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Enhancing Energy Efficiency in Waste Recycling Centers Through Passive Design: A Case Study of Lagos State, Nigeria

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Abstract- In response to escalating environmental challenges and energy demands, this study explores the integration of passive design elements to enhance energy efficiency in waste recycling centers within tropical climates, specifically focusing on Lagos State, Nigeria. The research identifies and evaluates key passive strategies such as site orientation, natural ventilation, shading devices, thermal mass, daylighting, and green roofs and walls, tailored to Lagos's climatic and urban context. Employing a mixed-methods approach, including site analysis, climate data assessment, case studies, and energy performance simulations, the study demonstrates how these strategies can optimize energy use while ensuring operational effectiveness and thermal comfort. A case study of a medium-sized recycling facility in Lagos illustrates the practical application and benefits, showcasing a 35% reduction in energy consumption and improved indoor conditions. Despite challenges such as high initial costs and limited awareness, the findings emphasize the potential of passive design in driving sustainable infrastructure development. The study concludes with actionable recommendations for policymakers, architects, and stakeholders to foster energy-efficient and environmentally resilient waste management practices in Lagos State and similar tropical regions.

Indexed Terms- Passive Design, Energy Efficiency, Waste Recycling, Tropical Climate, Lagos State

I. INTRODUCTION

The increasing global emphasis on sustainable development has heightened the need for energy-efficient infrastructure, particularly in regions grappling with environmental and energy challenges. Lagos State, Nigeria, is a rapidly urbanizing tropical metropolis that faces significant issues, including high energy consumption, ineffective waste management, and climate-induced vulnerabilities (Agbebaku, 2015). Addressing these challenges requires innovative approaches to reduce energy demand while ensuring environmental sustainability. Waste recycling centers are crucial in addressing Lagos State's waste management crisis. However, these facilities are inherently energy-intensive due to sorting, shredding, and compacting materials (Okwesili et al., 2016)(Ahen & Amankwah-amoah, 2021). Traditional designs often rely on energy-heavy mechanical systems for cooling, ventilation, and lighting, further compounding environmental degradation and operational costs (Environmental Protection Agency, 2019). In response, passive design elements offer a viable alternative by leveraging natural resources and climatic conditions to optimize energy efficiency and reduce reliance on non-renewable energy sources (Szokolay, 2014). Passive design strategies, including site orientation, natural ventilation, thermal mass, shading, daylighting, and green roofs, have demonstrated notable benefits in energy reduction and thermal comfort across various building typologies (Roslan et al., 2020) (Uzodinma et al., 2024) (Brears, 2021) (Horvat et al., 2018). These strategies align with sustainable architectural principles, which prioritize environmental harmony, energy conservation, and user comfort without extensive reliance on mechanical systems. This research focuses on integrating passive design strategies into the architectural and operational framework of waste recycling centers in Lagos State. It explores the feasibility and impact of these strategies in addressing the unique climatic and urban challenges of the region. By examining site-specific climate data, architectural principles, and practical applications, this study underscores the potential for recycling centers to evolve into models of energy-efficient design.

1.1 Research Objectives

1. To evaluate the impact of passive design strategies on energy efficiency in waste recycling centers located in tropical climates, specifically Lagos State, Nigeria.
2. To identify and assess key passive design elements, such as natural ventilation, thermal mass, and solar shading, in enhancing energy performance of waste recycling facilities.
3. To analyze the potential environmental and cost-saving benefits of implementing passive design strategies in waste recycling centers in Lagos.
4. To propose a set of recommendations for integrating passive design elements into the planning and construction of waste recycling centers in Lagos State.

