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Greening Nigeria's Cities: A Case Study on Renewable Energy in Sustainable Urban Development

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ABSTRACT

This study examines how renewable energy can be used in sustainable building projects in three major Nigerian cities: Lagos, Abuja, and Port Harcourt. It looks at the potential of solar panels (PV systems), wind energy, and converting biomass waste into energy to reduce both energy use and greenhouse gas emissions. To gather insights, the research involved interviews, site visits, and computer simulations using energy modelling software. The analysis included cost-benefit studies, sensitivity checks, and life cycle assessments to measure both economic and environmental outcomes. Results show that solar PV systems are the most efficient, cutting energy use by 25% to 35% and paying for themselves in 6 to 8 years. Biomass energy showed good potential in industrial areas, while wind energy is less common due to high upfront costs and slower returns. The study highlights key challenges such as high starting costs, limited technical skills, and weak enforcement of energy policies. To overcome these barriers, the paper suggests increasing financial support, strengthening policy implementation, investing in local skills development, and encouraging public-private partnerships to promote the use of renewable energy in Nigerian cities.

1. INTRODUCTION

The construction sector plays a major role in climate change, contributing around 39% of energy-related carbon dioxide emissions globally [1]. As climate concerns grow, the push for sustainable building practices has intensified. These practices aim to reduce resource use and environmental harm throughout a building's life span. A key part of this effort is adding renewable energy (RE) solutions to building designs, which helps cut down on fossil fuel use and supports long-term energy efficiency [2]. Technologies such as solar power, wind energy, biomass, and small-scale hydropower can help buildings lower their carbon emissions while providing more stable and cleaner energy sources.

In Nigeria, finding sustainable energy solutions is especially urgent. Cities like Lagos, Abuja, and Port Harcourt are expanding rapidly, which puts more pressure on already struggling energy systems. The national power grid is often unreliable and inefficient, leading many homes and businesses to depend on diesel generators that are both costly and polluting [3]. This energy gap affects economic progress and worsens environmental problems. Using renewable energy in urban building projects can help ease these challenges. However, despite Nigeria's rich solar and wind resources, renewable energy use in construction remains limited due to financial, technical, and policy issues [4].

Nigeria is also facing serious environmental threats due to climate change. Rising temperatures, irregular rainfall, and extreme weather are becoming more common, which increases the need for cooling in cities and raises energy demand [5]. At the same time, the country's heavy reliance on fossil fuels has made it one of the largest greenhouse gas emitters in sub-Saharan Africa, contributing to poor air quality and global warming [6]. Shifting urban energy systems toward renewables is therefore crucial for reducing emissions and improving environmental sustainability.

From an economic point of view, the impact of unreliable energy is also significant. Frequent power outages cost Nigeria an estimated $28 billion every year in lost productivity [7]. High electricity costs and unstable supply hurt both households and businesses. Renewable energy provides a promising alternative—it can lower energy expenses over time, reduce dependence on the national grid, and open up new economic opportunities. For example, investing in solar panel production and wind energy installation could create jobs and support urban economic growth [8].

This study focuses on the need to expand the use of renewable energy in sustainable building projects across Nigeria's urban centers. It explores how technologies like solar, wind, and biomass are currently being used, how effective they are in cutting energy use and emissions, and the main barriers to their wider adoption. The study also looks at the broader social and economic benefits of renewable energy and offers practical recommendations for overcoming existing challenges.

2. LITERATURE REVIEW

Understanding Sustainable Buildings and Renewable Energy

Sustainable buildings, also known as green buildings, aim to reduce their environmental impact across their entire life cycle. They focus on improving energy and water efficiency, reducing waste, and using environmentally friendly materials [9]. One critical strategy for achieving these goals is the integration of renewable energy (RE) solutions—energy generated from naturally replenished sources such as sunlight, wind, biomass, and hydropower [10].

The combination of sustainable building practices with renewable energy offers major benefits, including long-term cost savings, lower carbon emissions, and improved energy security [11]. Since buildings are responsible for about 28% of global energy-related CO_2 emissions, technologies such as solar PV panels, wind turbines, and biomass heating systems are increasingly being used to cut emissions and promote clean energy in the built environment [12]. In addition, renewable systems allow for decentralized energy generation, easing the burden on national grids and enhancing resilience during outages [13].

Global Practices and Emerging Trends

Around the world, countries are prioritizing renewable energy in buildings to meet climate targets and transition to low-carbon economies. In the European Union, the Energy Performance of Buildings Directive (EPBD) has driven adoption by requiring all new buildings to be nearly zero-energy by 2021 [14]. Germany's "Energiewende" policy is a leading example, combining financial incentives with strong policy support to expand solar PV usage in both residential and commercial buildings. By 2020, over 40% of energy used in Germany's building sector came from renewable sources [15, 16].

In the United States, programs like the LEED certification and federal tax incentives have encouraged renewable energy use in buildings. States with high solar potential, such as California and Texas, have embraced these technologies. In California, for example, solar energy accounted for nearly 25% of the electricity used in new homes as of 2022, reflecting a major shift toward clean energy integration in the housing sector [17, 18].

Developing countries have progressed more slowly due to financial, technical, and regulatory challenges [19]. However, India has made significant strides with rooftop solar installations supported by the National Solar Mission, targeting 40 GW of rooftop capacity by 2022 [20]. Similarly, South Africa's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) has helped promote large-scale renewable energy projects, although the adoption of RE at the building level remains limited [21].

Sustainable Building in Developing Countries

In many developing nations, sustainable building practices are gaining attention as a way to tackle energy shortages and the environmental impact of rapid urbanization. These countries face unique pressures, such as population growth, limited infrastructure, and energy supply gaps, which make clean, efficient urban development critical [22]. In Nigeria, urban expansion is driving up electricity demand, placing additional strain on an already unreliable national grid [23].

Despite these challenges, progress has been made elsewhere on the continent. Kenya has implemented a policy requiring solar water heating systems in new buildings, which has significantly boosted the use of solar technologies in cities [24]. Rwanda has taken steps to encourage energy-efficient construction and the use of renewables, especially in its rapidly growing capital, Kigali [25]. These examples demonstrate that with the right policies and support, sustainable building and renewable energy integration are achievable in African urban centers.

Nigeria has strong renewable energy potential, especially in solar and biomass. The country receives an average of 5.5 kWh/m^2 of solar radiation daily, making solar PV systems highly viable for urban energy needs [26]. In addition, the large volume of agricultural waste generated across Nigeria could serve as a valuable source of biomass energy [27]. However, this potential has not yet been fully tapped due to a range of barriers that are discussed further in this study.

