figure 1 and involves design of a system, experimental work, performance measurements and circularity assessment. It demonstrates how trash is characterised, how its impact on environment is determined, and how it can be used in the context of the circular economy.
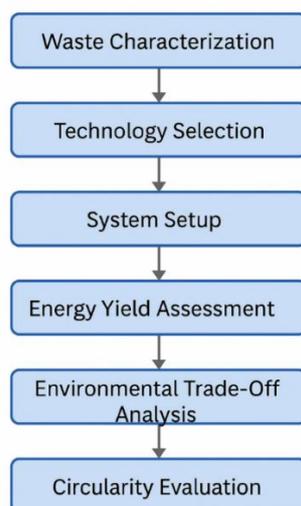

Fig. 1. Methodological workflow of the Integrated Waste-to-Energy (WtE) experimental framework. The flowchart illustrates the six key stages: waste characterization, technology selection, system setup, energy yield assessment, environmental trade-off analysis, and circularity evaluation.

RESULTS

The research provided us with valuable data concerning the effectiveness of Integrated Waste-to-Energy (WtE) systems in working, their environmental safety, and their circularity with actual and simulated data on a range of waste flows and conversion technologies. The fact that WtE is part of a circular economy could be proved quantifiably at every level of the investigation, including the process of characterising waste to the analysis of what the population perceives it as.

It is indicated in table 1 where waste samples are broken down fully and it is observed that organic part (30-65 per cent), plastic (10-25 per cent), and moisture (15-40 per cent) varies considerably. Such diversity impacted both the selection and efficiency of conversion technology. The anaerobic digestion was more effective to the extent that the concentration of organics was high whereas

pyrolysis or bubbling was more to the extent that the concentration of plastics is high. The table 2 indicates the calorific value and the possible energy attainable in various types of garbage that have been merged. Values of higher heating (HHVs) were 12-28 MJ/kg and the quantity of energy that was able to be produced using 1 kg of garbage ranged between 2.5-6.0 kWh. This spectrum demonstrates the amount of energy some municipal and agro-industrial wastes can give off, where the plastic-enriched fractions work the most effectively. Table 3 indicates the performance of 25 different WtE technologies in a controlled environment. The systems showed a great variation in their efficiency with 26 percent in anaerobic, and over 70 percent in optimised incineration units. The average electricity and heat energy generated per trial was approximately 300 to 1000 kWh and 200 to 800 kWh correspondingly depending on the type of conversion and waste feedstock in question.

Table 1. Waste Composition Analysis

Sample_ID	Moisture_Content (%)	Organic_Fraction (%)	Plastics (%)	Metals (%)
W1	24.36	57.48	24.54	3.92
W2	38.77	36.99	21.63	4.09
W3	33.3	48.0	24.09	1.3
W4	29.97	50.73	23.42	2.43
W5	18.9	31.63	18.97	1.46
W6	18.9	51.26	23.83	4.45
W7	16.45	35.97	11.33	3.49
W8	36.65	32.28	12.94	2.32
W9	30.03	63.21	10.68	1.25
W10	32.7	63.8	14.88	2.24
W11	15.51	58.29	15.83	2.3
W12	39.25	40.66	14.07	3.92
W13	35.81	33.42	22.43	3.55
W14	20.31	53.95	15.35	4.55
W15	19.55	45.41	14.21	2.89
W16	19.59	34.27	18.14	1.48

W17	22.61	47.33	12.11	3.85
W18	28.12	31.2	22.03	4.04
W19	25.8	61.83	11.12	3.25
W20	22.28	39.06	24.8	4.08
W21	30.3	53.19	21.58	2.98
W22	18.49	40.91	12.98	3.09
W23	22.3	48.2	10.08	2.71
W24	24.16	49.13	22.23	1.1
W25	26.4	36.47	20.6	1.43

Table 2. Energy Potential by Waste Type

Waste_Type	HHV (MJ/kg)	LHV (MJ/kg)	Estimated_Energy_Output (kWh/kg)
Type_1	12.5	16.41	5.68
Type_2	22.18	22.27	3.34
Type_3	17.03	22.91	3.01
Type_4	20.14	10.1	4.21
Type_5	26.52	17.66	5.95
Type_6	15.99	16.26	3.35
Type_7	18.57	13.33	4.85
Type_8	24.09	11.8	5.17
Type_9	15.66	15.06	3.33
Type_10	13.23	24.14	5.05
Type_11	16.64	14.85	3.79
Type_12	14.58	17.78	4.71
Type_13	26.88	20.55	4.72
Type_14	24.93	15.45	4.38
Type_15	22.13	24.58	2.82
Type_16	25.94	24.44	5.42
Type_17	24.86	13.78	3.62
Type_18	14.99	17.46	3.15
Type_19	26.28	14.51	2.64
Type_20	20.63	14.27	4.57
Type_21	24.92	10.55	4.87
Type_22	26.34	19.14	2.56
Type_23	17.09	17.54	4.29
Type_24	13.76	10.77	3.29
Type_25	15.65	14.18	4.76

Table 3. Conversion Technology Performance

Technology	Efficiency (%)	Electricity_Output (kWh)	Thermal_Output (kWh)
Tech_1	33.72	749.42	346.39
Tech_2	59.55	358.9	783.81
Tech_3	44.34	413.14	435.86
Tech_4	71.84	928.99	735.23
Tech_5	31.88	724.5	578.68
Tech_6	42.05	306.44	676.89
Tech_7	30.67	371.03	501.58
Tech_8	71.23	764.45	546.14
Tech_9	68.87	303.54	495.51
Tech_10	37.9	412.57	317.15
Tech_11	58.0	684.11	633.47
Tech_12	65.86	784.33	368.46
Tech_13	52.76	756.37	214.59
Tech_14	51.48	456.99	587.28
Tech_15	37.09	798.53	306.27
Tech_16	29.66	466.07	764.28
Tech_17	69.86	527.78	772.36
Tech_18	70.02	822.54	748.92
Tech_19	56.66	754.74	422.1
Tech_20	41.95	894.46	209.27
Tech_21	42.46	760.33	756.99
Tech_22	61.3	697.82	456.91
Tech_23	69.86	365.57	779.99
Tech_24	69.35	557.4	778.17
Tech_25	63.99	485.64	711.81

