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Optimizing Municipal Solid Waste Management: P-Graph Studio Application For Resource Recovery In Nigeria's Urban Centres

Aminu Aliyu Ahmed[1,2], **Wan Azlina Wan Ab Karim Ghani**[1,3], **Mus'ab Abdul Razak**[1], **Nik Nor Liyana Nik Ibrahim**[1,3, *]

[1]Department of Chemical and Environmental Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

[2]Department of Industrial Safety and Environmental Engineering Technology, Federal Polytechnic of Oil and Gas, Bonny.

[3]Sustainable Process Engineering Research Centre (SPERC), Department of Chemical & Environmental Engineering, Faculty of Engineering, Universiti Putra Malaysia

[*]**Corresponding author:** Nik Nor Liyana Nik Ibrahim
niknorliyana@upm.edu.my

Abstract

Poor management of municipal solid waste (MSW) remains a critical challenge in Nigeria, particularly in rapidly urbanizing cities such as Lagos, where the pace of population growth outstrips the efficiency of existing waste management systems, thereby straining environmental, social, and economic resilience. Current models rarely incorporate stakeholder perspectives or provide context-specific decision-support tools, and the application of process network synthesis (PNS) in waste management planning across Sub-Saharan Africa remains limited. This paper applies P-graph-based PNS to identify optimal conversion pathways for four dominant waste streams: plastic, nylon, paper, and food waste, using five stakeholder-preferred conversion technologies: material recovery, incineration, pyrolysis, anaerobic digestion, and landfill. Ten optimized solution structures were generated through accelerated branch and bound (ABB) across four combinatorial spaces. Among the solutions, the third trial demonstrated the most balanced performance, with Structure 3 achieving 39,441.30 t/y greenhouse gas emissions, ₦133.35 billion/y profit, and substantial material recovery outputs (233,293 t/y nylon, 170,117 t/y paper, 305,061 t/y plastic, and 105,177 t/y solid and 157,765 t/y liquid fertilizers). In contrast, Structure 1 maximized profits (₦139.89 billion/y) but with higher emissions (45,820.70 t/y), Structure 8 excelled in energy recovery (363,698 MJ/y heat, 183,564 MWh/y electricity), and Structure 10 optimized bio-oil production (324,486 t/y). Notably, Structure 4 in the First trial achieved zero emissions but generated comparatively lower profits, while the second and fourth trials showed inconsistent outcomes. By minimizing landfill use and leveraging Lagos's specific waste composition and stakeholder familiarity, the third trial's Structure 3 best aligned with circular economy principles and the Sustainable Development Goals (SDGs) 7, 11, 12, and 13. The study concludes that investments in sorting infrastructure, anaerobic digestion, and pyrolysis, supported through public–private partnerships and active community engagement, are critical to ensuring scalability and sustainability. Overall, this PNS framework offers a replicable, stakeholder-informed decision-support model for Sub-Saharan African megacities, demonstrating how MSW can be transformed into resources for sustainable urban development while strengthening policy formulation, infrastructure planning, and resilient low-waste ecosystems.

Keywords: *Process Network Synthesis, Municipal Solid Waste, Waste Conversion Technologies, Familiarity Level, Stakeholders, Community Engagement,*

INTRODUCTION

The exponential growth of municipal solid waste (MSW) generation has emerged as one of the most pressing environmental and public health challenges of the 21st century, particularly in rapidly urbanizing regions of the developing world (Agboola et al., 2025; Ragazou et al., 2024; Soni et al., 2023). Global MSW production is projected to reach 3.4 billion tons annually by 2050, representing a staggering 70% increase from 2016 levels, with developing nations accounting for most of this growth (Alam et al., 2024; Valavanidis, 2023). Nowhere is this crisis more acute than in Nigeria's commercial capital of Lagos, where an estimated 10,000-13,000 metric tons of waste are generated daily - of which only 40-60% is formally collected, leaving the remainder to be indiscriminately dumped in open spaces, drainage channels, or illegally burned (Alabi et al., n.d.; Allen-Taylor, 2022; Nwokike, 2020; OLADIMEJI, 2024). This systemic failure in waste management has created a perfect storm of environmental degradation, public health risks, and economic losses, with uncontrolled dumpsites leaching toxic substances into groundwater, emitting climate-altering methane, and serving as breeding grounds for disease vectors (Mor & Ravindra, 2023; Siddiqua et al., 2022). The situation is further exacerbated by Nigeria's abysmally low 4.7% recycling rate and the rapid urbanization of Lagos, whose population is growing at 3.4% annually and expected to exceed 20 million by 2030, inevitably accelerating waste generation rates beyond the capacity of existing management systems (Ayodele et al., 2018; Mbah et al., 2019; Block et al., 2024). However, advanced waste conversion technologies, including thermochemical processes (e.g., pyrolysis, gasification, and incineration) and biochemical methods (e.g., anaerobic digestion and composting), offer transformative solutions (Ashokkumar et al., 2022; Sarker et al., 2024). These technologies convert waste into energy, fertilizers, and reusable materials, reducing landfill dependence, mitigating greenhouse gas emissions, and promoting circular economy principles (Abubakar et al., 2022; Durak, 2023; Siwal et al., 2021).

Recent studies have demonstrated the transformative potential of advanced computational and optimization techniques in revolutionizing MSW management systems. Process Network Synthesis (PNS), particularly through the P-graph methodology, has emerged as a powerful tool for designing optimal waste conversion pathways that balance economic viability with environmental sustainability (Ali et al., 2022; Friedler et al., 1998; Van Fan et al., 2020). Ali et al. (2022) reported an improvement in decision-making efficiency by integrating process network synthesis (PNS) with machine learning (ML) models for municipal solid waste (MSW) management in Malaysia, while Rizwan et al. (2018) identified processing pathways that could reduce greenhouse gas emissions by up to 80% compared to conventional landfilling. The P-graph framework's unique ability to generate multiple feasible solutions with minimal data requirements makes it particularly valuable for data-scarce environments (Friedler et al., 1998; Tujah et al., 2023). Complementary to these optimization strategies, machine learning algorithms have demonstrated significant success in waste management by accurately forecasting municipal solid waste (MSW) generation patterns(Ali et al., 2019; Kang et al., 2023; Muhammad et al., 2021). Additionally, hybrid genetic algorithm-fuzzy logic systems have been used to optimize waste collection routes and supply chain networks (Namoun et al., 2022; Oyebode & Abdulazeez, 2023; Taweesan et al., 2025).

A thorough review of existing literature highlights critical gaps that this study aims to address, notably the limited application of Process Network Synthesis (PNS) and machine learning (ML) techniques to municipal solid waste (MSW) management in Sub-Saharan African megacities, where distinct challenges such as high organic waste content (50-70%), inadequate infrastructure, and institutional constraints necessitate context-specific solutions (Ali, Nik Ibrahim, et al., 2022; Namoun et al., 2022). This paper leverages the output of a comprehensive socioeconomic assessment system, which analyses the perception of the population and the interests of stakeholders in the use of advanced technologies of waste conversion in Lagos, to utilize a P-graph-based Process Network Synthesis (PNS) methodology in optimizing municipal solid waste (MSW) conversion routes. The analysis has been designed to meet the specific waste makeup of Lagos which has a heavy organic fraction and a high proportion of plastic regardless of the fact that the energy needs of the city and the infrastructural constraints were also considered. Through the synthesis of socio-economic implications and systematic PNS modeling, the study aims to determine some context-specific, sustainable, and technologically realistic approaches to MSW management, which will strike an equilibrium between environmental performance, energy recovery, and stakeholder acceptance.

