



## ENGINEERING-BASED APPROACHES TO INTEGRATED WASTE MANAGEMENT AND RESOURCE RECOVERY: A CASE STUDY OF SCHOOL ENVIRONMENTS

Eleke, C. N and Onuorah, O. E.

*Department of Civil Engineering Technology, Federal Polytechnic Oko,  
Anambra State, Nigeria*

*Corresponding author: chukwueleke@yahoo.com, 08130870401.*

### Abstract

Increased waste generation, especially in institutional environments such as universities, presents an urgent challenge for engineers and environmental scientists. This paper adopts an engineering perspective to analyze waste streams, characterize their physicochemical properties, and evaluate appropriate handling, treatment, and recovery processes. Emphasis is placed on the design and optimization of solid and liquid waste management systems, including recycling technologies, energy recovery pathways, and advanced treatment methodologies. The study examines the University of Nigeria, Nsukka (UNN), as a model academic environment, proposing a closed-loop system for sustainable resource utilization. Engineering strategies for material flow analysis, process integration, and life cycle assessment (LCA) are explored to inform sustainable waste handling.

**Keywords:** Waste management system, Recycling Technologies, Material Flow analysis, Closed-Loop system, Life cycle assessment (LCA).

### 1. Introduction

Waste generation is a byproduct of anthropogenic activity, and its accumulation in the absence of structured control mechanisms results in significant environmental degradation. In engineering terms, waste represents inefficiencies in process outputs, material use, and energy conversion. Engineering solutions to waste management therefore require systematic characterization, quantification, and design of infrastructure for treatment, recycling, or conversion.

In university settings, the variety and volume of waste are considerable due to academic, residential, and research activities. Solid wastes (plastics, paper, metals), liquid effluents (greywater, sewage), hazardous wastes (laboratory chemicals, biohazards), and e-waste all contribute to the waste footprint. This paper investigates engineering techniques for integrated waste management (IWM) and develops a recovery model suited to institutional environments.

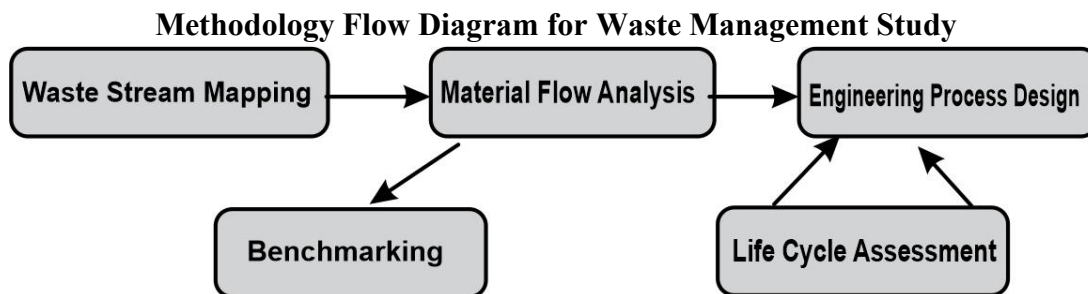
### 2. Methodology

The methodology integrates environmental systems engineering with empirical observation and qualitative analysis. The following approaches were used:

- **Waste Stream Mapping:** This involves the identification, categorization and spatial mapping of various types of waste generated at different functional units of the university,

such as hostels, laboratories, cafeterias and administrative blocks. It helps in understanding source load distributions and points of high waste concentration to inform targeted management strategies.

- **Material Flow Analysis (MFA):** This quantifies the flow of materials (solid, liquid and gaseous) from input to output within the university system. It involves developing flow diagrams and mass balance equations to track how waste is generated, transformed, stored and disposed. MFA is useful for pinpointing inefficiencies, leakages and recovery opportunities.
- **Engineering Process Design:** This step applies principles of chemical, civil and environmental engineering to conceptualize and specify technical units for waste treatment modules. Considerations include capacity, process efficiency, residence time, energy balance and automation.
- **Benchmarking:** Comparative analysis is conducted using national and international standards and best practices such as those from the USEPA, WHO and the Basel Convention. This allows for the evaluation of existing university waste practices against global metrics and the identification of performance gaps.
- **Life Cycle Assessment (LCA):** LCA is employed to evaluate the environmental impacts of waste management alternatives from cradle to grave. It accounts for inputs like energy and chemicals and outputs such as emissions and residues, allowing decisions-makers to select the most sustainable options. Key LCA indicators include carbon footprint, water footprint, and eutrophication potential. Environmental impact assessment of proposed solutions.



### 3. Waste Characterization and Classification

Waste Category	Examples	Source
Municipal Waste	Solid Food waste, paper, packaging	Dormitories, cafeterias, offices
Industrial Waste	Solid Scrap metals, oils, mechanical components	Workshops, laboratories
Construction/Demolition	Concrete, bricks, steel, wiring	Building sites, maintenance operations
Hazardous Waste	Solvents, acids, biological materials	Laboratories, hospitals
E-Waste	Computers, printers, cables	Offices, ICT centers
Liquid/Semi-Solid Waste	Greywater, blackwater, sludge	Restrooms, treatment plants

## 4. Engineering Solutions for Waste Treatment and Recovery

### 4.1 Processing Technologies by Waste Type

Waste Type	Mechanical/Thermal	Biological	Physicochemical
Organic Waste	Incineration, Pyrolysis	Composting, Anaerobic Digestion	-
Plastics	Shredding, Pelletizing	-	-
Paper	Baling, Re-pulping	-	-
Hazardous	Plasma Arc Gasification	-	AOPs, Membrane Filtration
Wastewater	-	Aerobic Treatment	Sedimentation, RO, Filtration
Glass/Metals	Crushing, Melting	-	-