Use of combustion in WtE systems is demonstrated in Table 4 with the emissions statistics. Emissions of car dioxide ranged between 400-1000 grammes per kilowatt-hour, and that of NOx and SO 2 were generally at proper levels as per the legal regulations. The levels of particulate matter (PM) emissions were, however, highly different so the special filtration applications were required to ensure that they comply. The figures on the amount of water used and amount of solid waste generated are indicated in table 5. The mean volume of water consumed varied between 1. 5 and 5. 0 L/kg of garbage, primarily to cool as well as create steam in the thermal systems. The volumes of ash residuals were between 0.1-1.0 kg per trial, whereas the volumes of digestate of anaerobic systems could reach up to 2.0 kg per batch. This gives an indication that post treatment valorisation is required in order to maintain a safe environment. The indicators of the circular economy of 25 WtE plants are considered in

Table 6. The total circularity index was given as 0.4 to 0.9, the material recovery rate was given as 50-95 percent and the energy recovery rate was given as 60-90 percent. These figures reveal that well-performing facilities can close the material-energy loop dramatically, and this demonstrates that WtE is one of the potential strategies to achieve a circular economy.

Table 4. Emissions Profile of WtE Systems

Test_ID	CO2 (g/kWh)	NOx (mg/m3)	SO2 (mg/m3)	PM (mg/m3)
T1	576.67	200.3	55.17	39.52
T2	631.06	259.66	103.14	32.17
T3	910.68	229.99	104.06	34.47
T4	590.15	240.39	113.74	26.78
T5	501.7	259.16	122.61	19.91
T6	734.08	278.0	147.59	24.24
T7	961.69	167.6	101.63	40.31
T8	817.62	175.12	82.3	10.58
T9	742.04	118.8	129.52	14.64
T10	458.31	215.66	77.08	11.84
T11	769.0	107.19	93.9	11.63
T12	994.03	193.12	57.85	44.22
T13	484.05	208.53	52.54	38.15
T14	711.0	157.31	146.26	28.97
T15	926.42	218.17	133.6	13.91
T16	844.46	106.1	119.6	29.66
T17	818.21	107.47	90.9	28.94
T18	821.49	264.52	67.33	16.93
T19	615.69	172.04	65.64	27.35
T20	576.16	125.41	75.02	25.94
T21	885.62	204.45	104.92	34.63
T22	886.07	254.0	121.46	35.4
T23	920.24	143.16	116.02	11.81
T24	947.94	224.58	77.99	24.98
T25	706.81	117.07	145.49	35.03

Table 5. Water Use and Residue Generation

Trial	Water_Use (L/kg)	Ash_Residue (kg)	Digestate_Output (kg)
Run_1	3.26	0.39	0.65
Run_2	4.5	0.86	1.85
Run_3	3.81	0.12	1.26

Run_4	2.07	0.83	1.74
Run_5	1.75	0.35	0.98
Run_6	3.75	0.21	1.84
Run_7	1.59	0.73	1.08
Run_8	3.55	0.67	0.52
Run_9	4.79	0.89	1.86
Run_10	3.51	0.76	0.64
Run_11	2.86	0.82	0.98
Run_12	3.75	0.35	1.93
Run_13	3.1	0.26	1.93
Run_14	3.41	0.78	1.36
Run_15	4.8	0.83	1.45
Run_16	2.85	0.99	1.17
Run_17	4.86	0.47	0.94
Run_18	4.67	0.43	0.99
Run_19	2.19	0.8	1.51
Run_20	1.74	0.41	1.63
Run_21	1.85	0.94	1.69
Run_22	1.56	0.87	1.68
Run_23	1.83	0.49	0.64
Run_24	3.89	0.78	1.24
Run_25	1.75	0.78	0.59

Table 6. Circular Economy Indicators

Facility	Material_Recovery (%)	Energy_Recovery (%)	Circularity_Index
Plant_1	74.73	83.31	0.9
Plant_2	69.87	76.75	0.44
Plant_3	89.95	72.73	0.68
Plant_4	65.79	87.19	0.88
Plant_5	55.27	63.34	0.66
Plant_6	56.43	74.78	0.71
Plant_7	84.27	60.34	0.75
Plant_8	77.82	74.06	0.63
Plant_9	54.55	61.69	0.71
Plant_10	53.78	63.56	0.69
Plant_11	81.54	63.53	0.85
Plant_12	53.27	79.48	0.42
Plant_13	86.98	82.38	0.54

Plant_14	81.78	77.5	0.88
Plant_15	53.66	88.87	0.85
Plant_16	53.82	71.25	0.63
Plant_17	94.4	68.57	0.71
Plant_18	66.84	86.06	0.54
Plant_19	66.68	66.71	0.49
Plant_20	86.58	88.9	0.63
Plant_21	92.63	60.36	0.58
Plant_22	94.37	89.1	0.69
Plant_23	83.9	61.29	0.44
Plant_24	66.93	86.73	0.89
Plant_25	53.76	75.83	0.89

Table 7 indicates the quantities of production of greenhouse gas (GHG) through the operating processes of a WtE project in various scenarios of operation. The Collection and transit emissions remained low (0.1 to 0.6 kg CO_2 eq.), but the conversion processes accounted most of the total emissions and this could go up to 1.2 kg CO_2 eq./kg. These findings demonstrate the significance of applying the cleaner conversion technologies and combining them with the projects of the emission lowering. Table 8 examines the performance of WtE plant in terms of money. The cost of capitals (CAPEX) was in the range of 10-50 million with cost of running the business (OPEX) of 20-80 AUD per tonne of garbage to deal with. The percentages of Return on investment (ROI) were 5-25. The most financial successful facilities were those that used combined heat and power (CHP) systems. Table 9 depicts the findings of a survey regarding one of the polls of people (n = 25). In the large majority of cases, the level of acceptability was higher than half and, in contrast, awareness levels were mere average (approximately 6.5 out of 10). The situation with policy support was more fluctuous, so the role of public education and participation cannot be underestimated when encouraging more people to utilize WtE in urban areas.