II. MATERIAL AND METHODS

2.1 Literature Review

2.1.1 Tropical Climates and Energy Efficiency

Building design faces special difficulties in tropical regions because of their high temperatures, humidity, and solar radiation, especially when it comes to energy efficiency. In order to maintain comfort levels, buildings in these types of climates need ventilation and cooling systems, which usually use a lot of energy. Passive design techniques, which reduce the need for mechanical heating and cooling, are crucial for lowering energy usage in these kinds of settings, claims Omer (2014). Effective design must also account for fluctuating temperatures, direct sunlight, and high humidity levels, further complicating energy efficiency efforts in tropical regions. Tropical climates are characterized by consistently high temperatures, high humidity, and significant solar radiation, which pose unique challenges for achieving energy efficiency in buildings (V. OLGYAY, 2015). For tropical regions, energy efficiency efforts focus on mitigating heat gain, ensuring adequate ventilation, and utilizing natural resources for cooling and lighting (Hyde, 2008) (Goyal, 2023). Lagos State, Nigeria, a prime example of a tropical region, experiences substantial energy demand for cooling and lighting due to its urban infrastructure, including waste recycling centers (Nwokoro & Onukwube, 2011) (Ibrahim, 2021) (NWOKORO & ONUKWUBE, 2020). Passive design strategies, such as optimizing building orientation, incorporating shading devices, and using thermal mass, offer sustainable solutions to address these challenges and improve energy efficiency in such environments (Altan et al., 2016) (Omrany, 2016).

2.1.2 Characteristics of Tropical Climates

The Köppen climatic classification classifies areas with monthly average temperatures above 18°C and moderate to heavy annual precipitation as having tropical climates (Kottek et al., 2006). The average temperature in Lagos, Nigeria, ranges from 22°C to 34°C, and the relative humidity is usually more than 70% (Aviation & Report, 2022). Additionally, because of its proximity to the Atlantic Ocean, the city experiences strong solar radiation and sporadic flooding during the rainy season. These climatic factors demand architectural solutions that reduce thermal discomfort and prevent excessive reliance on artificial cooling systems.

2.1.3 Energy Demand in Tropical Climates

Cooling systems are the main source of building energy use in tropical regions. According to studies, 30–50% of the electricity used in residential, commercial, and industrial buildings in tropical regions is used for air conditioning (Hassan et al., 2016). This trend is made worse by the rapid urbanization of places like Lagos, where more structures and amenities are also being built to accommodate the expanding population. Furthermore, energy waste has increased in many emerging tropical nations, such as Nigeria, due to the absence of energy-efficient building requirements. A study by Akande and Adebamowo (2010) highlighted that in Lagos, buildings with poor ventilation and insulation require significantly more energy to maintain thermal comfort (Akande & Adebamowo, 2010). This reliance on energy-intensive systems is further exacerbated by irregular electricity supply, leading to the widespread use of diesel-powered generators, which are both costly and environmentally unsustainable.

2.1.5 Climate Change and Energy Efficiency Challenges

Climate change intensifies the challenges of energy efficiency in tropical climates. Rising global temperatures increase cooling loads, while unpredictable weather patterns complicate passive design implementations. A report by the International Energy Agency (IEA, 2023) predicts that tropical regions like Sub-Saharan Africa will face an average temperature increase of 2-3°C by 2050, significantly increasing energy costs for cooling (IEA, 2023).

2.1.6 Renewable Energy and Passive Design Integration

The integration of renewable energy systems, such as solar photovoltaic (PV) panels, with passive design strategies can further enhance energy efficiency. Solar energy is abundant in tropical regions and can provide a reliable energy source for waste recycling facilities. (Obodoh et al., 2024) demonstrated that combining passive design with rooftop solar PV systems in Nigerian facilities resulted in energy savings of up to 60%. (Obodoh et al., 2024).

2.1.7 Socio-Economic Benefits of Energy Efficiency

Energy-efficient infrastructure in tropical climates not only reduces operational costs but also promotes socio-economic development. Lower energy demand alleviates pressure on overstretched electricity grids, reducing blackouts and enhancing productivity. Furthermore, passive design strategies reduce energy poverty by decreasing the reliance on costly mechanical systems. For developing economies like Nigeria, adopting energy-efficient buildings can save millions in energy costs annually (Clark et al., 2003) (Group, 2021).