Renewable Energy Options for Nigerian Cities

Several renewable energy technologies are suitable for use in Nigerian urban buildings, each with its own strengths and limitations. Solar power stands out as the most practical solution, thanks to Nigeria's abundant sunlight. Solar photovoltaic (PV) systems can be easily installed on rooftops and used for both residential and commercial electricity generation. The falling cost of PV technology has improved affordability, although the initial investment still presents a hurdle for many property developers [28]. Recent advances in battery storage technology have made solar power more reliable by allowing energy to be stored for use during low-sunlight periods, which is especially valuable for urban energy users [29].

Wind energy has seen limited adoption in Nigeria because average wind speeds are generally low. However, some coastal and northern regions have shown promise for small-scale wind energy development. Wind turbines could be used in combination with solar systems in such areas, though their use remains constrained by geographic and climatic factors [30].

Biomass energy, derived from organic materials such as agricultural waste and animal manure, offers another renewable option. It can be used for electricity, heating, and cooking. In urban settings, biomass energy could be incorporated into building designs through systems like biogas digesters and biomass boilers. Nonetheless, logistical issues—such as the difficulty of collecting and transporting feedstock—have limited its widespread use in cities [31].

Small-scale hydropower also presents opportunities, especially in areas with access to rivers or flowing water. These systems can provide a stable power source for certain communities. However, hydropower is better suited to rural locations than dense urban areas, where space and water access are limited [32].

Barriers to Renewable Energy Adoption in Nigeria

The slow adoption of renewable energy in Nigerian cities is largely due to several financial, technical, and regulatory challenges. One of the biggest obstacles is the high upfront cost of installing systems like solar PV. Although these technologies are becoming cheaper globally, the capital investment required remains unaffordable for many Nigerian developers and property owners, especially in lower-income areas [33]. Moreover, limited access to credit and the absence of low-interest loans have made it difficult to finance renewable projects. Many banks and financial institutions view these projects as risky, which discourages investment [34].

Technical constraints also hinder progress. There is a notable shortage of trained technicians capable of installing and maintaining renewable systems, particularly for complex technologies like solar PV and wind turbines [35]. This shortage drives up costs and reduces the long-term sustainability of installations. Additionally, most renewable components are imported, as Nigeria has little domestic manufacturing capacity for solar panels or wind turbines. This reliance on imports raises costs and causes delays in project delivery [36].

From a policy perspective, Nigeria has introduced various strategies to encourage renewable energy adoption, including the Renewable Energy Master Plan and the National Renewable Energy and Energy Efficiency Policy. However, enforcement remains weak, and bureaucratic inefficiencies have slowed implementation. Developers also lack strong incentives, such as tax breaks or subsidies, that would make RE adoption more attractive and financially viable [37].

Policy Landscape and Recommendations

Nigeria's policy framework has taken steps to promote renewable energy in buildings, but results have been mixed. The Renewable Energy Master Plan (REMP), led by the Energy Commission of Nigeria, aims to expand the country's renewable energy capacity to 13,000 MW by 2030 [38]. The National Renewable Energy and Energy Efficiency Policy (NREEEP) also supports the use of renewable systems and energy-saving materials in new construction projects [39]. However, both policies have struggled with enforcement, and without incentives, their real-world impact has been limited.

To improve adoption, several recommendations have been proposed. These include introducing tax relief and subsidies for renewable projects, building partnerships between the public and private sectors to fund installations, and investing in local training programs to grow technical expertise [40]. Implementing these measures could help overcome the current financial and technical barriers and move Nigeria closer to a more sustainable, energy-efficient urban future.

3. RESEARCH METHODOLOGY

Case Study Design and Site Selection

This research adopted a case study approach to examine how renewable energy is being integrated into sustainable building projects in Nigeria. This method was chosen because it allows for in-depth analysis of complex, real-world issues in specific contexts [41]. The study focused on three major urban centers—Lagos, Abuja, and Port Harcourt—selected for their rapid urban growth, high energy needs, and renewable energy potential. Lagos, Nigeria's commercial hub, has intense energy consumption and an urgent need for energy alternatives. Abuja, the capital, is undergoing major infrastructure development, making it an ideal setting for studying sustainable urban planning. Port Harcourt, the core of the oil and gas industry, was included to examine renewable integration in an industrialized urban environment [42].

Geographical and climatic conditions were also factored into the selection. Lagos, located on the coast, receives high solar radiation and has offshore wind energy potential. Abuja, situated centrally, benefits from consistent solar radiation and access to biomass from agricultural activity. Port Harcourt, despite its high humidity, also shows solar potential. These varied conditions provided a solid basis for comparing renewable energy solutions across different urban settings [43].

Data Collection

A mixed-methods approach was used to gather both primary and secondary data on renewable energy integration. Primary data came from 30 semi-structured interviews conducted across the three cities. Interviewees included architects, engineers, urban planners, developers, and government officials involved in renewable energy and sustainable urban development. These interviews explored their experience with renewable technologies, perceived challenges, and opinions on scalability and feasibility [44].

Site visits to selected buildings with renewable energy systems were also conducted to gather direct observations and technical data, including system performance and maintenance practices. Secondary data were sourced from official policy documents, academic publications, and government reports, such as the Nigerian Renewable Energy Master Plan (REMP) and the National Renewable Energy and Energy Efficiency Policy (NREEEP) [45].

Data Analysis

Qualitative data from the interviews were analyzed using thematic analysis to identify recurring issues related to the adoption of renewable energy in buildings. This method was suitable for uncovering stakeholder perspectives on policy, financial, and technical challenges [46]. NVivo software was used to code and categorize the interview transcripts, making it easier to extract key themes [47].

For quantitative analysis, energy performance simulations were conducted using EnergyPlus software. This tool modeled energy use in buildings with and without renewable energy systems under the specific climatic conditions of Lagos, Abuja, and Port Harcourt. The simulations assessed energy savings (in kWh), reductions in greenhouse gas (GHG) emissions (in metric tons of CO_2), and potential cost savings from reduced utility bills [48].

Financial and Environmental Impact Analysis

To assess the financial feasibility of integrating renewable systems, a cost-benefit analysis (CBA) was conducted. This analysis calculated the net present value (NPV) and internal rate of return (IRR) for various technologies, including solar PV, biomass digesters, and wind turbines. Projections were made over a 20-year lifespan, factoring in installation costs, savings from reduced grid use, and long-term maintenance expenses [49].

A sensitivity analysis was carried out to test how changes in factors such as equipment costs or energy prices would affect financial outcomes. This helped to assess the robustness of investment returns under different policy or market conditions [50]. A break-even analysis was also included to determine how long it would take for building owners to recover their initial investment in each renewable energy system [51].

Environmental impacts were assessed through a life cycle assessment (LCA), which measured emissions and energy use from the manufacturing, installation, operation, and end-of-life phases of renewable energy systems. Key indicators included energy payback periods and total GHG reductions over the life span of each system [52]. This provided a comprehensive view of both financial and ecological benefits.