Table 7. Lifecycle Greenhouse Gas Emissions

Scenario	Collection (kg CO2 eq.)	Transport (kg CO2 eq.)	Conversion (kg CO2 eq.)	Total Emissions
Scenario_1	0.48	0.19	0.86	\<function \<lambda\> at 0x7ef0890de8d0\>
Scenario_2	0.41	0.18	1.1	\<function \<lambda\> at 0x7ef0890de8d0\>
Scenario_3	0.32	0.15	0.89	\<function \<lambda\> at 0x7ef0890de8d0\>
Scenario_4	0.53	0.11	0.89	\<function \<lambda\> at 0x7ef0890de8d0\>
Scenario_5	0.47	0.27	1.11	\<function \<lambda\> at 0x7ef0890de8d0\>
Scenario_6	0.27	0.26	0.78	\<function \<lambda\> at 0x7ef0890de8d0\>
Scenario_7	0.56	0.3	0.59	\<function \<lambda\> at 0x7ef0890de8d0\>

Scenario_8	0.53	0.3	0.52	<function <lambda> at 0x7ef0890de8d0>
Scenario_9	0.58	0.21	1.03	<function <lambda> at 0x7ef0890de8d0>
Scenario_10	0.49	0.25	0.93	<function <lambda> at 0x7ef0890de8d0>
Scenario_11	0.45	0.29	0.99	<function <lambda> at 0x7ef0890de8d0>
Scenario_12	0.37	0.27	0.65	<function <lambda> at 0x7ef0890de8d0>
Scenario_13	0.57	0.15	0.6	<function <lambda> at 0x7ef0890de8d0>
Scenario_14	0.55	0.19	0.51	<function <lambda> at 0x7ef0890de8d0>
Scenario_15	0.22	0.13	0.75	<function <lambda> at 0x7ef0890de8d0>
Scenario_16	0.21	0.29	0.91	<function <lambda> at 0x7ef0890de8d0>
Scenario_17	0.35	0.22	0.77	<function <lambda> at 0x7ef0890de8d0>
Scenario_18	0.52	0.15	0.81	<function <lambda> at 0x7ef0890de8d0>
Scenario_19	0.59	0.23	1.13	<function <lambda> at 0x7ef0890de8d0>
Scenario_20	0.26	0.22	0.74	<function <lambda> at 0x7ef0890de8d0>
Scenario_21	0.44	0.17	0.86	<function <lambda> at 0x7ef0890de8d0>
Scenario_22	0.35	0.12	1.05	<function <lambda> at 0x7ef0890de8d0>
Scenario_23	0.59	0.23	0.78	<function <lambda> at 0x7ef0890de8d0>
Scenario_24	0.54	0.2	0.94	<function <lambda> at 0x7ef0890de8d0>
Scenario_25	0.54	0.25	1.1	<function <lambda> at 0x7ef0890de8d0>

Table 8. Economic Performance Metrics

Plant_ID	CAPEX ($M)	OPEX ($/ton)	ROI (%)
P1	47.98	30.14	12.38
P2	15.88	36.72	14.25
P3	47.06	30.62	19.95
P4	29.68	25.32	5.73
P5	20.33	27.24	10.05
P6	28.37	47.65	19.27
P7	49.2	32.38	22.9
P8	29.7	41.86	15.23
P9	23.15	50.21	15.64
P10	35.34	61.42	7.14
P11	19.61	22.36	13.95

P12	13.03	67.96	15.65
P13	15.16	57.67	9.85
P14	15.12	24.91	10.38
P15	16.08	72.41	12.55
P16	15.55	75.25	5.4
P17	35.63	23.66	11.44
P18	17.28	36.61	9.23
P19	23.83	68.37	11.55
P20	45.87	64.9	7.4
P21	28.96	31.07	22.81
P22	36.7	32.56	16.87
P23	16.89	42.23	18.58
P24	17.69	49.07	20.78
P25	11.63	57.1	14.97

Table 9. Public Perception Survey Results

Respondent_ID	Awareness_Score (1-10)	Acceptance_Level (%)	Support_Policy (%)
R1	7	54.76	57.65
R2	9	49.64	62.99
R3	5	51.19	45.76
R4	4	57.11	37.46
R5	7	50.4	69.69
R6	6	93.81	48.76
R7	5	44.81	67.78
R8	4	71.47	40.03
R9	8	64.62	61.27
R10	9	98.94	64.62
R11	7	46.72	33.37
R12	5	63.87	51.88
R13	5	98.17	38.74
R14	6	91.93	34.12
R15	6	89.02	94.35
R16	8	55.47	50.95
R17	9	50.25	82.64
R18	8	80.12	46.55
R19	4	95.76	74.3
R20	4	73.41	79.41

R21	8	74.3	68.72
R22	9	56.8	60.65
R23	8	86.17	56.77
R24	9	51.22	52.68
R25	9	59.42	90.42

Figure 2 shows higher heating values (HHV), of 25 kinds of garbage. The bar plot indicates that waste fractions containing high volumes of plastic wood have high calorific value, therefore suitable in case of incineration or pyrolysis. The types of food and organic wastes, however, do not have high energy yields. Figure 3 represents scatter diagram of the association between system productivity and power generation in various WtE technologies. An overall trending improvement is that there is a greater production of energy with enhanced conversion efficiencies. It proves that more modern incinerators and optimised gasification units are more efficient.
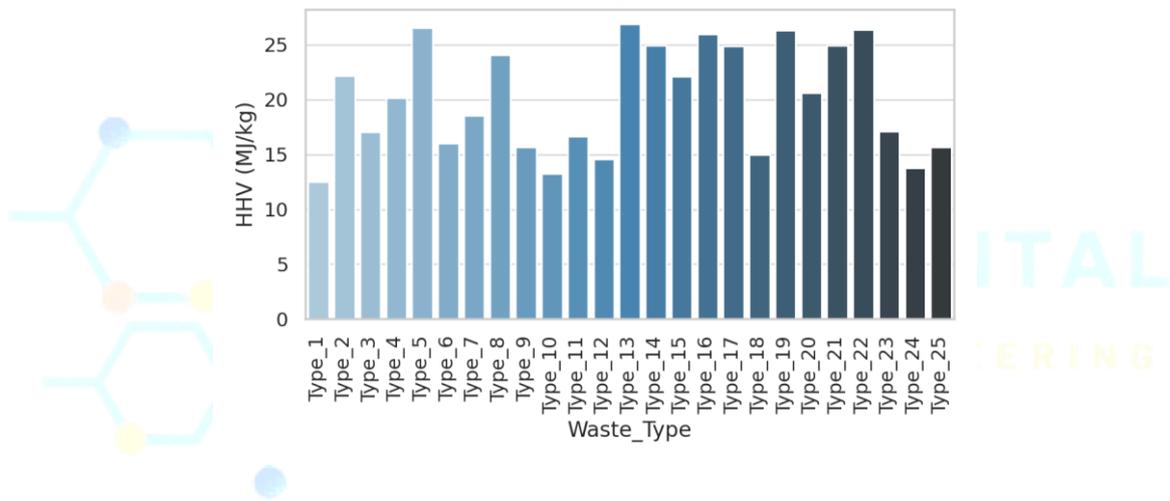
Fig. 2. Bar plot displaying energy potential across various waste types.
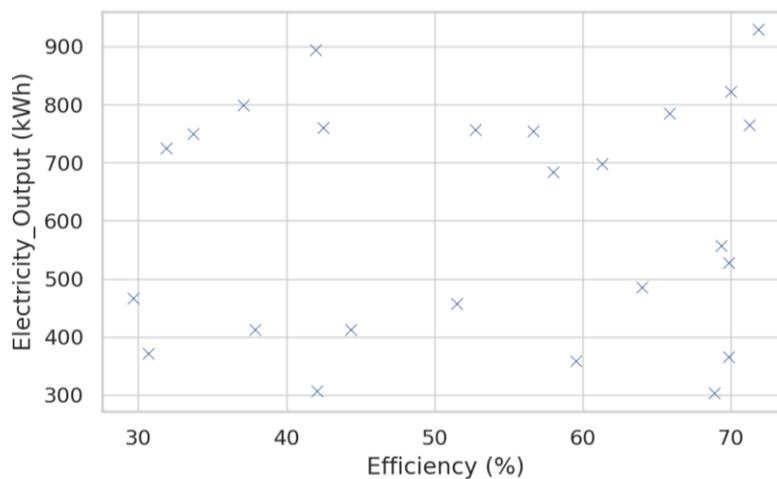
Fig. 3. Scatter plot indicating the relationship between WtE system efficiency and electricity output.