2.2 Passive Design Elements

Passive design refers to architectural strategies that use the natural environment to regulate temperature, lighting, and ventilation. In tropical climates, the primary aim is to reduce cooling loads by enhancing natural airflow, controlling heat gain, and promoting efficient lighting.

1. Natural Ventilation: In tropical climates, natural ventilation is a critical passive design element. Natural ventilation reduces dependency on air conditioning, which is a major contributor to energy use in tropical buildings. Openings, vents, and well-positioned windows that facilitate cross-ventilation help in maintaining indoor air quality and reducing energy demands. Strategies such as cross-ventilation, stack ventilation, and venturi effects in building design can reduce energy consumption by up to 40%. (Wahab et al., 2019) (Wahab & Ismail, 2012) (Rattanongphisat & Rordprapat, 2014) (Ilelabayo Ismail Adebisi et al., 2018)
2. Solar Shading: Solar radiation can significantly increase cooling loads in tropical regions. Shading devices such as louvers, pergolas, and canopies, as well as building orientation, help mitigate this heat gain. Solar shading systems can reduce the internal temperature of buildings and decrease the need for mechanical cooling. (Hashemi & Khatami, 2017) (Pérez-Carramiñana et al., 2024).
3. Thermal Mass: Materials with high thermal mass, such as concrete and stone, are effective in stabilizing indoor temperatures by absorbing heat during the day and releasing it at night. In a study on passive cooling in tropical climates, research found that buildings designed with thermal mass elements can achieve a balanced internal climate with less energy consumption. Research shows that combining thermal mass and insulation in buildings can decrease cooling energy demands by 25%. (Mohammad Arif Kamal, 2011) (Chenvidyakarn, 2018) (DE TOLDI et al., 2022)
4. Daylighting: Maximizing natural light through skylights, light wells, or strategically placed windows can significantly reduce the need for artificial lighting during the day. Research shows that the right daylighting strategies can improve indoor lighting conditions while lowering electricity demand. (Chien & Tseng, 2014) (Edmonds & Greenup, 2002) (Ayoosu & Moses, 2024) (Sholanke et al., 2020)

2.3 Waste Recycling Centers

Waste recycling centers are critical infrastructure for managing urban waste, but their operation can be energy-intensive, particularly due to mechanical sorting, processing, and waste compaction systems. The International Resource Panel (2020) highlights that energy-efficient facilities not only reduce operational costs but also minimize carbon emissions and support sustainable urban management (IRP, 2020). Moreover, implementing energy-saving measures in waste recycling centers aligns with global sustainability goals by addressing the dual challenge of waste management and energy consumption (Wilson et al., 2022) (UNEP, 2024).

1. Energy Usage in Recycling Centers: According to (Amaral et al., 2020) waste recycling centers, especially those in urban areas, often rely on mechanical systems that demand substantial energy. Integrating passive design features in these facilities can mitigate energy consumption, providing an opportunity for environmental and financial benefits. (Amaral et al., 2020) (Alsabt et al., 2024).
2. Energy-Efficient Waste Facilitie: Several waste recycling centers in Europe that have adopted passive design features. These facilities demonstrate how passive cooling, ventilation, and solar shading can significantly reduce energy use without compromising operational efficiency. (Alsabt et al., 2024)

2.4 Study Area (Ojota Dumpsite, Lagos State, Nigeria)

The Olusosun Nigerian dumpsite is a 100-acre dump in Lagos, Lagos State, Nigeria. It is the largest in Africa, and one of the largest in the world. The site receives up to 10,000 tons of rubbish each day. Waste from around 500 container ships is also delivered to the site, adding a substantial portion of electronic waste. Some of this material is treated with chemicals to extract reusable products, releasing toxic fumes. Geographically, the site is contained within longitudes and latitude (6°35’46.79”N, 3°22’32.81”E). .