Study Limitations

Despite its comprehensive approach, the study faced several limitations. Relying on interviews as a primary data source introduced the risk of bias, as responses were based on personal opinions and experiences. To improve validity, these findings were cross-verified with secondary sources, including official reports and technical literature [53]. Site visits were informative, but their limited number meant that results may not be fully generalizable to all renewable projects in the selected cities.

Financial estimates in the CBA were based on projections and similar international case studies due to the lack of detailed financial records for local projects. While these references helped fill data gaps, they may not fully reflect the Nigerian market context. Likewise, the simulations used to estimate energy savings and GHG reductions were based on standard performance models and may not capture real-world deviations caused by local maintenance practices, system degradation, or user behavior [54].

Future research should focus on gathering long-term operational data from renewable energy projects currently in use across Nigerian cities. This would improve the accuracy of financial and environmental evaluations. As technologies and policies continue to evolve, ongoing monitoring will be crucial for understanding how renewable energy can more effectively support sustainable urban development in Nigeria.

4. RESULTS AND DISCUSSION

Energy Landscape of Selected Urban Centers

The three cities studied—Lagos, Abuja, and Port Harcourt—show different patterns in energy demand, renewable energy potential, and urban development. Lagos, as Nigeria's economic center, consumes about 40% of the country's total electricity [55]. Due to this high demand, solar energy has proven to be the most practical renewable option for both homes and businesses. With an average solar radiation of 5.5 kWh/m^2/day, Lagos is well-suited for rooftop solar PV installations, which can generate significant energy savings.

Abuja, the nation's capital, is expanding quickly, especially in terms of residential construction. As energy needs grow, government incentives have encouraged the adoption of solar PV systems, particularly in new housing estates. This has positioned Abuja as one of the leading cities in Nigeria for integrating solar energy into urban development [56].

Port Harcourt, heavily reliant on the oil and gas sector, often experiences power outages despite being an energy-producing city. While fossil fuels still dominate, interest in alternative energy is increasing. Biomass waste-to-energy systems have shown promising results in industrial settings, while residential use of solar energy is gradually expanding [57].

Adoption of Renewable Energy in Buildings

Although still in the early stages, the use of renewable energy technologies in buildings is increasing across all three cities, with solar PV systems being the most commonly used. In Lagos, many commercial buildings have adopted rooftop solar PV systems to reduce their dependence on diesel generators. One example is a commercial facility that saved approximately 45,000 kWh of electricity in one year—cutting its use of grid power by 25% [58].

In Abuja, solar PV systems have become more common in residential communities. Some housing estates have reported annual energy savings of up to 35,000 kWh, with overall electricity usage reduced by about 30% [59].

Port Harcourt has also made progress. A municipal facility in the city implemented a waste-to-energy system that converts organic waste into biogas for electricity generation. This project has reduced its grid electricity use by 20%, producing about 10,000 kWh annually [60]. While solar use is growing in homes, high installation costs continue to slow its widespread adoption.

Summary of Case Study Results

The case studies (Figure 1) revealed varying levels of success in adopting renewable technologies across the three cities. In Lagos, a large commercial solar PV project led to a 25% drop in grid electricity use, with yearly savings of 45,000 kWh. Abuja's example of a hybrid solar-diesel residential system reduced reliance on the grid by 30%, saving about 35,000 kWh annually [61]. In Port Harcourt, a biomass waste-to-energy system used in a public facility generated 10,000 kWh per year and cut grid energy usage by 20%, highlighting the viability of biomass energy in industrial and institutional settings [62].

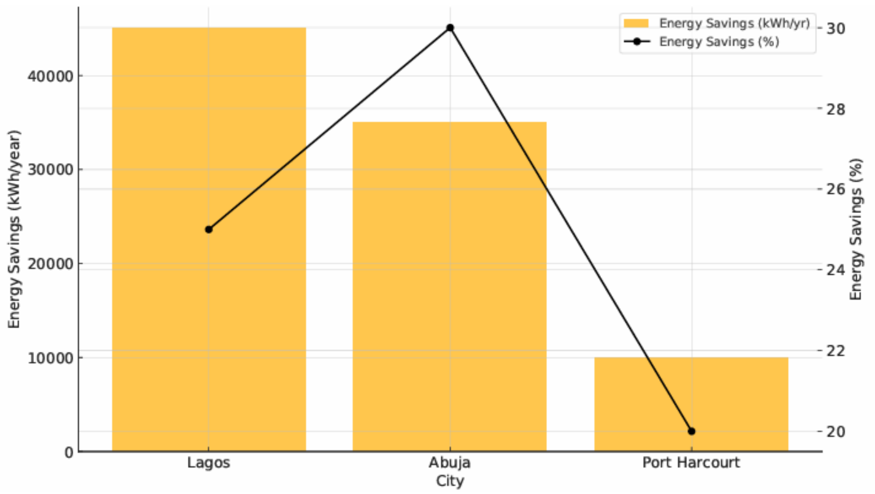

Figure 1. Annual Energy Savings by Renewable Energy Solutions in Nigerian Urban Centers

The study shows that solar PV systems offer the highest energy savings among the renewable technologies evaluated, particularly in Lagos and Abuja. In Lagos, commercial solar PV installations achieved annual savings of 45,000 kWh (25%), while in Abuja, residential estates saved 35,000 kWh (30%) annually. In contrast, Port Harcourt's waste-to-energy system, though promising, yielded a more modest 10,000 kWh per year, reducing grid reliance by 20%. Lagos and Abuja outperformed Port Harcourt due to stronger solar adoption, higher energy demands, and more supportive infrastructure. Both cities benefit from strong solar radiation, but Port Harcourt's coastal climate—with higher humidity and cloud cover—reduces solar efficiency. Moreover, renewable energy projects in Lagos and Abuja are often better funded, supported by government incentives, and located in buildings with larger rooftop space or higher daily energy consumption.

Comparing Lagos and Abuja, Lagos recorded higher total energy savings due to large-scale commercial use, while Abuja achieved a higher percentage reduction because of efficient hybrid systems in residential estates. These results are based on direct observations from site visits, stakeholder interviews, and data modelling. They are further supported by policy reports such as the Renewable Energy Master Plan and NREEEP. Overall, Lagos and Abuja are leading in solar integration, while Port Harcourt shows early potential for industrial-scale biomass applications.

Comparative Analysis of Renewable Energy Technologies

A comparative analysis was conducted (see Table 1) to assess how solar PV, wind energy, and biomass technologies perform in terms of energy savings, cost-effectiveness, and environmental benefits. Among these, solar photovoltaic (PV) systems delivered the highest energy savings in all three cities, with reductions ranging from 25% to 35%. These results varied depending on the size and efficiency of each installation. Wind energy showed some promise, particularly in areas with stronger wind conditions—such as coastal regions near Lagos and parts of northern Nigeria. Projects in these locations achieved energy savings between 15% and 20%. However, the adoption of wind energy remains low due to its high initial costs and the need for advanced technical equipment and maintenance expertise [59].