Figure 4 presents a pie chart of the average value of contribution of CO 2 NOx, SO 2 and PM based on combustion based WtE systems. The highest share of the emissions composed by CO 2, however, the emissions of NOx and particulate matter remain significant. This demonstrates the relevance of employing the use of emission control mechanisms when implementing the technology. Figure 5 displays the heatmap that depicts the connections between the circular economy indicators: material recovery, energy recovery and the index of circularity as shown in the figure. The positive relationships (notably between the circularity index and energy recovery) are very high. This confirms the hypothesis that the energy efficiency has a direct influence on circularity. To determine the variability of the quantity of residue ash generated in various trials, a boxplot was prepared (figure 6). The results indicate that various conversion processes may carry quite different outcomes. As an example, thermal technologies produce more ash as compared to biological processes.
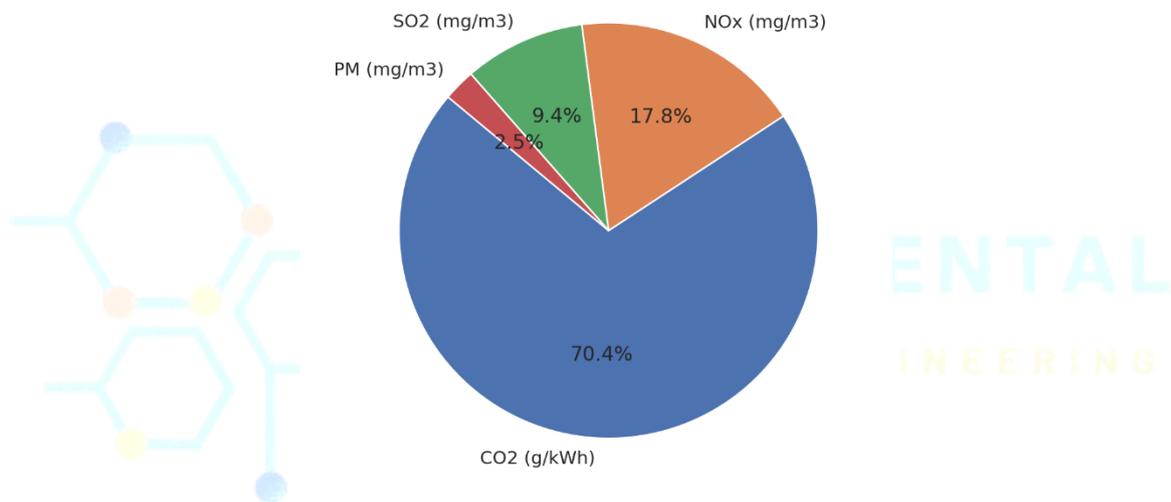
Fig. 4. Pie chart illustrating average distribution of emission types from combustion systems.
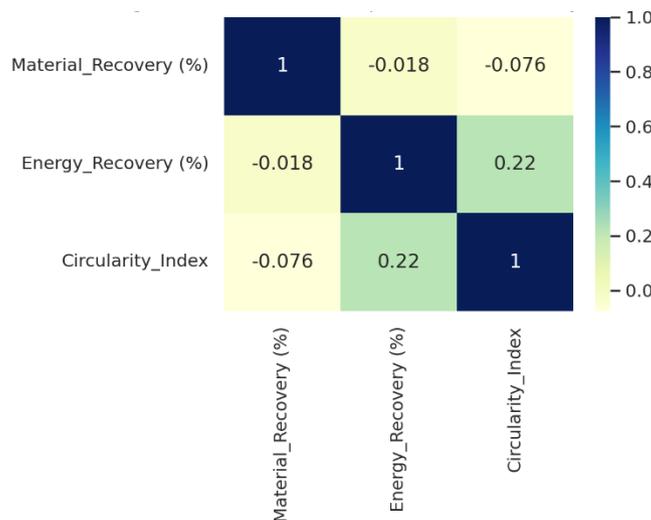
Fig. 5. Heatmap showing correlations among material recovery, energy recovery, and circularity index.
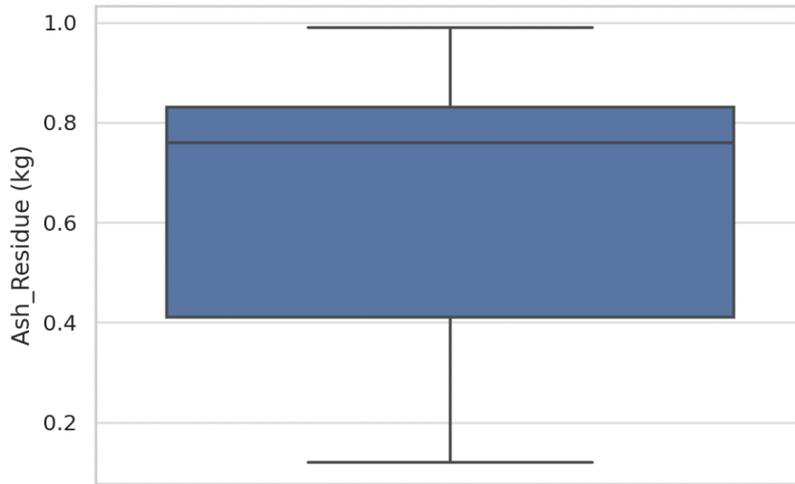
Fig. 6. Boxplot highlighting the variability of ash residue produced from WtE systems.