MATERIALS AND METHODS

Description of the Study Area

Nigeria, the largest country in Africa by population and landmass, spans 923,768 km2 and is home to over 220 million people, projected to exceed 300 million by 2050(Abdulfatah, 2023; Onyeabor, 2024; Pona et al., 2021). Bordered by the Gulf of Guinea, Benin, Chad, Cameroon, and Niger, it comprises 36 states and the Federal Capital Territory, Abuja, with Kano and Lagos as key economic hubs ((Ndabula et al., 2021; Tewogbola, 2025). Despite a 2.7% GDP growth rate, rapid urbanization strains infrastructure, particularly municipal solid waste management (MSWM). Similarly, Lagos, Nigeria’s most populous state with 21 million residents, produces 13,000–15,000 tons of waste daily, managed inadequately by the Lagos State Waste Management Authority, which handles only 40% of waste, leaving much to unregulated dumpsites or open burning (Ajayi, 2022; Allen-Taylor, 2022; Nwokike, 2020; OLADIMEJI, 2024). Both states rely on informal recycling sectors for materials like plastics and metals, but these lack formal integration (Akanle & Shittu, 2018; Koko et al., 2023; Ogwueleka & Naveen, 2021). Enhanced recycling, community engagement, and integrated waste management strategies are critical to address these challenges, reduce landfill dependency, and promote a circular economy (Aiguobarueghian et al., 2024; Akanle & Shittu, 2018; Karim et al., 2025)

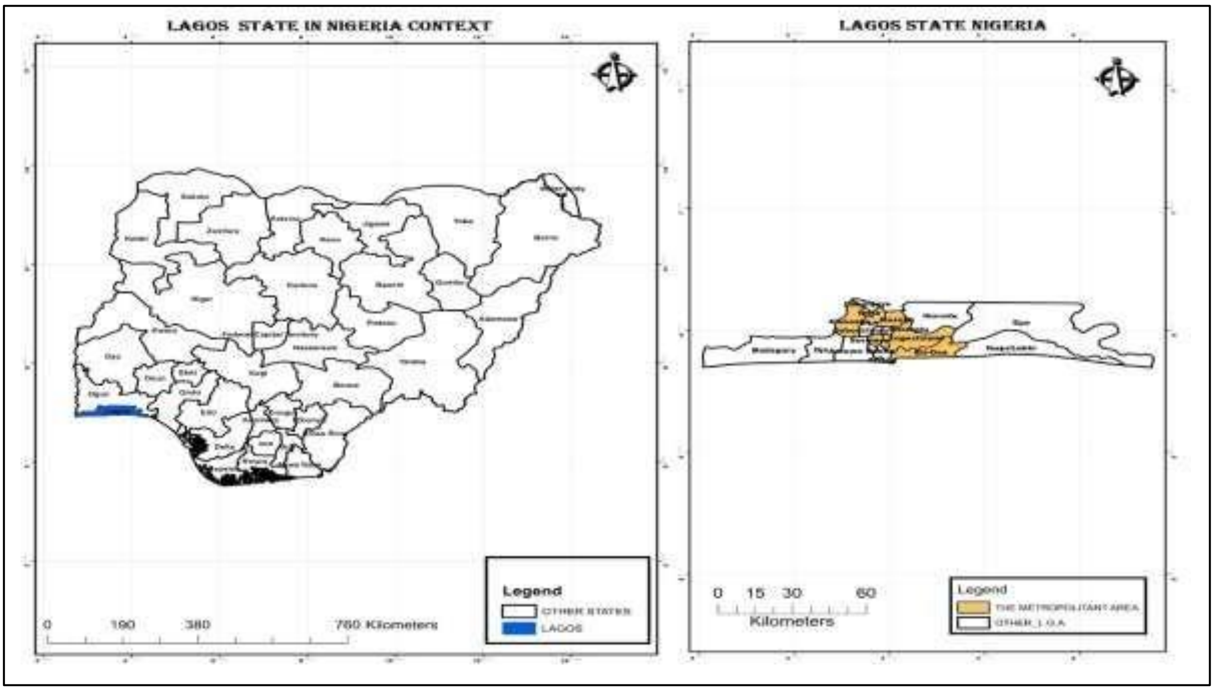

Figure 1. Map of the study area

Selection of Waste Conversion Technology

The selection of municipal solid waste (MSW) conversion technologies for process network synthesis, facilitated by P-graph Studio, centers on harmonizing the synthesis framework with the ranking of conversion technologies, which was determined through a prior socio-economic impact assessment conducted in Lagos State, Nigeria. The structured questionnaire assessed familiarity with seven advanced waste conversion technologies: Pyrolysis, Incineration, Anaerobic Digestion, Gasification, Landfill, Composting, and Material Recovery. Mean familiarity scores and standard deviations were calculated for each technology. Technologies were ranked based on their mean scores, with higher means indicating greater familiarity and thus higher ranking. The analysis took into account regional differences in waste management infrastructure, stakeholder awareness, and socio-economic contexts, as informed by prior studies (Amos et al., 2024; Mshelia et al., 2020). The resulting rankings reflect community and stakeholder preferences and awareness levels, guiding the prioritization of technologies for sustainable MSW management in each region**.**

Data for the Process Network Synthesis using P-Graph Studio

The process network synthesis for municipal solid waste (MSW) conversion technologies using P-graph Studio relies on a robust integration of primary and secondary data sources to ensure comprehensive and context-specific modelling. Primary data, collected directly from stakeholders and communities in Lagos State, Nigeria, encompass the annual volumes of key waste streams—namely food waste, plastic waste, nylon waste, and paper waste—alongside the prevailing market prices of these raw materials and the products derived from their conversion, such as energy, compost, or recycled materials. These data are critical for capturing the local waste management landscape and economic dynamics. Secondary data, meticulously sourced from extant literature and industry reports, include capital expenditure (CAPEX) and operational expenditure (OPEX) for waste conversion equipment (e.g., incinerators, pyrolysis units, and anaerobic digesters), conversion rates or efficiencies of these technologies, and supplementary product prices that are not readily available locally due to limited market data or nascent technological adoption in the region. This dual-sourcing strategy enhances the reliability and scalability of the P-graph model, enabling a nuanced optimization of MSW conversion pathways that balances economic viability, technological feasibility, and environmental sustainability. The synthesized dataset is processed iteratively within P-graph Studio to evaluate multiple configurations, ensuring the resulting framework is both empirically grounded and adaptable to the socio-economic and infrastructural constraints of Nigeria's urbanizing contexts.

Generation of Feasible Municipal Solid Waste Conversion Pathways

Generation of optimal municipal solid waste (MSW) conversion pathways using the P-graph framework is structured into four key stages to ensure systematic and efficient process network generation. The first stage focuses on defining the operating units, which encompass a range of waste conversion technologies categorized into thermochemical processes (pyrolysis and incineration), biological processes (anaerobic digestion), mechanical and material recovery processes (material recovery facilities and pre-treatment operations), and energy recovery processes (gas turbines for biogas and electricity generation), with landfilling included as a baseline scenario for comparative assessment. The selection of these operating units is guided by their socio-economic suitability, scalability, and industrial relevance, ensuring that the framework remains grounded in practical applicability.