Biomass energy, particularly through waste-to-energy systems, also demonstrated strong potential. In Port Harcourt, such systems provided moderate energy savings of 20% to 30%, but their greatest impact was environmental. By converting organic waste into biogas, these systems significantly reduced greenhouse gas emissions, making them a valuable option for industrial and public infrastructure applications [63].

Figure 2 presents a comparative analysis of estimated annual energy savings from three renewable energy technologies—solar photovoltaic (PV), wind energy, and biomass—across the three case study cities: Lagos, Abuja, and Port Harcourt. The values, expressed in kilowatt-hours per year (kWh/yr), are based on actual case study data, supported by secondary estimates derived from system performance benchmarks, stakeholder interviews, and site observations.

Lagos demonstrated the highest energy savings from solar PV systems, with an estimated 45,000 kWh/yr. This figure is based on a commercial-scale installation that achieved a 25% reduction in grid electricity consumption [58]. Wind energy savings in Lagos were estimated at 30,000 kWh/yr, reflecting potential capacity in coastal regions with moderate wind speeds [59]. Biomass systems, though less prevalent, were estimated to provide annual savings of approximately 20,000 kWh, assuming moderate adoption in industrial zones where organic waste is readily available [63].

In Abuja, solar PV also led in energy savings with an estimated 35,000 kWh/yr. This value is drawn from housing estates that have integrated solar PV systems into their infrastructure, achieving a 30% reduction in electricity use [59]. Wind energy was estimated to contribute 25,000 kWh/yr, based on regional wind resource availability and projected system efficiency [59]. Biomass systems, supported by agricultural activity surrounding the city, were estimated to provide savings of 15,000 kWh/yr, though large-scale implementation remains limited.

Port Harcourt, with its industrial profile and reliance on fossil fuels, showed lower but noteworthy levels of renewable energy adoption. A municipal waste-to-energy facility accounted for approximately 10,000 kWh/yr in energy savings, demonstrating the environmental and energy potential of biomass in public infrastructure [60], [62]. Solar PV and wind systems were estimated to contribute 10,000 kWh and 15,000 kWh annually, respectively, based on current residential use patterns and geographic feasibility.

These figures highlight the dominance of solar PV systems in urban energy strategies, with consistent performance and broader adoption across all three cities. Wind energy remains underutilized due to its higher upfront costs and infrastructure requirements, though its potential is evident in Lagos and Abuja. Biomass offers significant environmental benefits, particularly through waste repurposing, though logistical and policy challenges have limited its scale.

Energy Savings and Environmental Benefits

Simulations carried out using EnergyPlus software revealed significant energy and environmental gains from integrating renewable energy into buildings in Nigerian cities. In Lagos, a commercial building fitted with a solar PV system reduced its yearly energy use by 25%, which amounted to savings of around 50,000 kWh. This energy reduction also led to a decrease of approximately 50 tons of carbon dioxide emissions annually, demonstrating the strong environmental advantage of solar power [64].

In Abuja, residential estates using hybrid systems that combine solar and diesel power achieved a 30% cut in their reliance on the national grid. These systems saved about 35,000 kWh of energy per year and reduced carbon emissions by 35 tons annually [61]. Port Harcourt's waste-to-energy project also showed measurable benefits. By converting organic waste into biogas for electricity, the system reduced grid electricity use by 20%, generating 10,000 kWh annually. This resulted in an estimated reduction of 20 tons of carbon dioxide emissions per year [62].

Figure 3 illustrates that solar energy contributed the highest CO_2 emissions reductions in Lagos and Abuja, underscoring its strong environmental benefits in these cities. Lagos and Abuja benefit from high solar radiation levels, widespread adoption of rooftop PV systems, and supportive government policies. These factors have enabled solar installations to perform efficiently, with systems in both cities achieving substantial annual CO_2 reductions—45 tons in Lagos and 35 tons in Abuja. The energy payback period for solar PV systems in these regions is also favourable, ranging between two and three years, which enhances their overall sustainability and environmental impact [65, 66].

Table 1. Comparative Analysis of Renewable Energy Solutions in Nigerian Urban Centers

Renewable Energy Source	Energy Savings (%)	Capital Cost (USD/kW)	Payback Period (Years)	GHG Emissions Reduction (tons of CO_2/year)
Solar Photovoltaic (PV)	25 – 35	1,200 – 1,800	6 – 8	50 – 70
Wind Energy (Small-scale)	15 – 20	2,000 – 2,500	10 – 12	30 – 50
Biomass (Waste-to-Energy)	20 – 30	1,800 – 2,200	8 – 10	40 – 60

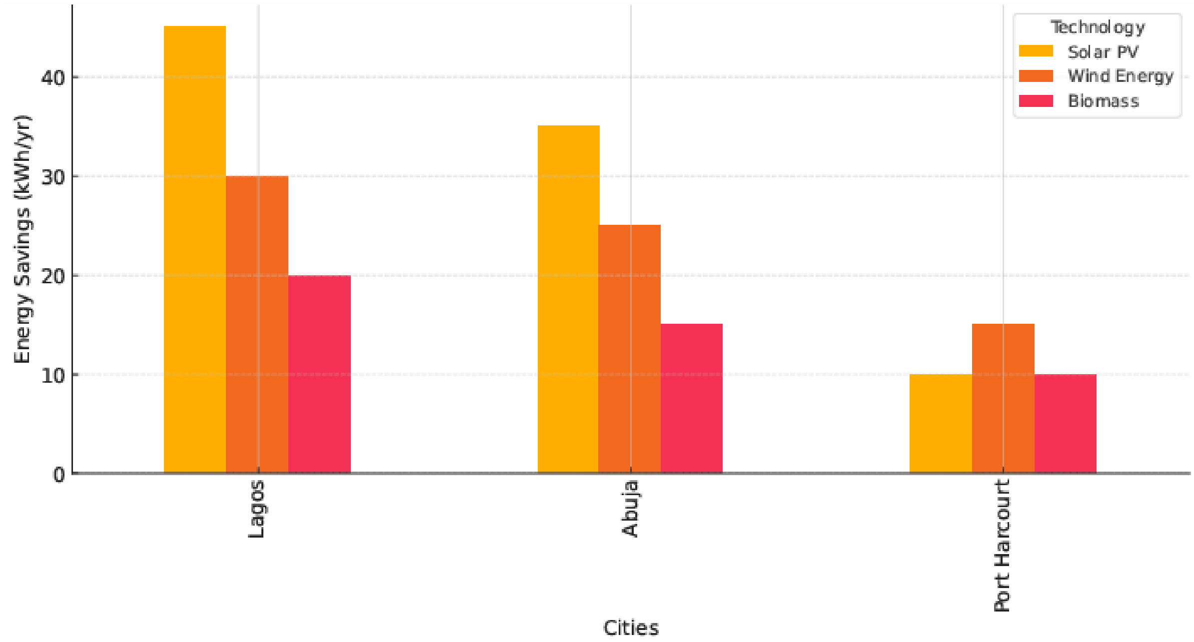

Figure 2. Energy Savings by Renewable Energy Technology in Lagos, Abuja, and Port Harcourt