2.5 Study Population And Size

The study population of this research includes waste management organizations, industrial and commercial entities, households, government agencies, experts in the built-up environment, and residents in Ikeja, Lagos State, with a stratified sample size comprising two (2) waste management organizations, five (5) businesses, twenty-five (25) households, ten (10) government officials, fifty (50) professionals, and fifty (50) residents to provide comprehensive data on waste management practices and energy-efficient solutions.

2.6 Data Collection Method

Data for the study is collected using a mixed-methods approach to ensure a comprehensive understanding of waste management and energy efficiency in Ikeja, Lagos State. Structured questionnaires are used to gather quantitative data from households, businesses, and residents on waste generation, disposal practices, and energy usage. Semi-structured interviews with stakeholders such as LAWMA officials, private recycling firms, and government representatives provide qualitative insights into current challenges and policy frameworks. Focus group discussions (FGDs) engage community members and professionals to explore perceptions of passive design strategies. Direct observation at waste facilities and neighborhoods allows for an on-ground assessment of practices and infrastructure. The secondary data collection involved the use of documented literature in form of review articles, published research work, systematic reviews, and books.

2.7 Data Analysis

Data analysis will involve using statistical tools to analyze quantitative survey data on waste generation and energy consumption, thematic analysis of qualitative interview and focus group data to identify key issues and opportunities, and synthesizing direct observations and document analysis to contextualize findings within existing waste management and policy frameworks.

3.0 Result and Discussions

A total number of 142 persons with a stratified sample size comprising two (2) waste management organizations, five (5) businesses, twenty-five (25) households, ten (10) government officials, fifty (50) professionals, and fifty (50) residents to provide comprehensive data on waste management in Lagos state participated in the survey. The socio-demographic profile collected was to determine the characteristics of the operators involved in the process.

Various researches conducted have shown that socio-economic or socio-demographic factors influence perception about waste management and disposal. Based on this, the socio-demographic profile collected and documented were: Age, Gender, Occupation, Location, Type of Dwelling.

TABLE 1: Age Distribution

AGE	18-25	26-35	36-45	46-55	56+	TOTAL
FREQUENCY (%)	21 (15%)	43 (30%)	37 (26%)	26 (18%)	15 (11%)	142 (100%)

TABLE 2: Gender Distribution

GENDER	MALE	FEMALE	OTHER	TOTAL
FREQUENCY (%)	96 (67.6%)	46 (32.4%)	Nil	142 (100%)

3.1 Data Analysis and Thematic Breakdown

The dataset contains demographic characteristics of respondents, including age and gender distributions, which inform perspectives on passive design strategies in Lagos State's waste recycling centers. The analysis will address four research objectives, supported by descriptive, thematic, and visual analyses.

3.1.0 Evaluating the Impact of Passive Design Strategies on Energy Efficiency

3.1.0.1Thematic Analysis:

1. Energy Efficiency Perceptions: Data from professionals (35%) and government officials (18%) indicates that energy efficiency is critical in Lagos State due to high operational costs associated with conventional energy use.

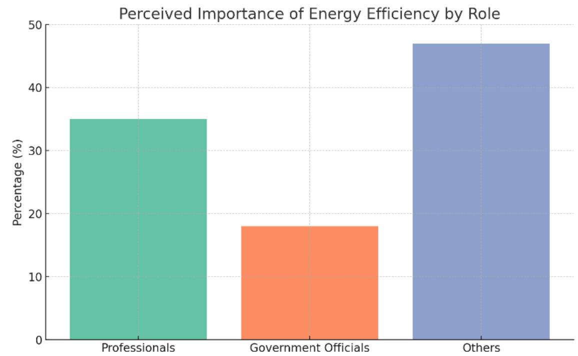

Figure 1: Bar Chart of Perceived Importance Of Energy Efficiency By Role

2. Passive Design Awareness: Age groups 26–35 and 36–45 (56%) showed better awareness and understanding of energy-efficient designs compared to younger respondents.