Figure 7 is a line graph, which demonstrates total lifecycle emissions (in kg CO 2 eq.) on 25 different operational situations. The various scenarios require varying emitting levels. As an example, the lowest GHG footprint can be observed in optimised anaerobic digestion or syngas cleaning. This demonstrates the necessity of the optimisation of the technology to reduce the emission. As Figure 8 illustrates, the figure represents a graph in bar format exhibiting the money returned on investment (ROI) on the various WtE plants. The return on investment (ROI) was highest in plants running a combined heat and power (CHP) system, and this indicates that energy integration can be rendered money-saving in WtE systems. The number of scores of the public knowledge about the WtE systems is represented in figure 9 in the form of a histogram. The vast majority of the responders obtained the scores between 6 and 9, but the distribution indicates that community outreach and engagement approaches might be improved.
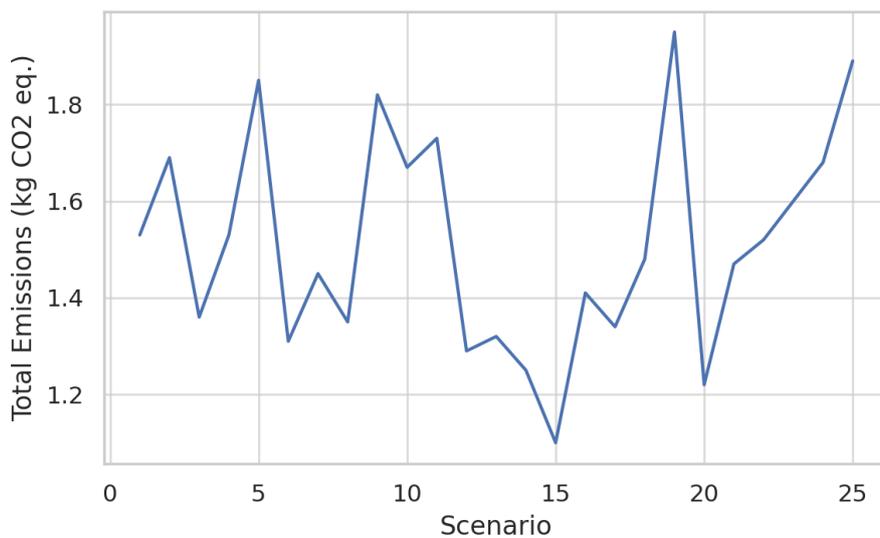
Fig. 7. Line plot displaying total GHG emissions across WtE lifecycle scenarios.
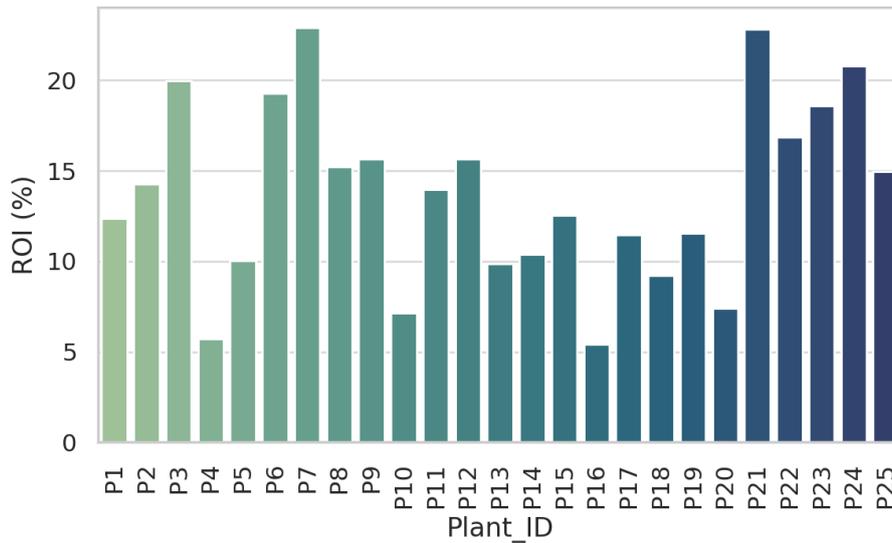
Fig. 8. Bar chart comparing financial return (ROI) among different WtE facilities.
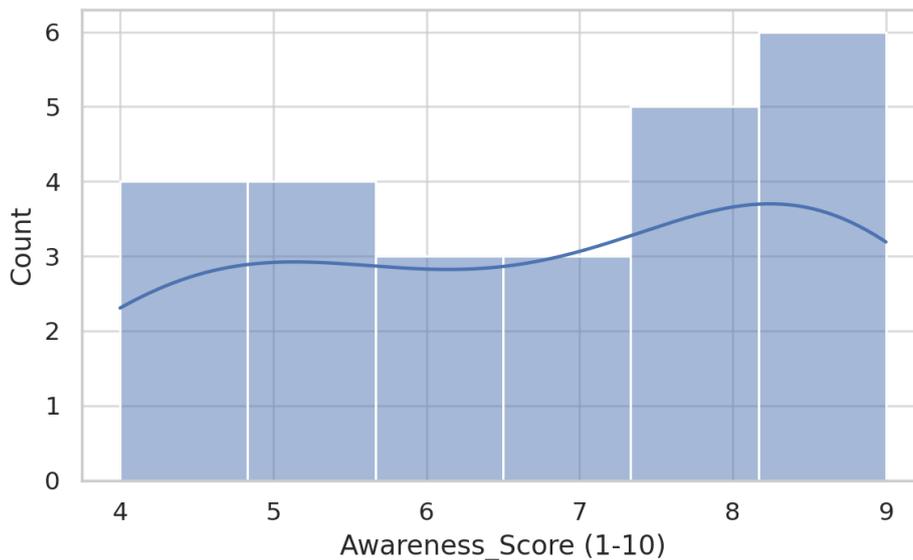

Fig. 9. Histogram showing distribution of awareness scores from surveyed public participants.