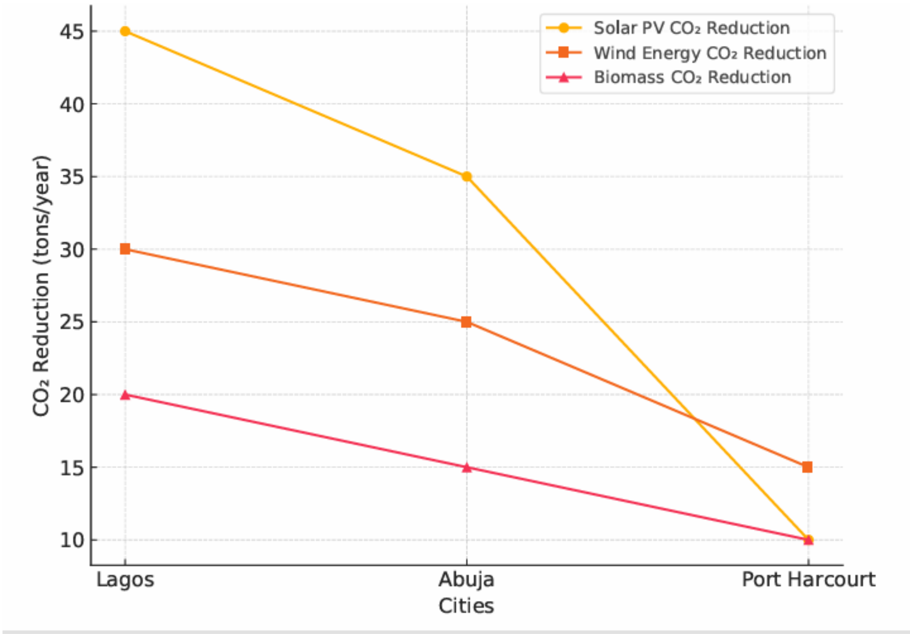

Figure 3. Annual CO_2 Emissions Reductions from Renewable Energy Solutions

In contrast, solar energy in Port Harcourt resulted in lower emissions reductions, with only 10 tons of CO_2 saved annually. This outcome is due to several local challenges. The city's humid, cloudy climate reduces solar panel efficiency, and its energy landscape is dominated by fossil fuel-driven industrial activities, where solar integration remains limited. Additionally, there is less policy support and infrastructure development for solar adoption compared to Lagos and Abuja. Interestingly, biomass waste-to-energy systems in Port Harcourt proved more effective than solar in emissions reduction, particularly in industrial and public facilities. These systems help mitigate methane emissions from organic waste, contributing to a notable 20-ton CO_2 reduction annually despite offering lower direct energy savings [66]. This highlights the importance of selecting renewable solutions that align with each city's environmental conditions, energy demand profile, and resource availability.

Cost-Benefit Analysis (CBA)

The cost-benefit analysis (CBA), as shown in Table 2, evaluated the financial viability of different renewable energy systems by comparing their installation costs with long-term savings from reduced electricity bills and lower dependence on the national grid. In Lagos and Abuja, solar photovoltaic (PV) systems showed a positive net present value (NPV) and a payback period of 6 to 8 years, confirming that they are economically viable. These results are consistent with global trends, where solar PV systems have shown competitive financial performance in similar urban environments [66, 67].

In Port Harcourt, biomass-based waste-to-energy systems also returned a positive NPV with a slightly longer payback period of 8 to 10 years. This is largely due to the availability of low-cost organic waste and the added environmental benefit of reducing methane emissions from landfills. On the other hand, small-scale wind energy systems were found to be less financially appealing. With a payback period of 10 to 12 years and higher capital costs, they produced a neutral NPV. These findings suggest that wind energy projects in Nigeria would require policy incentives or subsidies to become economically attractive [68].

These findings highlight that solar PV and biomass are the most financially viable renewable energy options for Nigeria's urban buildings. Meanwhile, wind energy remains less competitive without additional financial support. Similar studies in other developing countries have drawn the same conclusion, reinforcing the importance of government policies to improve the investment outlook for wind technologies [69].

Sensitivity Analysis

A sensitivity analysis was carried out to examine how changes in key variables—such as equipment costs and government subsidies—affect the financial viability of renewable energy investments. The aim was to assess how resilient each technology is under shifting economic or policy conditions. The results are presented in Table 3. In Lagos and Abuja, solar PV systems remained financially viable even with a 10% rise in equipment costs. This resilience is largely due to the ongoing global decline in the cost of solar technology, which helps offset minor increases in local installation expenses [70].

By contrast, wind energy systems were found to be much more vulnerable to cost changes. A 10% increase in equipment costs or a 10% reduction in government subsidies had a significant negative impact on the financial returns of wind projects. This suggests that wind energy in Nigeria is highly dependent on policy support, including subsidies and incentives, to remain financially attractive. Biomass waste-to-energy systems showed moderate sensitivity. Their financial performance is closely tied to the cost and availability of organic waste materials. While a 10% increase in equipment costs had little impact, a reduction in subsidies or a 15% increase in fuel-related logistics costs affected their viability more noticeably.

Overall, the analysis confirms that solar PV systems are the most financially robust, even when facing moderate increases in costs or changes in subsidies. Wind energy, however, is highly sensitive to such changes, underlining the importance of sustained government support to make it a competitive option in Nigeria [71].

Life Cycle Assessment (LCA)

This section evaluates the long-term environmental impact of three key renewable energy technologies—solar PV, wind energy, and biomass—through a Life Cycle Assessment (LCA). The LCA tracks each system's energy use and emissions from production and installation to operation and decommissioning. The analysis focuses on two main indicators: the Energy Payback Period (EPP) and annual reductions in greenhouse gas (GHG) emissions [72].

The Energy Payback Period (EPP) measures how long it takes a system to generate the same amount of energy that was consumed during its production and installation. It is calculated as:

$$EPP = \frac{\text{Total Energy Used for Production}}{\text{Annual Energy Output}} \quad (1)$$

a. Solar PV systems showed the shortest EPP, ranging from 2 to 3 years. With about 6,000 kWh/kW needed for production and annual outputs of 2,500–3,000 kWh/kW in Nigerian cities, solar PV becomes energy-positive quickly.
b. Wind energy systems had an EPP of 5 to 6 years. With higher embodied energy (around 10,000–12,000 kWh/kW) and moderate output (~2,000 kWh/year), they take longer to offset their production energy.
c. Biomass systems had a payback period of 4 to 5 years, depending on how efficiently the feedstock is collected and processed.
d. GHG savings were calculated by comparing renewable generation to the emissions from grid electricity, using a Nigerian grid emission factor of 0.7 kg CO_2 per kWh. The formula used is:
e. GHG Reduction (tons CO_2/year) = (Annual Output × 0.7) / 1,000
f. Solar PV systems showed the highest reductions, achieving 50–70 tons of CO_2 savings per year for systems around 30 kW capacity.
g. Biomass waste-to-energy systems followed, reducing 40–60 tons annually by displacing fossil fuel energy and avoiding methane emissions from waste.
h. Wind energy systems reduced 30–50 tons of CO_2 annually depending on wind availability and location.