The second stage involves the comprehensive identification of input waste streams. including food waste, plastics waste, nylon waste, and paper waste—along with their potential output products, such as recycled materials, heat energy, biochar, electricity, biogas, compost, liquid and solid fertilizers, biofuels, and greenhouse gases (GHGs), the latter being treated as emissions. This step establishes a complete material balance, ensuring that all possible conversion routes are considered in subsequent analyses.

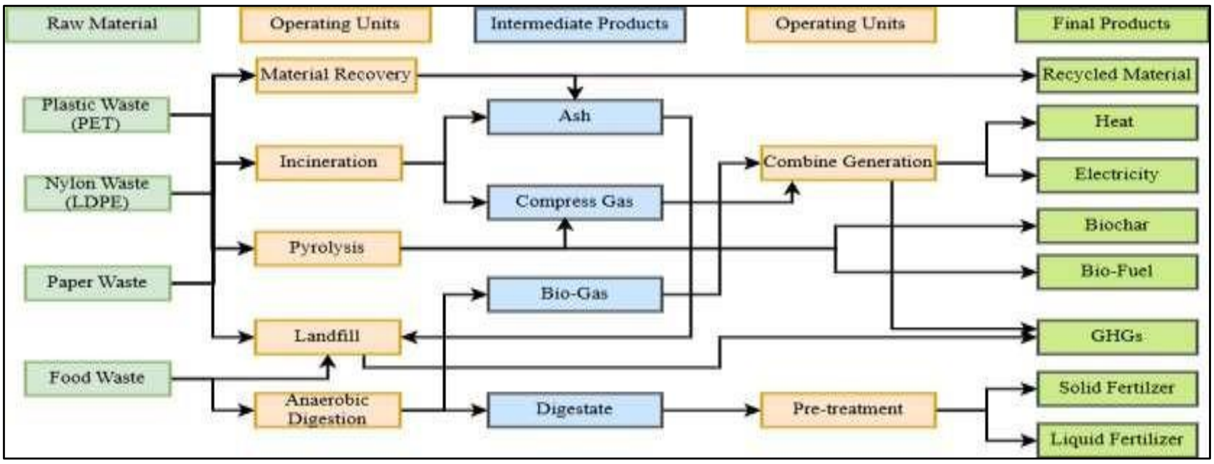

Figure 2. Municipal solid waste streams

The third stage entails the generation of the maximal structure within the P-graph framework, which represents all possible interconnections between input materials, operating units, and output products. This involves detailed input-process-output mapping, where each waste stream is systematically linked to its feasible conversion technologies, and each operating unit is connected to its potential products. The P-graph Studio software is employed to visually construct this maximal structure, ensuring that no viable pathway is overlooked prior to optimization. The rationale behind this stage lies in its ability to exhaustively capture the solution space before applying optimization algorithms.

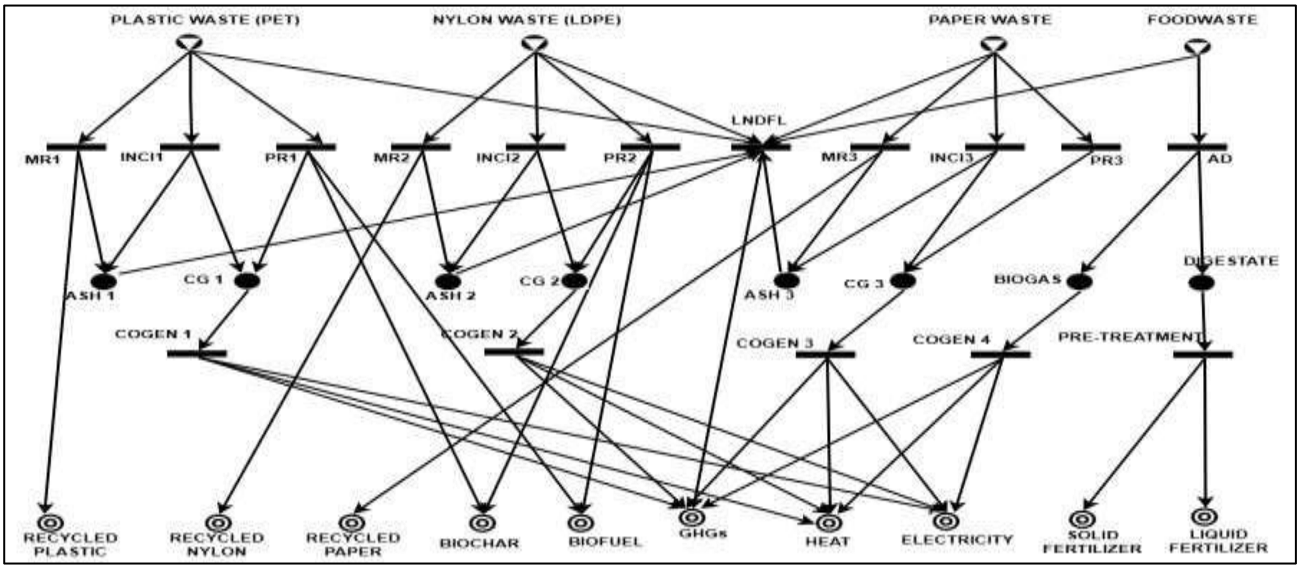

Figure 3. Description of maximal structure generation

The fourthand final stage involves the optimization of feasible pathways using the Accelerated Branch-and-Bound (ABB) algorithm, which efficiently evaluates the combinatorial possibilities within the maximal structure.

Objective functions are defined based on economic criteria (minimizing cost or maximizing profit), environmental criteria (minimizing GHG emissions), or multi-objective considerations (identifying Pareto-optimal solutions that balance competing priorities). The ABB solver in P-graph Studio systematically assesses all feasible solutions, generating a ranked list of optimal pathways such as those yielding the highest energy output or the lowest environmental impact, while maintaining computational efficiency even for large-scale problems. This integrated approach ensures a rigorous, transparent, and reproducible framework for MSW conversion pathway synthesis, facilitating informed decision-making in waste management and resource recovery. The operating units combinatorial followed four distinct patterns as shown in Fig. 4 below.