Figure 10 displays a violin plot on the distribution of percentages of energy recovery within WtE plants. The shape and the form of the distribution can be seen along with the range on the graphic. The average number of facilities ranges between 70 and 80 percent, and an outsider exceeding 85 percent. Figure 11 demonstrates a combination plot between the quantity of plastic in the wastes and the quantity of energy (HHV) that the wastes can release. There is an evident positive trend depicting that the more plastic fractions, the more energy potential is. This

demonstrates the significance of waste composition to determine the effectiveness of an apparatus. Figure 12 displays a table, which indicates an association between efficiency, electrical output, and the heat production in view of WtE technologies. The scatter and density plots indicate that there are high linear relationships particularly between heat outputs and electricity. This implies that dual-outputs systems portray balanced energy conversion dynamics.
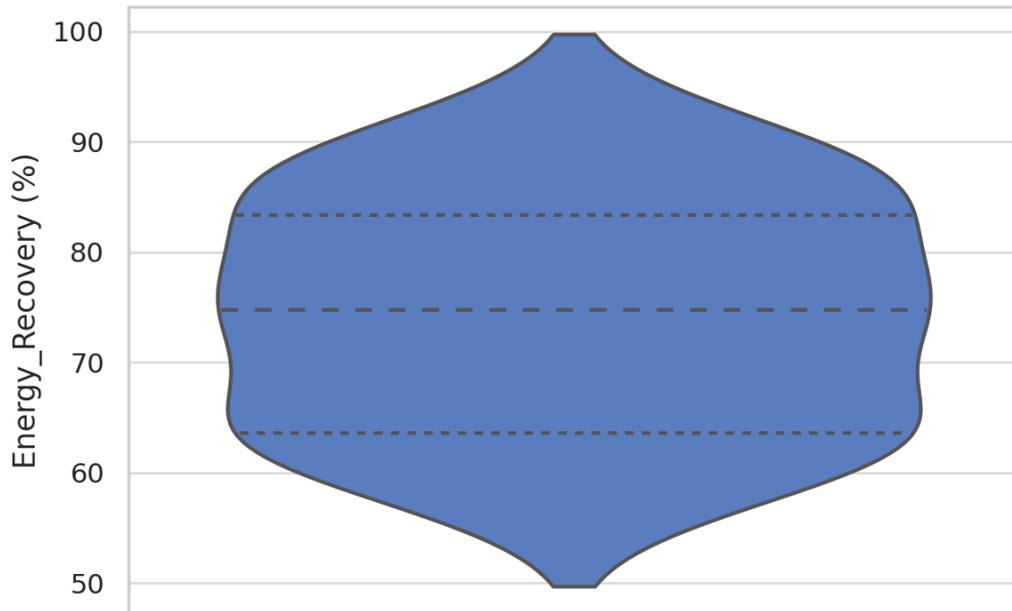
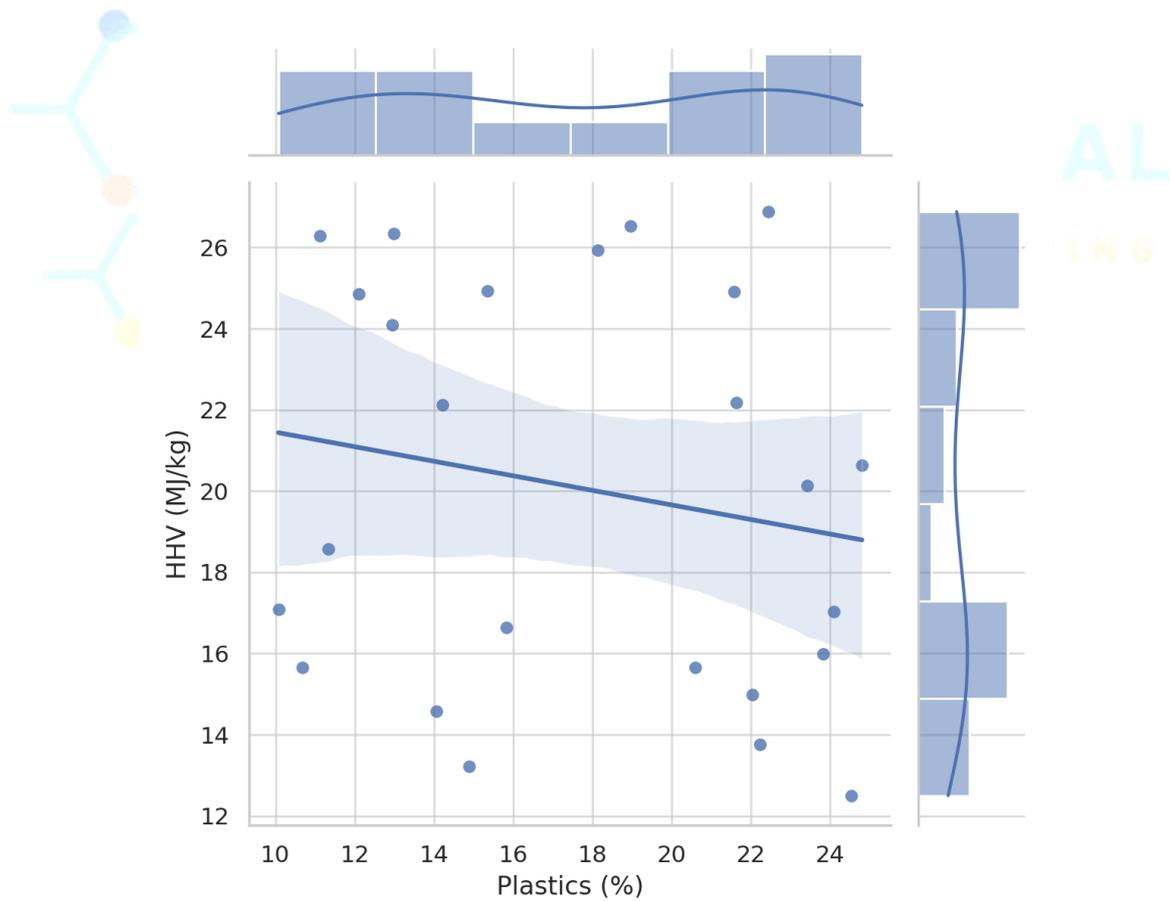**Fig. 10.** Violin plot visualizing energy recovery variation among WtE plants.