Among the three technologies, solar PV systems are the most environmentally efficient (Table 4). They provide the fastest energy payback and the greatest annual GHG reductions. Biomass systems offer strong environmental benefits by transforming organic waste into clean energy while offsetting methane emissions. Wind energy, while clean, has a longer payback period and is more site-dependent. These findings highlight the value of choosing technology based on both economic and environmental performance in urban planning [72, 73].

Table 2. Cost-Benefit Analysis for Renewable Energy Solutions

Renewable Energy Source	Capital Cost (USD/kW)	Payback Period (Years)	Net Present Value (NPV)
Solar Photovoltaic (PV)	1,200 – 1,800	6 – 8	Positive
Wind Energy (Small-scale)	2,000 – 2,500	10 – 12	Neutral
Biomass (Waste-to-Energy)	1,800 – 2,200	8 – 10	Positive

Table 3. Sensitivity Analysis – Impact of Variable Changes on Financial Viability

Variable	Solar PV	Wind Energy	Biomass
10% increase in equipment costs	Moderate	Significant	Low
10% decrease in government subsidy	Moderate	Significant	Moderate
15% increase in fuel costs	Low	Low	Moderate

Table 4. Life Cycle Assessment (LCA) of Renewable Energy Solutions

Renewable Energy Source	Energy Payback Period (Years)	GHG Emissions Reduction (tons CO_2/year)
Solar Photovoltaic (PV)	2 – 3	50 – 70
Wind Energy (Small-scale)	5 – 6	30 – 50
Biomass (Waste-to-Energy)	4 – 5	40 – 60

Challenges Identified

Despite the promising outcomes of renewable energy projects in Nigerian cities, several challenges still limit widespread adoption. The biggest barrier is the high upfront cost of installing systems, especially for wind and biomass technologies. Without government subsidies or financial support, these costs remain unaffordable for many homeowners and developers. Another issue is the lack of skilled local labor. Many installations require foreign technical support, which increases costs and slows down project delivery [74].

Furthermore, inconsistent enforcement of renewable energy policies, combined with the limited availability of financial incentives—such as tax breaks or subsidies—discourages private sector investment. While Nigeria has introduced renewable energy policies, weak enforcement and lack of clear implementation strategies continue to hinder progress [75].

Discussion

This section interprets the study's findings on energy savings, cost-effectiveness, environmental impacts, and policy gaps. It also compares the results with global literature and offers insight into the practical challenges and opportunities for scaling renewable energy solutions in Nigeria's urban buildings.

Energy Savings and Environmental Impact

Solar PV systems were the most effective in reducing electricity consumption, delivering savings of 25% to 35% across both residential and commercial buildings. These figures are consistent with global studies on solar PV, especially in regions with strong solar radiation like Nigeria [76, 77]. Energy savings in Lagos and Abuja were comparable to projects in other sub-Saharan African countries, where similar systems report savings between 20% and 35% depending on the building type [78].

In terms of environmental impact, solar PV systems provided the highest reduction in greenhouse gas (GHG) emissions—50 to 70 tons of CO_2 annually per building. These outcomes match international findings that highlight solar energy as a leading solution for reducing urban carbon footprints [79]. The biomass waste-to-energy system in Port Harcourt also showed strong environmental benefits, cutting emissions by 40 to 60 tons of CO_2 annually. These systems help manage organic waste while also reducing methane emissions, which are especially harmful to the climate [80].

Life cycle assessments (LCA) confirmed solar PV's environmental advantages, with energy payback periods of just 2 to 3 years. In comparison, wind and biomass systems had longer payback periods of 4 to 6 years, making solar more appealing in terms of both energy and emissions performance [81].

Financial Viability of Renewable Systems

The cost-benefit analysis (CBA) highlighted solar PV as the most financially viable option. Projects in Lagos and Abuja showed a positive net present value (NPV) and a 6–8 year payback period. These findings are consistent with global trends where declining solar technology costs and favorable climate conditions have made solar PV cost-competitive [82, 83].

Biomass waste-to-energy systems also proved financially viable, with an 8–10 year payback period. This was largely due to the low cost of feedstock and income from electricity generation. These results support previous studies showing that biomass systems work well in regions with abundant organic waste [84].

In contrast, wind energy systems faced financial hurdles. Their payback periods were longer—10 to 12 years—due to higher capital costs and less favorable wind conditions in many Nigerian cities. Without financial support, these systems are not competitive compared to solar or biomass [85, 86].

Sensitivity to Costs and the Importance of Policy

Sensitivity analysis revealed that solar PV systems remained financially sound even when equipment costs increased by 10%. This shows the robustness of solar investments, especially in sun-rich regions like Nigeria [85]. However, wind energy projects were highly sensitive to cost changes and depended heavily on policy incentives to remain viable. Without strong government support, wind energy remains a risky investment [86].

Biomass systems showed moderate sensitivity to fluctuations in feedstock supply and cost. Their success depends on stable waste collection systems and steady energy demand, particularly from industrial users. In places like Port Harcourt—where waste disposal is a major issue—biomass offers an effective solution but requires coordination between stakeholders [87].

Overall, the analysis shows that strong policy support is essential for renewable energy adoption. Without financial incentives—such as subsidies, tax relief, or low-interest loans—costlier technologies like wind and biomass are unlikely to scale [88]. The success of solar PV systems across Nigeria demonstrates the impact well-designed policies and incentives can have on accelerating renewable energy deployment [84].

Key Barriers and Opportunities for Scale-Up

Several obstacles continue to restrict renewable energy growth in Nigeria's cities. High capital costs remain a major challenge, especially for wind and biomass systems. Even though solar PV has become more affordable, many small businesses and households still cannot afford the upfront costs without financing options [78, 82, 89].

Another key challenge is the lack of technical skills within Nigeria. Complex systems often rely on foreign technicians, which raises costs and slows adoption. Building a local workforce through technical education and vocational training is essential for lowering project costs and scaling the industry [89].

Policy enforcement is also a major gap. Although Nigeria has solid renewable energy frameworks—such as the Renewable Energy Master Plan (REMP) and the National Renewable Energy and Energy Efficiency Policy (NREEEP)—poor enforcement has weakened their impact. Research from other developing countries also shows that policy inconsistency is a major barrier to renewable energy adoption [86, 90].