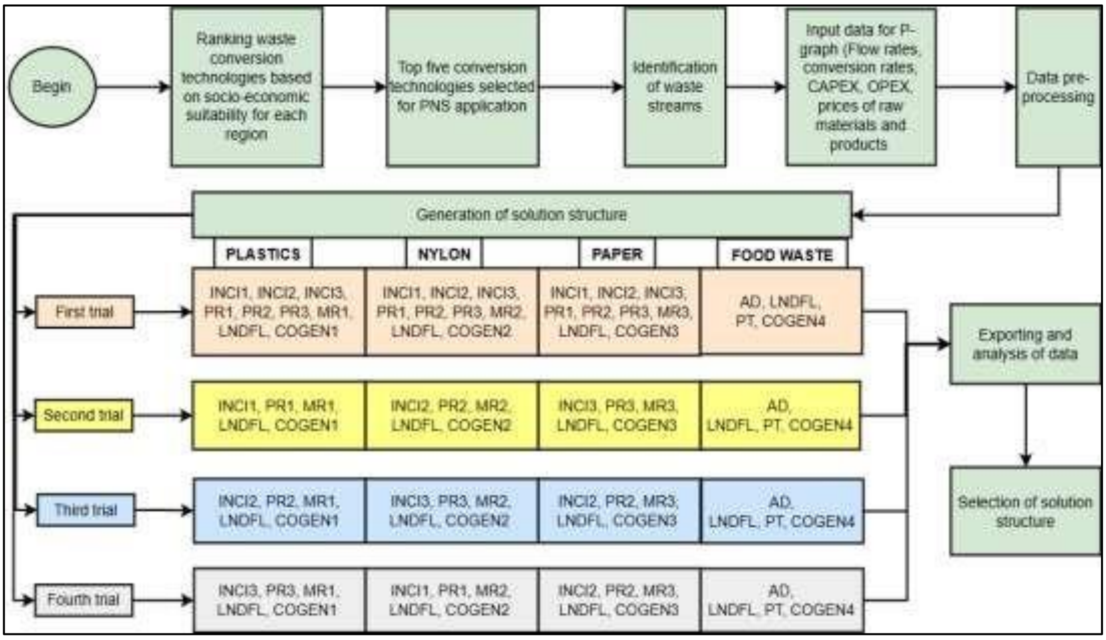

Figure 4. Framework for process network synthesis

Result and Discussion

Selection of Waste Conversion Technology for Process Network Synthesis

The selection of municipal solid waste (MSW) conversion technologies for process network synthesis in Lagos is informed by a ranking derived from stakeholder and community familiarity surveys conducted in 2024, prioritizing the top five technologies as outlined in Table 1 below.

Table 1. Ranking of Municipal Solid Waste Conversion Technology

Ranking	Lagos
1st	Material Recovery
2nd	Incineration
3rd	Pyrolysis
4th	Anaerobic Digestion
5th	Landfill

The ranking of advanced waste conversion technologies reveals distinct regional patterns: In Lagos. Material Recovery, ranked first with a mean familiarity score reflecting Lagos's strong emphasis on recycling and resource recovery driven by its economic hub status and private sector initiatives, is selected as the cornerstone technology for maximizing material reuse. Incineration, securing the second position, leverages its historical application in managing medical and municipal waste, offering a robust waste-to-energy option to complement recycling efforts. Pyrolysis, ranked third, highlights Lagos's technological advancement, providing a promising avenue for converting plastic and organic waste into valuable products like biochar and fuel. Anaerobic Digestion, fourth in the ranking, is chosen for its potential to produce biogas from organic waste, aligning with sustainable energy goals despite moderate awareness. Landfill, rounding out the top five with an established yet less innovative role, is retained as a transitional disposal method to address residual waste, ensuring a balanced approach that addresses current infrastructure limitations while paving the way for more advanced technologies.

Operating Units Combinatorial for the Process Network Synthesis

The waste conversion process integrates multiple operating units to transform the municipal solid waste streams into valuable products. For each combinatorial problem, the P-graph selects operating units to generate the solution structures. The selection of these units is guided by waste composition, economic feasibility, and operational efficiency, ensuring a sustainable and cost-effective waste management solution.

Table 2: Selected Operating Units for Each PNS Combinatorial by P-Graph

PNS COMBINATORIAL	**OPERATING UNITS**															
	AD	COGEN_1	COGEN_2	COGEN_3	COGEN_4	INCI_1	INCI_2	INCI_3	LNDFIL	MR_1	MR_2	MR_3	PR_1	PR_2	PR_3	PRE_TREATMENT
FIRST TRIAL	✓	-	-	-	✓	-	-	-	-	✓	✓	✓	-	-	-	✓
SECOND TRIAL	✓	✓	✓	✓	✓	-	✓	✓	-	✓	✓	✓	✓	✓	✓	✓
THIRD TRIAL	✓	✓	✓	✓	✓	✓	-	✓	-	✓	✓	✓	✓	✓	✓	✓
FOURTHTRIAL	✓	✓	✓	-	✓	-	✓	-	-	✓	✓	✓	✓	✓	✓	✓

Table presents four combinatorial pathways for Process Network Synthesis (PNS), each integrating different operating units for municipal solid waste conversion. The first trial employs only anaerobic digestion (AD), cogeneration-4 (COGEN_4), material recovery (MR_1–MR_3), and pre-treatment, excluding all incineration equipment, pyrolysis equipment, and landfill. The second and third trials expand the network by incorporating multiple cogeneration units (COGEN_1–COGEN_4), pyrolysis (PR_1–PR_3), and selective incineration (INCI_2–INCI_3 in trial 2; INCI_1 and INCI_3 in trial 3), enhancing energy recovery but omitting landfill. The fourth trial reduces cogeneration participation (excluding COGEN_3) while maintaining AD, MR_1–MR_3, and PR_1–PR_3 but only activates INCI_2. Notably, landfill (LNDFIL) is excluded in all trials, suggesting a preference for waste valorisation over disposal. Furthermore, high capital or operational costs may have rendered some units (e.g., specific cogeneration or incineration plants) economically unviable for certain pathways, leading to their exclusion in favour of cheaper alternatives like material recovery (MR) or anaerobic digestion (AD)

Profit and Emission Generation

Ten alternative solution structures offered by the P-graph analysis of the municipal solid waste conversion were compared in terms of profit generation and greenhouse gas (GHG) emission under four trials. The findings reveal the definite difference, and certain structures were very high in economic returns and they were also characterised by high emissions. In contrast, other ones were also low in terms of profitability. Still, they provided a better result than other structures in terms of the environment, with low or even zero emissions in certain instances.

Table 2. Summary of GHGs Emission and Profit Generated for Each PNS Combinatorial

Solution Structure	**First Trial**		**Second Trial**		**Third Trial**		**Fourth Trial**	
	GHGs [t/y]	**Profit Generated [Naira/y]**	**GHGs [t/y]**	**Profit Generated [Naira/y]**	**GHGs [t/y]**	**Profit Generated [Naira/y]**	**GHGs [t/y]**	**Profit Generated [Naira/y]**
Structure1	39,441.30	133,350,000,000.00	47,415.50	135,245,000,000.00	45,820.70	139,885,000,000.00	49,010.40	137,348,000,000.00
Structure2	39,441.30	118,250,000,000.00	39,441.30	133,350,000,000.00	39,441.30	135,757,000,000.00	57,244.20	135,427,000,000.00
Structure3	39,441.30	117,979,000,000.00	39,441.30	131,894,000,000.00	39,441.30	133,350,000,000.00	39,441.30	133,350,000,000.00
Structure4	0	106,894,000,000.00	59,766.30	129,982,000,000.00	56,113.00	131,899,000,000.00	39,441.30	133,170,000,000.00
Structure5	39,441.30	106,033,000,000.00	51,792.10	128,087,000,000.00	49,733.60	127,771,000,000.00	47,675.20	131,430,000,000.00
Structure6	39,441.30	102,878,000,000.00	51,792.10	126,631,000,000.00	45,820.70	127,516,000,000.00	47,675.20	131,250,000,000.00
Structure7	0	98,583,600,000.00	47,415.50	124,493,000,000.00	49,733.60	125,364,000,000.00	49,010.40	130,047,000,000.00
Structure8	39,441.30	61,813,900,000.00	59,766.30	114,611,000,000.00	64,618.80	115,370,000,000.00	47,675.20	116,329,000,000.00
Structure9	0	56,165,300,000.00	78,292.50	113,342,000,000.00	6,379.38	113,429,000,000.00	47,675.20	116,059,000,000.00
Structure10	0	50,728,800,000.00	50,881.10	113,211,000,000.00	45,820.70	112,567,000,000.00	47,675.20	115,879,000,000.00