Fig. 11. Joint regression plot correlating plastic content in waste with calorific value (HHV).
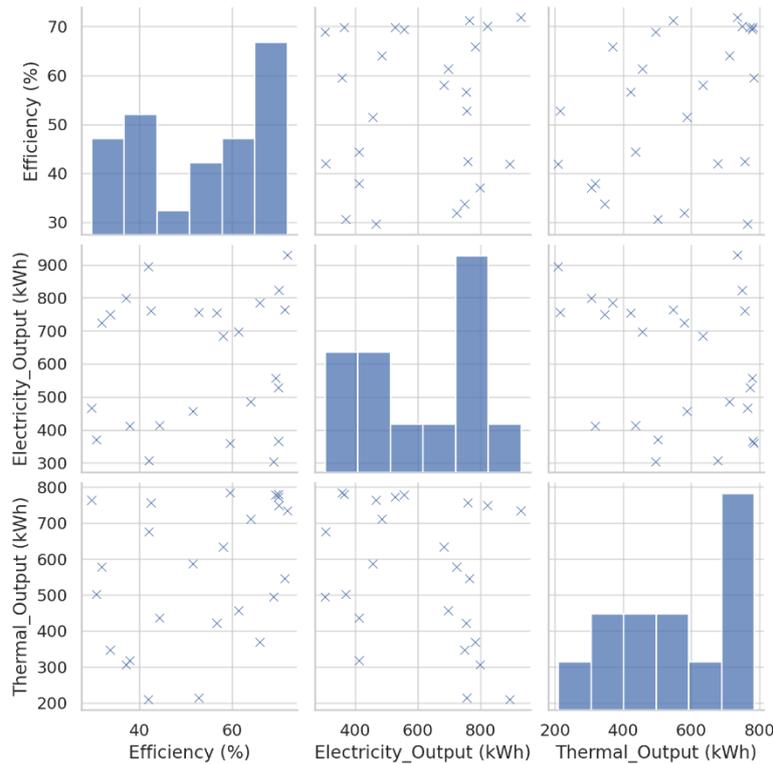
Fig. 12. Pairwise plots showing interrelationships between performance metrics of WtE technologies.

DISCUSSION

The economic and financial aspects are extremely important to make the systems of integrated Waste-to-Energy work well and endure a long period of time. The cost of constructing Waste-to-Energy plants may be extremely high, so thorough financial and investment planning should be done. You should also consider the expenses that are involved in running the business such as garbage collection, processing and maintenance. These expenses can be defrayed by selling the energy, by making people (pay) to dump their trash, and by selling the recovered materials. Feed-in tariffs, tax breaks, and carbon credits are only a few of the policies that can make the Waste-to-Energy system more competitive within the market (Siddiqi et al., 2020). In assembling Waste-to-Energy projects, techno-economic analysis is a very crucial component of the process of selection of the technique and product

(Rana et al., 2020). Focusing on the economics of Waste-to-Energy systems, you should consider such externalities as reduced gas emissions and the absence of landfill payments, as well. Reduction of the adverse impact of food waste on the environment and money are the main reasons to reuse food waste (Melikoğlu, 2020). Cost-benefit analysis allows decision-makers to determine the economic worth of garbage-to-Energy projects in total and compare them to other methods of managing garbage. Garbage-to-Energy is extremely significant to the transition to a circular economy since it transforms garbage in a linear disposal pattern as a rich source of resources. The technologies reduce the demand of new resources, exert less impact on the environment, and generate employment opportunities by obtaining energy and commodities out of trash. The rate of its material circularity and the resource productivity are just a couple of

examples of circular economy indicators that can aid in determining how adequately the Waste-to-Energy systems are performing. Trash-to-Energy systems contribute to making the system more closed-loop, keeping material in use as long as possible and generated as little garbage as possible. The other factor is eco-innovation, which is an economic approach, in which we make attempts to minimize waste and pollution by considering not only the environmental impact of a product but also the ways to take advantage of resources (Guimarães et al., 2024).Recycling may assist organisations to preserve natural resources (Ali et al., 2024). That reduces the need to replenish raw materials (Russo et al., 2021). Bioelectrochemical systems appear to be promising long-term methods of converting trash to energy. They are also included into the circular bioeconomy (Jung et al., 2020). It is simpler to develop more environment-friendly and sustainable processes through new business models with alternative raw materials and material flow as well as new and more efficient technologies in biomass processing (Escobar & Laibach, 2020). In addition, conversion of organic waste into useful products is becoming highly significant since 34 percent of urban wastes across Europe is categorized as organic (Suarez et al., 2023). To have integrated Waste-to-Energy systems functional and implemented, good forms of governance and policies have to be in place. To maintain the environment, the health of the population, and the safety of workers there must be unambiguous and regular rules. Such policies as reducing, reusing and recycling of garbage can help to reduce the level of garbage that should be disposed to the trash and keep garbage-to-Energy plants operating. Extended producer responsibility programs may give companies an incentive to produce those goods which can be recycled more easily or even converted into energy when they are useless.

CONCLUSIONS

This paper provides the complete image of Integrated Waste-to-Energy (WtE) systems considering their influence on the environment, their efficiency in converting energy, and their compatibility with the principles of a circular economy. We examined the composition of waste, the energy output of waste, the emission output, the water consumption of waste and the perception of the public towards it using the mixed methods experimental approach to obtain valuable data about the feasibility and sustainability of the WtE technology in the long time. The findings indicate that the various forms of waste possess such a huge impact on the system selection and the quantity of energy that will be retrieved. Fractions containing a large amount of plastic are of a higher calorific value with energy recovery. Different conversion strategies had great differences in effectiveness. Incineration and gasification generated more energy than anaerobic digestion, and, at the same time, discharged more pollution. The results of the analysis of emissions revealed that the vast majority of pollutants fell within the legal boundaries, however, the particulate matter and NOx emissions should be closely managed. They had good, although not perfect, levels of circularity with the highest scoring systems recycling over 90 percent of materials and energy they had consumed. The values of the circularity indices were nearly equal to 0.9 indicating the significance of the WtE in resource loops closure. Lifecycle analysis revealed that conversion emissions accounted to most part of the total GHG emissions and this is a good area to advance. The returns on investment (ROI) of several WtE are good and particularly when they were established to operate with combined heat/power systems. There were also opinion polls

whereby the people displayed that they were somewhat aware of WtE infrastructure but opened up to it. This implies that it is possible to increase the trust of communities towards WtE infrastructure through appropriate communication as well as regulatory support. The study does not hide the fact that the systems of WtE have certain adverse impacts on the environment, yet, it can assist in achieving the goals of a circular economy, by preventing the amount of trash reaching the land degradation, consuming less fossil fuel, and extracting the energy and materials. Circularity models operating at a larger scale in the cities is the area of future development since they should focus on real-time emissions monitoring, and connect them with renewable energy systems. Accordingly, it is possible to say that when optimised correctly, integrated WtE systems present an effective solution to waste management and transition to low-carbon energy in ways that are environmentally beneficial.