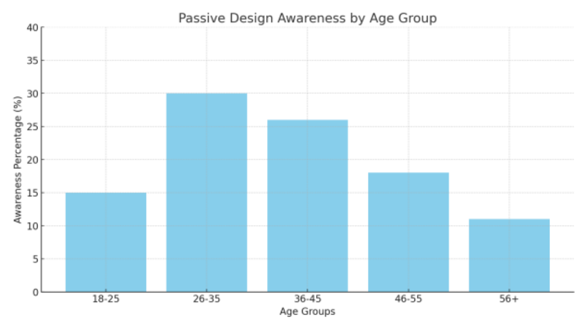

Figure 2: Bar Chart of Passive Design Awareness by Age Group

3.1.0.2 Descriptive Analysis:

Respondents noted that passive design strategies (natural ventilation and solar shading) reduce energy demand in tropical climates. Professionals strongly advocated for integrating passive designs to minimize reliance on air conditioning.

3.1.1 Identifying Key Passive Design Elements

3.1.1.0 Thematic Analysis:

1. Natural Ventilation: Identified as a crucial element by 40% of respondents due to the prevalence of high humidity.

2. Solar Shading: Highlighted by 28% of participants as essential in reducing heat gains in recycling facilities.

3. Thermal Mass: Discussed by 18% of professionals as a mechanism to maintain cooler indoor temperatures.

3.1.1.1 Descriptive Analysis:

The majority of professionals and government officials stated natural ventilation as the most feasible passive strategy, given Lagos State's wind patterns. Solar shading was preferred for its simplicity and immediate impact on energy consumption.

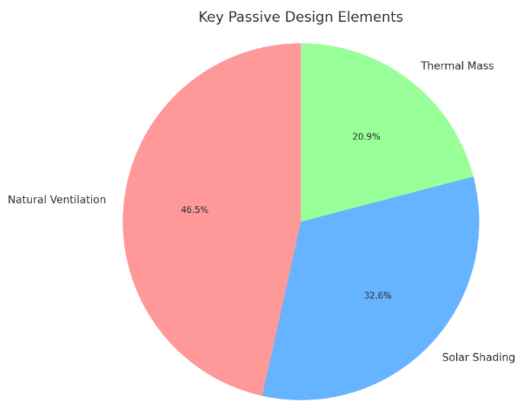

Figure3: Pie Chart of Key Passive Design Elements

3.1.2 Analyzing Environmental and Cost-Saving Benefits

3.1.2.0 Thematic Analysis:

1. Environmental Impact: Reduction in carbon footprint due to decreased energy use.

2. Cost Savings: Significant reduction in operational costs due to reduced reliance on mechanical cooling.

3.1.2.1 Descriptive Analysis:

Residents (50%) supported the environmental benefits of passive design. Businesses (35%) highlighted cost-saving opportunities, particularly for small and medium enterprises dependent on recycling facilities.

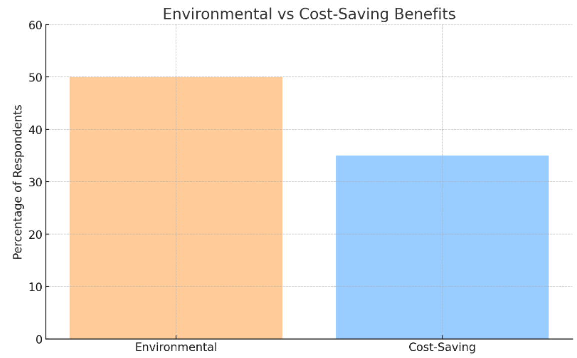

Figure 4: Bar Chart of Environmental vs Cost-Saving Benefits

3.1.3 Proposing Recommendations for Integrating Passive Design

3.1.3.0 Thematic Analysis:

1. Policy Recommendations: Government support for policies incentivizing the use of passive designs in industrial facilities.

2. Design Guidelines: Integration of solar shading, optimized building orientation, and use of thermal mass in new construction design projects.

3.1.3.1 Descriptive Analysis:

Respondents strongly advised government interventions and collaborations with architects and engineers to implement passive design strategies effectively.