In Table 2 above, the analysis revealed significant variability in performance, with Structure 1 consistently achieving the highest profits, peaking at 139,885,000,000 Naira/y in the third trial but with moderate to high emissions (45,820.70 t/y in the third trial, ranging up to 49,010.40 t/y in the fourth trial), indicating a configuration likely reliant on high-yield but emission-intensive technologies such as pyrolysis or incineration, making it ideal for economically driven scenarios where emission mitigation strategies, such as carbon capture or advanced scrubbers, can be implemented to comply with environmental regulations. Structure 2 demonstrated notable consistency in emissions (39,441.30 t/y in three trials) and strong profits (up to 135,757,000,000 Naira/y in the third trial), but a spike in emissions to 57,244.20 t/y in the fourth trial suggests sensitivity to process adjustments, reducing its reliability compared to other structures. Structure 3 emerged as a standout for balanced performance, maintaining stable emissions (39,441.30 t/y across all trials) and competitive profits (peaking at 133,350,000,000 Naira/y in the third and fourth trials), likely due to a well-optimized mix of technologies such as material recovery and controlled pyrolysis, offering a reliable and sustainable option for stakeholders seeking to balance economic and environmental objectives. Structure 4 was particularly remarkable in the first trial, achieving zero GHG emissions with a respectable profit of 106,894,000,000 Naira/y, suggesting a heavy reliance on low-emission technologies like material recovery and anaerobic digestion, which are environmentally superior but less profitable than emission-intensive alternatives; however, later trials showed increased emissions (up to 59,766.30 t/y in the second trial) with higher profits (up to 133,170,000,000 Naira/y in the fourth trial), indicating variability in process configuration or waste input composition. Structures 5 and 6 performed moderately, with emissions ranging from 39,441.30 to 51,792.10 t/y and profits up to 131,430,000,000 Naira/y, but they were outshone by Structures 1–4 due to lower economic returns or higher environmental impact. Structure 7 mirrored Structure 4's environmental potential in the First trial with zero emissions but yielded a lower profit (98,583,600,000 Naira/y), and its performance in later trials (emissions up to 49,010.40 t/y, profits up to 130,047,000,000 Naira/y) was less competitive. Structures 8, 9, and 10 consistently underperformed, with Structure 8 generating the lowest profits in the first trial (61,813,900,000 Naira/y) and high emissions in later trials (up to 64,618.80 t/y), Structure 9 exhibiting an alarming emission peak (78,292.50 t/y in the second trial) despite low profits in the first trial (56,165,300,000 Naira/y), and Structure 10 being the least profitable overall (50,728,800,000 Naira/y in the first trial), rendering these structures unsuitable for large-scale implementation.

Energy Generation

The P-graph analysis also assessed the potential of each solution structure for the energy (heat and electricity) generation, and the potentials of the outputs were markedly different among the ten structures as well as the four trials. It was observed that some of the structures yielded elevated energy recovery, mostly and typically associated with thermochemical reactions, yet others yielded relatively lower yields yet matched with environmentally friendly procedures like material recovery and biological treatment.

Table 3. Energy Generation Across the PNS Combinatorial

Solution Structure	**First Trial**		**Second Trial**		**Third Trial**		**Fourth Trial**	
	Heat [MJ/y]	**Electricity [MWh/y]**	**Heat [MJ/y]**	**Electricity [MWh/y]**	**Heat [MJ/y]**	**Electricity [MWh/y]**	**Heat [MJ/y]**	**Electricity [MWh/y]**
Structure1	236,648.00	118,324.00	265,887.00	134,272.00	274,924.00	137,462.00	268,545.00	140,652.00
Structure2	236,648.00	118,324.00	236,648.00	118,324.00	236,648.00	118,324.00	317,948.00	165,353.00
Structure3	236,648.00	118,324.00	236,648.00	118,324.00	236,648.00	118,324.00	236,648.00	118,324.00
Structure4	0	0	307,056.00	163,091.00	312,663.00	158,047.00	236,648.00	118,324.00
Structure5	236,648.00	118,324.00	277,817.00	147,142.00	274,386.00	138,909.00	286,051.00	143,025.00
Structure6	236,648.00	118,324.00	277,817.00	147,142.00	274,924.00	137,462.00	286,051.00	143,025.00
Structure7	0	0	265,887.00	134,272.00	274,386.00	138,909.00	268,545.00	140,652.00
Structure8	236,648.00	118,324.00	307,056.00	163,091.00	363,698.00	183,564.00	286,051.00	143,025.00
Structure9	0	0	368,810.00	206,319.00	38,276.30	19,138.10	286,051.00	143,025.00
Structure10	0	0	305,286.00	152,643.00	274,924.00	137,462.00	286,051.00	143,025.00