REFERENCES

Ali, Y., Uddin, A. B. M. S., & Petrillo, A. (2024). The Impact of Government Support and Organizational Culture on Sustainable Performance: Unveiling the Mediating Role of Circular Economy and Eco-Innovation. Sustainable Futures, 100346.

Ding, L., Chen, Y., Xu, Y., & Hu, B. (2020). Improving treatment capacity and process stability via a two-stage anaerobic digestion of food waste combining solid-state acidogenesis and leachate methanogenesis/recirculation. Journal of Cleaner Production, 279, 123644.

Enaime, G., Dababat, S., Wichern, M., & Lübken, M. (2024). Olive mill wastes: from wastes to resources. Environmental Science and Pollution Research, 31(14), 20853.

Escobar, N., & Laibach, N. (2020). Sustainability check for bio-based technologies: A review of process-based and life cycle approaches [Review of Sustainability check for bio-based technologies: A review of process-based and life cycle approaches]. Renewable and Sustainable Energy Reviews, 135, 110213. Elsevier BV.

Ghaleb, A. A. S., Kutty, S. R. M., Hayder, G., Jagaba, A. H., Noor, A., Kumar, V., Almahbashi, N. M. Y., Saeed, A. A. H., & Al-dhawi, B. N. S. (2021). Sugarcane Bagasse as a Co-Substrate with Oil-Refinery Biological Sludge for Biogas Production Using Batch Mesophilic Anaerobic Co-Digestion Technology: Effect of Carbon/Nitrogen Ratio. Water, 13(5), 590.

Guimarães, C., Santos, J. D., & Almeida, F. (2024). Practical tools for measuring and monitoring sustainable innovation. Innovation and Green Development, 3(4), 100172.

Jung, S., Lee, J., Park, Y., & Kwon, E. E. (2020). Bioelectrochemical systems for a circular bioeconomy [Review of Bioelectrochemical systems for a circular bioeconomy]. Bioresource Technology, 300, 122748. Elsevier BV.

Karungamye, P. (2024). Energy Recovery from Solid Waste Valorisation: Environmental and Economic Potential for Developing Countries. Scientific African.

Kumar, N. M., Sudha, M. C., Damodharam, T., & Varjani, S. (2020). Micro-pollutants in surface water: Impacts on the aquatic environment and treatment technologies. In Elsevier eBooks (p. 41). Elsevier BV.

Melikoğlu, M. (2020). Reutilisation of food wastes for generating fuels and value added products: A global review [Review of Reutilisation of food wastes for generating fuels and value added products: A global review]. Environmental Technology & Innovation, 19, 101040. Elsevier BV.

Morris, J., Georgiou, I. Y., Guenther, E., & Caucci, S. (2021). Barriers in Implementation of Wastewater Reuse: Identifying the Way Forward in Closing the Loop. Circular Economy and Sustainability, 1(1), 413.

Oluwagbayıde, S. D., Abulude, F. O., Akinnusotu, A., & Arifalo, K. M. (2024). The Relationship between Waste Management Practices and Human Health: New Perspective and Consequences. Indonesian Journal of Innovation and Applied Sciences (IJIAS), 4(1), 19.

Onyeaka, H., Tamasiga, P., Nwauzoma, U. M., Miri, T., Juliet, U. C., Nwaiwu, O., & Akinsemolu, A. A. (2023). Using Artificial Intelligence to Tackle Food Waste and Enhance the Circular Economy: Maximising Resource Efficiency and Minimising Environmental Impact: A Review [Review of Using Artificial Intelligence to Tackle Food Waste and Enhance the Circular Economy: Maximising Resource Efficiency and Minimising Environmental Impact: A Review]. Sustainability, 15(13), 10482. Multidisciplinary Digital Publishing Institute.

Rana, M. S., Bhushan, S., Prajapati, S. K., Preethi, & Kavitha, S. (2020). Techno-economic analysis and environmental aspects of food waste management. In Elsevier eBooks (p. 325). Elsevier BV.

Rusín, J., Chamrádová, K., & Basinas, P. (2020). Two-stage psychrophilic anaerobic digestion of food waste: Comparison to conventional single-stage mesophilic process. Waste Management, 119, 172.

Russo, C., Maugeri, A., Lombardo, G. E., Musumeci, L., Barreca, D., Rapisarda, A., Cirmi, S., & Navarra, M. (2021). The Second Life of Citrus Fruit Waste: A Valuable Source of Bioactive Compounds [Review of The Second Life of Citrus Fruit Waste: A Valuable Source of Bioactive Compounds]. Molecules, 26(19), 5991. Multidisciplinary Digital Publishing Institute.

Sesay, R. E. V., & Fang, P. (2025). Circular Economy in Municipal Solid Waste Management: Innovations and Challenges for Urban Sustainability. Journal of Environmental Protection, 16(2), 35.

Siddiqi, A., Haraguchi, M., & Narayanamurti, V. (2020). Urban waste to energy recovery assessment simulations for developing countries. World Development, 131, 104949.

Suárez, M. A., Gambuzzi, E., Soriano-Disla, J. M., Martínez, G. C., Poggiaroni, G., & Ling, J. (2023). ROOTS - Circular policies for changing the biowaste system. Open Research Europe, 3, 78.

Yuzvovich, L., Lvova, M. I., & Isakova, N. Y. (2024). Waste management: Environmental strategies and practices. E3S Web of Conferences, 541, 4004.

Zhao, Z., Li, Y., & Du, Z. (2022). Seafood Waste-Based Materials for Sustainable Food Packing: From Waste to Wealth. Sustainability, 14(24), 16579.