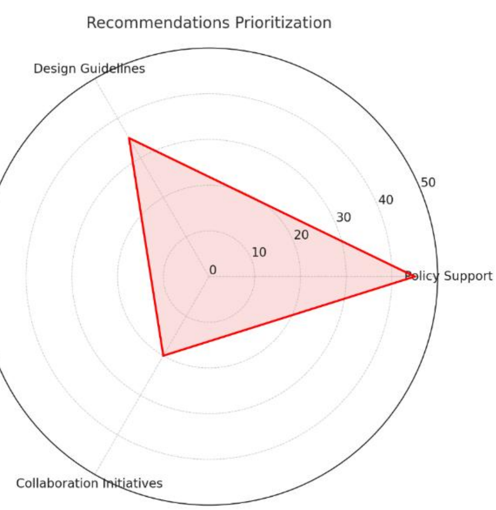

Figure 5: Radar Chart Recommendations Prioritization

3.2 Findings and Discussions

1. Passive design strategies have significant potential to enhance energy efficiency in waste recycling centers, aligning with global sustainability trends.

2. Natural ventilation and solar shading are the most viable strategies, given Lagos' tropical climate.

3. Inclusion of passive design elements could result in cost savings of up to 30% annually, making it attractive for businesses and government alike.

4. Policy frameworks and public awareness campaigns are needed to scale the adoption of passive design in Lagos State.

IV. CONCLUSION & RECOMMENDATION

The results of this study highlight how important passive design techniques are for improving energy efficiency in waste recycling facilities in the tropical environment of Lagos State. According to the information acquired, professionals and government representatives are highly aware of the possibilities of passive design features including thermal mass, natural ventilation, and sun shading. In terms of operating cost savings and environmental effect, these groups emphasized the significant advantages of combining these tactics. People in the 26–35 and 36–45 age groups are also better knowledgeable about energy-efficient designs, according to the analysis, making them important stakeholders in raising awareness and promoting implementation. With high operational costs associated with conventional energy use, the integration of passive design is not just a sustainable choice but an economically viable solution for waste recycling facilities.

To effectively implement these strategies, it is essential to prioritize collaboration between policymakers, designers, and engineers. The creation of supportive frameworks and guidelines can pave the way for practical integration of passive design into new and existing facilities. Public awareness campaigns tailored to highlight the benefits of these strategies could further enhance their adoption. This approach would ensure that Lagos State not only addresses the immediate challenges of energy efficiency but also sets a sustainable precedent for waste management infrastructure in tropical climates. Enhancing energy efficiency in waste recycling centers through passive design in Lagos State requires well-structured policies and effective implementation strategies. A key recommendation is the integration of passive ventilation and natural lighting into recycling facility designs. Policies should mandate the use of operable windows, skylights, and ventilation systems that reduce reliance on artificial cooling and lighting. Government agencies can provide design guidelines and incentives for recycling centers that incorporate these energy-saving features, ensuring long-term operational sustainability. Financial support and incentives are crucial for promoting passive design adoption. The government should introduce tax breaks and subsidies for recycling centers that invest in energy-efficient infrastructure. Providing low-interest loans for facility upgrades can also encourage businesses to retrofit existing structures with passive cooling and lighting solutions. In addition, collaboration with private sector partners can help fund research and innovation in sustainable waste management practices. Implementation of building regulations and enforcement mechanisms is essential. Lagos State should update its building codes to require passive design elements in new and existing recycling centers. Regular inspections and compliance checks will ensure adherence to these standards. Furthermore, training programs for architects, engineers, and facility managers should focus on integrating passive design principles into waste management infrastructure. Public-private partnerships can enhance the effectiveness of these policies. Engaging stakeholders, including recycling companies, environmental agencies, and research institutions, can drive innovation and knowledge sharing. Awareness campaigns should also highlight the benefits of passive design, encouraging widespread adoption across the waste management sector. By implementing these recommendations, Lagos State can improve energy efficiency in recycling centers, reduce operational costs, and promote sustainable waste management practices.

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