Policy Implications and Recommendations

Nigeria's current renewable energy policies—particularly the Renewable Energy Master Plan (REMP) and the National Renewable Energy and Energy Efficiency Policy (NREEEP)—outline ambitious targets for solar, wind, biomass, and hydropower adoption. However, weak enforcement and lack of local adaptation have limited their effectiveness [90]. Policy implementation varies by city: Lagos benefits from local solar initiatives, Abuja has gained from federal housing solar programs, while Port Harcourt lags due to industrial fossil fuel dominance and minimal incentive application.

To accelerate renewable energy adoption across urban centers, the following targeted recommendations are proposed:

a. Expand Financial Incentives: Government-backed subsidies, tax reliefs, and low-interest loans should be scaled up to address high upfront costs. Tailored incentives should support rooftop solar in Lagos, residential solar in Abuja, and biomass installations in Port Harcourt's industrial zones. This approach mirrors effective models from India and South Africa where incentives drove market growth [90].
b. Strengthen and Localize Policy Enforcement: Existing policies must be made legally enforceable and context-sensitive. In Lagos, local building codes should require renewable integration in commercial structures. Abuja can introduce mandatory energy standards for new residential estates, while Port Harcourt should link biomass adoption to environmental compliance for industries [91].
c. Build Local Technical Capacity: Investments in technical training will reduce reliance on foreign expertise [89]. In Lagos, training should focus on PV systems and battery storage; in Abuja, on off-grid and hybrid systems; and in Port Harcourt, on biomass energy for waste-to-power applications. Public-private partnerships, as demonstrated in Kenya and Ethiopia, can support curriculum development and workforce training [92, 93].
d. Promote Public-Private Partnerships (PPPs): PPPs can mobilize capital and expertise for urban energy projects. In Lagos, this can include solar for public institutions; in Abuja, hybrid systems for government and housing developments; and in Port Harcourt, biomass solutions for industrial parks. Frameworks similar to South Africa's REIPPPP can help de-risk investments [94].

In sum, while solar PV is already proving viable in Nigeria's urban centers, scaling up renewable energy adoption—especially for wind and biomass—requires strong, localized policy support, financial mechanisms, technical capacity building, and collaboration between the public and private sectors.

5. CONCLUSION

This study has shown the strong potential of renewable energy solutions—particularly solar photovoltaic (PV) systems—for addressing the rising energy demands in Nigeria's urban centers: Lagos, Abuja, and Port Harcourt. Among the technologies assessed, solar PV emerged as the most effective, offering energy savings of 25% to 35% and a relatively short payback period of 6 to 8 years. These systems reduce reliance on the national grid while delivering environmental benefits, including annual greenhouse gas (GHG) emissions reductions of 50 to 70 tons of CO_2.

Biomass waste-to-energy systems also demonstrated promise, especially in industrial contexts, achieving energy savings of up to 20% and contributing to emission reductions. However, wind energy remains the least viable option due to its high capital cost and extended payback period, making it less attractive without government support.

The cost-benefit analysis confirmed the financial viability of solar PV and biomass systems for urban buildings, while the sensitivity analysis revealed that solar PV maintains strong financial performance even under fluctuating equipment costs and shifting policy conditions. Wind energy, by contrast, proved highly sensitive to such variables, underscoring the need for targeted subsidies and policy incentives to improve its feasibility. Life cycle assessment results further emphasized the environmental advantages of solar PV, with short energy payback times and substantial long-term emissions reductions.

Despite these positive findings, several challenges continue to slow the adoption of renewable energy in Nigeria. Chief among these are high upfront costs—especially for wind and biomass—alongside a shortage of skilled local professionals, which increases the cost of installation and system maintenance. Inconsistent policy enforcement and a lack of robust financial incentives further limit the expansion of renewable energy technologies.

To address these barriers, this study recommends a range of strategic policy actions. First, the Nigerian government should enhance financial incentives, including subsidies, tax relief, and low-interest loans, to encourage private sector investment. Second, better enforcement of existing renewable energy policies, such as the Renewable Energy Master Plan (REMP) and the National Renewable Energy and Energy Efficiency Policy (NREEEP), is essential to establish a stable and supportive regulatory environment. Third, investment in technical training and education programs is critical to build local capacity and reduce dependence on foreign expertise. Finally, fostering public-private partnerships (PPPs) can help mobilize funding and accelerate the implementation of renewable energy projects at scale.

Overall, the integration of renewable energy technologies into Nigeria's urban buildings presents a powerful opportunity to cut energy costs, improve energy security, and reduce environmental impacts. With the right mix of policy support, financial tools, and capacity-building initiatives, renewable energy can serve as a cornerstone of sustainable urban development in Nigeria. Future research should focus on gathering real-time performance data from active projects and exploring hybrid systems that combine solar, wind, and biomass to meet the diverse energy needs of urban areas.

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Retrofit Kolom Beton Bertulang Menggunakan *Concrete* dan *Steel Jacketing* untuk Mengatasi *Soft Story Building*

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ABSTRAK

Ketidakberaturan struktur akibat tuntutan arsitektur, seperti perbedaan tinggi lantai yang signifikan, dapat menimbulkan kondisi *soft story* (ketidakberaturan vertikal tipe 1a) yang berisiko menyebabkan kegagalan pada kolom. Penelitian ini bertujuan untuk mengevaluasi efektivitas metode *retrofit* kolom dalam mengatasi kondisi *soft story*. Tiga model dianalisis: (1) model eksisting dengan *soft story* pada lantai 1, (2) model 1 yaitu model eksisting dengan *soft story* pada lantai 1 dengan *retrofit concrete jacketing*, dan (3) model 2 adalah model eksisting dengan *soft story* pada lantai 1 dengan *retrofit steel jacketing*. *Retrofit* diterapkan pada kolom sisi terluar lantai 1, dengan analisis menggunakan metode respons spektrum pada sistem struktur Rangka Pemikul Momen Khusus (SRPMK). Hasil analisis menunjukkan peningkatan kekakuan tingkat sebesar 26,12% pada model 1 dan 11,95% pada model 2, yang berhasil menghilangkan kondisi *soft story*. Selain itu, terjadi peningkatan kapasitas kolom yang ditunjukkan oleh penurunan nilai *Demand to Capacity (D/C) Ratio* masing-masing sebesar 4,11% dan 6,75%, serta peningkatan kapasitas aksial dan momen sebesar 58,58% dan 78,43% pada model 1, serta 273,11% dan 65,27% pada model 2.

1. PENDAHULUAN

Dalam proses perancangan gedung, terdapat beberapa aspek yang perlu diperhatikan, salah satunya adalah ketidakberaturan dalam arah horizontal dan vertikal. Salah satu bentuk ketidakberaturan vertikal adalah ketidakberaturan tingkat lunak, yang dikenal sebagai *soft story*.