The energy produced (heat and electricity), as depicted in Table 3 above, reveals significant variability in energy outputs across the trials, with heat generation ranging from 0 to 368,810.00 MJ/y and electricity from 0 to 206,319.00 MWh/y. Structure 1 consistently performed well, peaking in the third trial with 274,924.00 MJ/y of heat and 137,462.00 MWh/y of electricity, and further improving in the fourth trial to 268,545.00 MJ/y and 140,652.00 MWh/y, suggesting a robust configuration likely leveraging incineration or pyrolysis for high energy recovery. Structure 2 showed stability in the first three trials (236,648.00 MJ/y heat, 118,324.00 MWh/y electricity) but achieved the highest energy output in the fourth trial (317,948.00 MJ/y heat, 165,353.00 MWh/y electricity), indicating a potential optimization of technology mix or waste input in that trial, possibly emphasizing incineration with enhanced energy capture. Structure 3 maintained consistent outputs across all trials (236,648.00 MJ/y heat, 118,324.00 MWh/y electricity), reflecting a stable but less dynamic configuration, possibly relying on a balanced mix of material recovery and anaerobic digestion with steady energy yields. Structure 4 produced no energy in the first trial (0 MJ/y, 0 MWh/y), likely due to a focus on non-energy-generating technologies like material recovery or landfill, but showed strong performance in the third trials (307,056.00 MJ/y heat, 163,091.00 MWh/y electricity in the second; 312,663.00 MJ/y heat, 158,047.00 MWh/y electricity in the third), before reverting to baseline levels in the fourth trial (236,648.00 MJ/y heat, 118,324.00 MWh/y electricity), suggesting variability in process efficiency or waste composition. Structures 5 and 6 mirrored each other closely, with moderate increases in energy output from the first trial (236,648.00 MJ/y heat, 118,324.00 MWh/y electricity) to the second and third trials (up to 277,817.00 MJ/y heat, 147,142.00 MWh/y electricity for Structure 5; 274,924.00 MJ/y heat, 137,462.00 MWh/y electricity for Structure 6), and identical outputs in the fourth trial (286,051.00 MJ/y heat, 143,025.00 MWh/y electricity), indicating similar technology configurations with incremental improvements. Structure 7, like Structure 4, produced no energy in the first trial (0 MJ/y, 0 MWh/y), but improved significantly in later trials, matching Structure 1's fourth trial output (268,545.00 MJ/y heat, 140,652.00 MWh/y electricity), suggesting a shift to energy-intensive technologies like incineration. Structure 8 achieved the highest energy output in the third trial (363,698.00 MJ/y heat, 183,564.00 MWh/y electricity), likely due to optimized incineration or pyrolysis processes, but dropped to 286,051.00 MJ/y heat and 143,025.00 MWh/y electricity in the fourth trial, indicating sensitivity to operational changes. Structure 9 was the weakest in the first trial (0 MJ/y, 0 MWh/y) and third trial (38,276.30 MJ/y heat, 19,138.10 MWh/y electricity), but peaked in the second trial (368,810.00 MJ/y heat, 206,319.00 MWh/y electricity), the highest overall, suggesting an outlier configuration possibly involving high-efficiency incineration or waste-to-energy processes, though its inconsistency across trials raises reliability concerns. Structure 10 also produced no energy in the first trial but showed steady improvement, reaching 305,286.00 MJ/y heat and 152,643.00 MWh/y electricity in the second trial, and 286,051.00 MJ/y heat and 143,025.00 MWh/y electricity in the fourth trial, performing comparably to Structures 5 and 6. The variability across trials highlights the influence of waste composition and technology selection, with zero-energy outputs in Structures 4, 7, 9, and 10 in the First trial likely reflecting reliance on non-energy-generating processes like landfill or material recovery, while high-energy trials (e.g. Structure 9 second trial; Structure 8 third trial) suggest optimized waste-to-energy configurations. For maximizing energy generation, Structure 2 in the fourth trial (317,948.00 MJ/y heat, 165,353.00 MWh/y electricity) is recommended as the best trial due to its superior energy output, likely driven by an optimized mix of incineration and pyrolysis, balancing high heat and electricity production.

Bio-oil and Biochar Production

The P-graph analysis also evaluated the potential of the various solution structures in the production of bio-oil and biochar that could serve as useful by-products of the municipal solid waste conversion. The findings represented in Table 4 reveal a significant variation in the trials with certain structures not producing anything in the initial trials but with significant production in subsequent trials, and this is especially where thermochemical conversion pathways like pyrolysis were more pronounced. Although some of the arrangements yielded high concentrations of bio-oil at moderate concentrations of biochar, some showed a more balanced recovery of both products, highlighting the role of technology choice and integration of processes in determining resource recovery potential.

Table 4. Level of Bio-Oil and Biochar Production Across the PNS Combinatorial

Solution Structure	**First Trial**		**Second Trial**		**Third Trial**		**Fourth Trial**	
	Bio-Oil [t/y]	**Biochar [t/y]**	**Bio-Oil [t/y]**	**Biochar [t/y]**	**Bio-Oil [t/y]**	**Biochar [t/y]**	**Bio-Oil [t/y]**	**Biochar [t/y]**
Structure1	0	0	95,690.70	63,793.80	127,588.00	21,264.60	106,323.00	42,529.20
Structure2	0	0	0	0	127,588.00	21,264.60	271,000.00	69,975.40

Structure3	0	0	95,690.70	63,793.80	0	0	0	0
Structure4	0	0	232,922.00	118,686.00	251,096.00	103,603.00	106,323.00	42,529.20
Structure5	0	0	137,231.00	54,892.40	251,096.00	103,603.00	164,677.00	27,446.20
Structure6	0	0	232,922.00	118,686.00	251,096.00	103,603.00	271,000.00	69,975.40
Structure7	0	0	232,922.00	118,686.00	123,508.00	82,338.60	271,000.00	69,975.40
Structure8	0	0	232,922.00	118,686.00	123,508.00	82,338.60	164,677.00	27,446.20
Structure9	0	0	95,690.70	63,793.80	127,588.00	21,264.60	164,677.00	27,446.20
Structure10	0	0	127,588.00	101,926.00	324,486.00	21,264.60	271,000.00	69,975.40

Table 4 reveals significant variability in bio-oil and biochar outputs, with bio-oil production ranging from 0 to 324,486.00 t/y and biochar from 0 to 118,686.00 t/y. In the first trial, all structures produced no bio-oil or biochar (0 t/y), suggesting a configuration prioritizing non-pyrolysis technologies like material recovery, landfill, or anaerobic digestion, which do not generate these products. The second trial marked a shift, with Structures 1, 3, and 9 producing 95,690.70 t/y bio-oil and 63,793.80 t/y biochar, Structures 4, 6, 7, and 8 yielding higher outputs at 232,922.00 t/y bio-oil and 118,686.00 t/y biochar, Structure 5 at 137,231.00 t/y bio-oil and 54,892.40 t/y biochar, and Structure 10 at 127,588.00 t/y bio-oil and 101,926.00 t/y biochar, indicating increased reliance on pyrolysis, particularly for Structures 4, 6, 7, and 8, which achieved the highest biochar yields. The third trial showed further diversification, with Structure 10 producing the highest bio-oil output (324,486.00 t/y) but a low biochar yield (21,264.60 t/y), suggesting a pyrolysis configuration optimized for liquid fuel production; Structures 4, 5, and 6 also performed strongly, producing 251,096.00 t/y bio-oil and 103,603.00 t/y biochar, while Structures 1 and 9 matched Structure 2's output (127,588.00 t/y bio-oil, 21,264.60 t/y biochar), and Structures 7 and 8 yielded 123,508.00 t/y bio-oil and 82,338.60 t/y biochar; Structure 3 produced nothing, reverting to non-pyrolysis processes. The fourth trial saw Structures 2, 6, 7, and 10 achieving the highest bio-oil production (271,000.00 t/y) and biochar at 69,975.40 t/y, while Structures 5, 8, and 9 produced 164,677.00 t/y bio-oil and 27,446.20 t/y biochar. Structure 4 matched Structure 1's output (106,323.00 t/y bio-oil, 42,529.20 t/y biochar), and Structure 3 again produced nothing. The absence of production in the first trial across all structures indicates a baseline configuration avoiding pyrolysis, possibly due to high capital costs or low waste input suitability (e.g., insufficient plastic or nylon waste). The second and third trials reflect increased pyrolysis adoption, with Structures 4, 6, 7, and 8 consistently producing high biochar yields, likely due to optimized pyrolysis conditions favouring solid residue formation, while Structure 10's third trial peak in bio-oil suggests a focus on liquid product maximization, possibly using fast pyrolysis with high plastic waste input. The fourth trial's high bio-oil outputs in Structures 2, 6, 7, and 10 indicate a robust pyrolysis-based configuration, balanced with moderate biochar production, suggesting improved process efficiency or waste composition (e.g., higher plastic/nylon ratios). Structure 3's consistent zero output in the first, third, and fourth trials highlights a preference for alternative technologies, rendering it unsuitable for bio-oil and biochar goals.