## 5. Results and Discussion: Proposed Recovery Framework for UNN

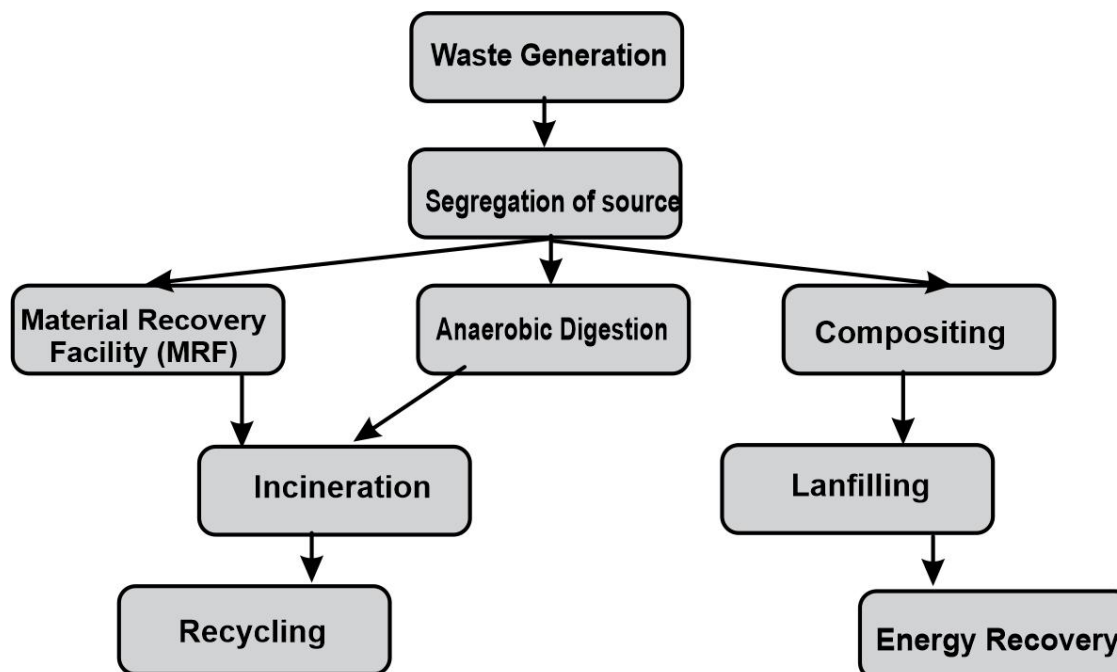
An integrated system is proposed involving:

- **Decentralized Sorting Facilities:** These are small-scale sorting stations located at major waste generation points across the campus, such as hostel, dining areas and academic buildings. They allow for the immediate segregation of waste into categories such as organics, recyclables and hazardous materials improving the efficiency of downstream processing.
- **Material Recovery Facilities (MRFs):** These centralized hubs receive pre-sorted or partially sorted waste and employ mechanical and manual techniques to further separate materials like plastics, metals and glass for recycling. MRFs are essential for maximizing resource recovery before waste is sent to treatment or disposal.
- **Anaerobic Digesters:** These systems biologically treat organic waste in oxygen-free environments to produce biogas (methane and CO<sub>2</sub>) and digestate. The biogas can be used to generate electricity or heat, while the digestate serves as a soil amendment. Locating digesters near high-organic waste zones like cafeterias enhances efficiency.
- **Wastewater Treatment Units:** Modular treatment units use physical, chemical and biological processes to treat greywater and blackwater generated on campus. These units often include sedimentation tanks, aeration chambers and tertiary treatment filters to meet discharge or reuse standard.
- **Renewable Energy Integration:** Solar panels and other renewables technologies can be used to power compactors, waste collection vehicles and treatment facilities. This reduces the carbon footprint of waste handling operations and supports a more sustainable self-sufficient waste management ecosystem. Solar-powered compaction and transport system.

### Projected Impact Table

Indicator	Current Baseline	After Implementation	Improvement (%)
Waste Diversion Rate	25%	65%	+160%
Carbon Emissions (tons/year)	100	60	-40%
Operational Waste Cost (₦/yr)	12,000,000	7,000,000	-41.7%
Energy Generated (kWh/yr)	0	45,000	N/A

### Integrated Waste Processing System Flowchart



## 6. Conclusion and Engineering Recommendations

Engineering disciplines offer robust tools for tackling waste challenges through innovation, process control, and systems design. In the context of academic environments, these strategies must integrate education, policy, and infrastructure. The UNN case model demonstrates that through localized recycling systems, energy recovery, and stakeholder engagement, universities can lead in circular economy adoption.

### Recommendations:

- Implement environmental audit and LCA as mandatory planning tools: Regular environmental audits and life cycle assessments (LCA) help institutions identify hotspots of inefficiency, pollution and resource misuse. Making these tools a part of the planning and budgeting process ensures that sustainability is embedded in the decision-making framework from the start.

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- Design and deploy sensor-equipped bins for real-time waste monitoring: Smart waste bins equipped with sensors can provide data on fill levels, waste composition and usage pattern. This allows for more efficient collection scheduling, reduces overflow and supports data-driven optimization of waste logistics.
- Establish partnerships with recycling industries for closed-loop logistics: Collaborating with recyclables, creating a circular system where waste materials are reintegrated into production cycles, thus minimizing raw material use and waste generation.
- Expand curricula to include waste engineering and environmental systems analysis: Embedding topics such as sustainable waste management, material recovery and environmental modeling into engineering and science curricula equips students with the tools and mindsets to innovate in the waste management space.
- Visualize data from waste processes using SCADA or IoT dashboards: Supervisory Control and Data Acquisition (SCADA) systems and IoT platforms enable real-time tracking and visualization of waste processing systems. These tools enhance operational transparency and allow for early failures or inefficiencies.

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