Recycled Material Generated

The P-graph analysis also looked at the recovery of recyclable material nylon, paper and plastics in the various solution structure. The findings as indicated in Table 5 shows that consistency and combination of recovered materials are highly variable, and plastics were the most consistent output in all structures and trials, and nylon and paper displayed fluctuation in output based on the process configuration. Certain structures showed equal recovery of the three materials, whereas others showed preference to one or two of the recycling paths, as technological integration varied and material recovery was prioritised.

Table 5. Recycled Material Produced Across the PNS Combinatorial

Solution Structure	First Trial			Second Trial			Third Trial			Fourth Trial		
	Recycled Nylon [t/y]	Recycled Paper [t/y]	Recycled Plastic [t/y]	Recycled Nylon [t/y]	Recycled Paper [t/y]	Recycled Plastic [t/y]	Recycled Nylon [t/y]	Recycled Paper [t/y]	Recycled Plastic [t/y]	Recycled Nylon [t/y]	Recycled Paper [t/y]	Recycled Plastic [t/y]
Structure1	233,293.00	170,117.00	305,061.00	233,293.00	0	305,061.00	233,293.00	0	305,061.00	233,293.00	0	305,061.00
Structure2	233,293.00	0	305,061.00	233,293.00	170,117.00	305,061.00	233,293.00	0	305,061.00	0	0	305,061.00
Structure3	233,293.00	170,117.00	305,061.00	233,293.00	0	305,061.00	233,293.00	170,117.00	305,061.00	233,293.00	170,117.00	305,061.00

Structure4	233,293.00	170,117.00	305,061.00	0	0	305,061.00	0	0	305,061.00	233,293.00	0	305,061.00
Structure5	0	170,117.00	305,061.00	0	170,117.00	305,061.00	0	0	305,061.00	0	170,117.00	305,061.00
Structure6	233,293.00	0	305,061.00	0	0	305,061.00	0	0	305,061.00	0	0	305,061.00
Structure7	233,293.00	170,117.00	305,061.00	0	0	305,061.00	0	170,117.00	305,061.00	0	0	305,061.00
Structure8	233,293.00	170,117.00	0	0	0	305,061.00	0	0	305,061.00	0	0	305,061.00
Structure9	0	0	305,061.00	0	0	305,061.00	233,293.00	0	305,061.00	0	170,117.00	305,061.00
Structure10	233,293.00	170,117.00	0	233,293.00	0	0	0	0	305,061.00	0	0	305,061.00

Recycled materials for nylon waste, paper waste, and plastic waste vary across structures and trials, with recycled nylon ranging from 0 to 233,293.00 t/y, recycled paper from 0 to 170,117.00 t/y, and recycled plastic consistently at 305,061.00 t/y across most structures and trials, except for Structure 10 in the second trial (0 t/y). In the first trial, Structures 1, 3, 4, 7, and 10 produced the maximum output for all three materials (233,293.00 t/y nylon, 170,117.00 t/y paper, 305,061.00 t/y plastic), indicating a strong emphasis on material recovery processes tailored for diverse waste streams. Structure 2 omitted paper recycling, Structure 5 omitted nylon, Structure 6 omitted paper, Structure 8 omitted plastic, and Structure 9 produced only plastic, suggesting selective material recovery configurations likely driven by waste input availability or equipment specificity. In the second trial, Structures 1 and 3 maintained high nylon and plastic outputs but dropped paper (except Structure 2, which included paper), while Structures 4, 6, 7, 8, and 9 produced only plastic, and Structure 10 produced only nylon, reflecting a shift toward selective recycling, possibly due to cost optimization or waste composition changes favouring plastic recovery. The third trial saw Structures 1 and 3 again producing high outputs (nylon and plastic for Structure 1; all three for Structure 3), while Structures 2, 4, 5, 6, 7, and 8 focused on plastic, Structure 7 included paper, and Structure 9 added nylon, indicating varied recovery priorities; Structure 10 produced only plastic, suggesting a streamlined process. The fourth trial showed that Structures 1, 3, and 4 produced nylon and plastic (Structure 3 also included paper), while Structures 2, 6, 7, 8, and 10 produced only plastic, and Structures 5 and 9 included paper, reflecting continued variability in material recovery focus. The consistent plastic output (305,061.00 t/y) across most structures and trials highlights the dominance of plastic recycling, likely due to high market demand, favorable conversion efficiencies in material recovery facilities, or abundant plastic waste inputs (e.g., plastic and nylon waste). Nylon and paper recycling were less consistent, with outputs often dropping to zero, possibly due to lower market value, higher processing costs, or challenges in sorting and processing these materials compared to plastics. Structures 1 and 3 demonstrated the most robust performance, particularly in the first and third trials, by consistently recycling all three material types, suggesting a comprehensive material recovery configuration optimized for diverse waste streams. Structure 4 also performed well in the first trial but shifted to plastic-only in later trials, indicating adaptability but reduced diversity. Structures 5, 6, 7, 8, 9, and 10 showed selective recycling, often prioritizing plastic, which may reflect cost-driven decisions or limitations in waste input quality (e.g., insufficient paper or nylon content). The variability across trials suggests sensitivity to waste composition, equipment efficiency, or economic factors, with the first trial achieving the broadest material recovery across multiple structures. For maximizing recycled material production, Structure 3 in the third trial is recommended as the best trial, producing 233,293.00 t/y of nylon, 170,117.00 t/y of paper, and 305,061.00 t/y of plastic, offering a balanced and comprehensive recycling output, likely driven by an optimized material recovery facility that handles diverse waste inputs effectively.

Fertilizer Production

The P-graph analysis also evaluated the potential of fertilizer generation, the solid and liquid productions of the solution structures as represented in Table 6 below. A few structures repeated their production of solid fertilizer and liquid fertilizer over a number of trials, yet, in other cases, a few structures had zero production in some of the trials, a phenomenon indicative of the exclusion of fertilizers-producing technologies in those conditions.

Table 6. Liquid and Solid Fertilizer Produced Across the PNS Combinatorial

Solution Structure	**First Trial**		**Second Trial**		**Third Trial**		**Fourth Trial**	
	Solid Fertilizer [t/y]	**Liquid Fertilizer [t/y]**	**Solid Fertilizer [t/y]**	**Liquid Fertilizer [t/y]**	**Solid Fertilizer [t/y]**	**Liquid Fertilizer [t/y]**	**Solid Fertilizer [t/y]**	**Liquid Fertilizer [t/y]**
Structure1	105,177.00	157,765.00	105,177.00	157,765.00	105,177.00	157,765.00	105,177.00	157,765.00
Structure2	105,177.00	157,765.00	105,177.00	157,765.00	105,177.00	157,765.00	105,177.00	157,765.00
Structure3	0	0	105,177.00	157,765.00	105,177.00	157,765.00	105,177.00	157,765.00

Structure4	105,177.00	157,765.00	105,177.00	157,765.00	105,177.00	157,765.00	105,177.00	157,765.00
Structure5	105,177.00	157,765.00	105,177.00	157,765.00	105,177.00	157,765.00	105,177.00	157,765.00
Structure6	0	0	105,177.00	157,765.00	105,177.00	157,765.00	105,177.00	157,765.00
Structure7	0	0	105,177.00	157,765.00	105,177.00	157,765.00	105,177.00	157,765.00
Structure8	0	0	0	0	105,177.00	157,765.00	105,177.00	157,765.00
Structure9	0	0	105,177.00	157,765.00	105,177.00	157,765.00	0	0
Structure10	105,177.00	157,765.00	105,177.00	157,765.00	105,177.00	157,765.00	0	0

Table 6 shows consistent fertilizer outputs where present, with solid fertilizer at 105,177.00 t/y and liquid fertilizer at 157,765.00 t/y across most structures and trials, but notable absences (0 t/y) in certain cases, reflecting variability in technology selection or waste input suitability. In the first trial, Structures 1, 2, 4, 5, and 10 produced both solid (105,177.00 t/y) and liquid (157,765.00 t/y) fertilizers, likely due to a strong reliance on anaerobic digestion, which effectively converts food waste into nutrient-rich digestate (solid) and liquid byproducts suitable for agricultural use, while Structures 3, 6, 7, 8, and 9 produced none, suggesting configurations prioritizing pyrolysis, incineration, material recovery, or landfill, which do not generate fertilizers. The second trial saw an increase in fertilizer production, with Structures 1, 2, 3, 4, 5, 6, 7, 9, and 10 producing the standard outputs (105,177.00 t/y solid, 157,765.00 t/y liquid), indicating broader adoption of anaerobic digestion, possibly due to optimized food waste inputs or improved process efficiencies; Structure 8 remained at zero, likely continuing to focus on non-fertilizer-producing technologies. In the third trial, all structures except Structure 8 produced both fertilizers at the same levels (105,177.00 t/y solid, 157,765.00 t/y liquid), reflecting near-universal integration of anaerobic digestion, suggesting a trial configuration highly favorable to fertilizer production, possibly driven by abundant food waste or economic incentives for fertilizer markets. The fourth trial showed a slight decline, with Structures 1, 2, 3, 4, 5, 6, 7, and 8 producing both fertilizers (105,177.00 t/y solid, 157,765.00 t/y liquid), while Structures 9 and 10 dropped to zero, indicating a shift away from anaerobic digestion, perhaps due to changes in waste composition (e.g., reduced food waste) or prioritization of other outputs like bio-oil or energy. The consistent fertilizer outputs (105,177.00 t/y solid, 157,765.00 t/y liquid) across most structures and trials where present highlight the reliability of anaerobic digestion for converting food waste into valuable agricultural products, with the quantities suggesting a standardized process design optimized for digestate and liquid fertilizer yields. The zero outputs in Structures 3, 6, 7, 8, and 9 in the first trial, Structure 8 in the second trial, and Structures 9 and 10 in the fourth trial indicate configurations that either excluded anaerobic digestion or lacked sufficient organic waste inputs, possibly due to high plastic, nylon, or paper content better suited for pyrolysis or material recovery. Structure 8's persistent zero output in the First and second trials, only producing fertilizers in the third and fourth trials, suggests a gradual shift toward anaerobic digestion, possibly driven by trial-specific adjustments in waste allocation or equipment use. Structures 1, 2, 4, and 5 demonstrated the most consistent performance, producing fertilizers across all trials, indicating robust configurations that effectively integrated anaerobic digestion regardless of trial conditions. The third trial stands out for its near-universal fertilizer production (nine out of ten structures), reflecting an optimal balance of waste inputs and technology selection, likely prioritizing food waste processing through anaerobic digestion to maximize fertilizer yields.

CONCLUSION

The third trial stands as the most effective configuration, delivering an ideal balance of substantial economic gains, robust resource recovery, and controlled environmental impacts across various structures, positioning it as the foundation of this study's recommendations. Specifically, Structure 3 in the third trial excelled with consistent GHG emissions (39,441.30 t/y), high profits (133,350,000,000 Naira/y), comprehensive recycled material production (233,293.00 t/y nylon, 170,117.00 t/y paper, 305,061.00 t/y plastic), and reliable fertilizer outputs (105,177.00 t/y solid, 157,765.00 t/y liquid), reflecting an optimized integration of material recovery and anaerobic digestion, ideal for sustainable waste management in Lagos's context. Structure 1 in the third trial achieved the highest profit (139,885,000,000 Naira/y) but with higher emissions (45,820.70 t/y), leveraging pyrolysis and incineration, suitable for profit-driven scenarios with emission mitigation strategies like carbon capture. Structure 8 in the third trial led in energy production (363,698.00 MJ/y heat, 183,564.00 MWh/y electricity), and Structure 10 in the third trial maximized bio-oil output (324,486.00 t/y), highlighting the trial's versatility in supporting energy and biofuel markets. In contrast, the first trial's limited scope, with Structures 4 and 7 achieving zero emissions but lower profits (e.g., Structure 4: 106,894,000,000 Naira/y), prioritized low-emission technologies like material recovery and anaerobic digestion but lacked the economic and output diversity of the third trial. The second trial showed higher emissions (e.g., Structure 9: 78,292.50 t/y GHG) and inconsistent outputs, while the fourth trial, despite strong energy (Structure 2: 317,948.00 MJ/y heat, 165,353.00 MWh/y electricity) and bio-oil/biochar outputs (Structures 2, 6, 7, 10: 271,000.00 t/y bio-oil), saw reduced fertilizer production in Structures 9 and 10, indicating less comprehensive resource recovery. The third trial's superiority is evident in its near-universal fertilizer production (nine structures at 105,177.00 t/y solid, 157,765.00 t/y liquid), robust energy outputs across multiple structures, and balanced material recovery, driven by a strategic mix of operating units (Table 2: anaerobic digestion, multiple cogeneration units, pyrolysis, and material recovery) that effectively utilized Lagos's organic-rich waste stream for fertilizers and plastics for recycling and bio-oil. This trial's configurations minimized reliance on landfill, aligning with circular economy principles, and leveraged stakeholder familiarity with material recovery and incineration (Table 1) to ensure practical adoption. Structures 5, 6, 7, 8, 9, and 10 were less consistent, with Structures 8 and 9 showing intermittent outputs (e.g., zero fertilizers in early trials) and Structure 9's high emissions in the second trial, underscoring the third trial's reliability. The study's socio-economic assessment reinforced the third trial's alignment with local needs, as anaerobic digestion supports agricultural fertilizer demand, and material recovery addresses recycling market potential. These findings advance Sustainable Development Goals (SDGs) 7 (Affordable and Clean Energy), 11 (Sustainable Cities), 12 (Responsible Consumption and Production), and 13 (Climate Action) by transforming MSW into valuable resources. For optimal implementation, Structure 3 in the third trial is strongly recommended as the primary strategy, balancing high profits, comprehensive recycling, and fertilizer production with moderate emissions, achievable through investments in advanced sorting for quality waste inputs, optimized anaerobic digestion for organic waste, and targeted pyrolysis for plastics. Where environmental priorities dominate, Structure 4's first trial (zero emissions) remains a viable secondary option, though less economically competitive. Profit-focused stakeholders may consider Structure 1's third trial with emission controls. To ensure scalability, policymakers should support public-private partnerships, subsidies for low-emission technologies, and community engagement to address socio-cultural barriers, particularly in Lagos's informal sector. Further P-graph simulations should refine the third trial's configurations, optimizing waste input ratios, technology parameters (e.g., pyrolysis temperature, digestion retention time), and cost efficiencies, while life cycle assessments (LCAs) could quantify broader impacts like water and land use.

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