Ketidakberaturan vertikal tingkat lunak, *soft story*, dapat terjadi pada bangunan yang memiliki salah satu lantai dengan perbedaan ketinggian signifikan dibandingkan lantai lainnya. Kondisi ini dapat ditemukan pada lantai dasar bangunan maupun lantai lainnya. *Soft story* didefinisikan sebagai lantai yang memiliki kekakuan atau daktilitas yang tidak memadai dalam menahan beban seismik. Dampak dari *soft story* pada suatu bangunan menjadi signifikan apabila bangunan tersebut menerima beban lateral yang besar, seperti beban gempa. Fenomena *soft story* bila terjadi pada lantai dasar bangunan, yang berarti bahwa apabila kolom pada lantai dasar mengalami kegagalan, maka bangunan dapat mengalami keruntuhan total dan tidak dapat digunakan kembali [1].

Pada tanggal 25 April 2015, terjadi gempa dengan magnitude 7.8 SR di Kathmandu, Nepal yang menyebabkan keruntuhan gedung akibat kondisi *soft story* di lantai dasar [2] seperti pada Gambar 1 dan pada tanggal 12 Mei 2008, terjadi gempa dengan magnitude 7.9 SR di Wenchuan, China. Di Dujiangyan terjadi kegagalan kolom akibat kondisi *soft story* pada lantai dasar [3] ditunjukkan di Gambar 2.

Retrofit kolom adalah perkuatan atau perbaikan elemen kolom dalam suatu struktur bangunan untuk meningkatkan kapasitasnya. Metode yang umum digunakan dalam perkuatan kolom, adalah *Concrete Jacketing* dan *Steel Jacketing*. Perkuatan menggunakan *Concrete Jacketing* dilakukan dengan menambahkan lapisan beton baru pada elemen eksisting, sehingga meningkatkan dimensi dan kapasitas struktur. Sedangkan *Steel Jacketing* dilakukan dengan menambahkan pelat baja atau profil *angle* pada elemen *eksisting* untuk meningkatkan kekuatan dan kekakuan [4-5]. Kedua metode perkuatan ini memiliki karakteristik dan efektivitas yang berbeda.

Gambar 1. Keruntuhan Gedung Dengan Kondisi *soft story* akibat gempa Nepal [2]

Gambar 2. Kondisi *soft story* pada lantai dasar di Dujiangyan [3]

2. TINJAUAN PUSTAKA

Kajian Literatur

Struktur dengan ketidakberaturan tingkat lunak (*soft story*) memiliki risiko kegagalan struktural yang lebih tinggi akibat beban lateral, seperti gempa bumi. Bangunan dengan konfigurasi *soft story* cenderung mengalami deformasi lateral yang signifikan, sehingga meningkatkan potensi kegagalan struktur. Berbagai studi yang telah dilakukan untuk mengurangi atau mengatasi efek dari *soft story*, antara lain melalui penggunaan elemen *bracing*, penambahan dinding pengisi, serta pemanfaatan material dengan karakteristik berbeda [6–10].

Untuk meningkatkan ketahanan struktur terhadap beban lateral, berbagai metode *retrofit* telah dikembangkan. Salah satunya adalah penambahan *voute* segitiga pada sambungan kolom-balok serta penggunaan material beton resin poliester sebagai penguat [11–12]. Studi lain yang dilakukan oleh Islam [13] mengevaluasi efektivitas penggunaan balok tarik dan teknik *jacketing* pada kolom dalam meningkatkan kapasitas struktur terhadap beban lateral dan vertikal. Hasil studi tersebut menunjukkan bahwa metode tersebut secara signifikan dapat mengurangi deformasi serta meningkatkan stabilitas bangunan, terutama pada struktur dengan elemen kolom yang memiliki tingkat kelangsingan tinggi. Selain itu, metode *retrofit* menggunakan *Carbon Fiber Reinforced Polymer (CFRP) wrapping* yang dikombinasikan dengan penambahan *bracing* juga telah diteliti. Hasil studi menunjukkan adanya peningkatan kekuatan struktural yang signifikan, perubahan *mode shape*, serta penurunan *drift ratio* sehingga memenuhi kriteria desain seismik [14].

Matiyas et al. [15] menyajikan tinjauan komprehensif mengenai berbagai teknik analisis dan metode *retrofit* yang diterapkan pada struktur bertingkat dengan *soft story*. Metode-metode tersebut mencakup penggunaan elemen struktural seperti baja dan beton, penambahan dinding geser, *bracing*, serta perangkat disipasi energi, yang secara umum menunjukkan hasil yang menjanjikan dalam meningkatkan performa seismik bangunan. Selanjutnya, Manos et al. [16] meneliti kerentanan bangunan beton bertulang bertingkat dengan *soft story* di lantai dasar terhadap beban gempa. Mereka mengevaluasi skema *retrofit* yang melibatkan penambahan dinding pengisi beton bertulang pada lantai dasar, yang dikombinasikan dengan *concrete jacketing* pada elemen rangka sekitarnya. Hasil penelitian menunjukkan peningkatan yang signifikan pada kekakuan, kekuatan, serta kapasitas disipasi energi plastis struktur.

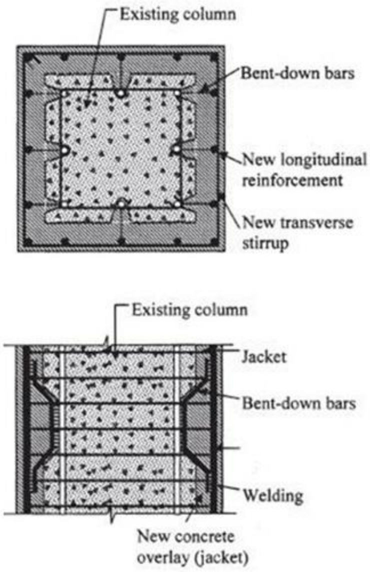
Berdasarkan tinjauan literatur yang telah dilakukan, belum ditemukan studi yang secara langsung membandingkan penerapan *concrete jacketing* dan *steel jacketing* pada struktur *soft story* dalam kondisi yang sama. Perbedaan utama dalam studi ini adalah tidak digunakannya elemen tambahan seperti dinding pengisi atau perangkat disipasi energi lainnya. *Retrofit* difokuskan hanya pada elemen kolom, dengan dua metode yaitu *concrete jacketing* dan *steel jacketing*.

***Retrofitting* Struktur Bangunan**

Retrofitting pada struktur bangunan umumnya diklasifikasikan menjadi dua jenis, yaitu *retrofitting* lokal dan *retrofitting* global. *Retrofitting* lokal dilakukan pada elemen struktur tertentu yang tidak mampu menahan beban atau gaya gempa sesuai dengan ketentuan. Metode ini bersifat terbatas pada area yang mengalami kelemahan struktural, seperti dengan penambahan tulangan lentur atau teknik *jacketing* pada kolom menggunakan material seperti beton, baja, atau *Fiber Reinforced Polymer* (FRP). Sedangkan *retrofitting* global bertujuan untuk meningkatkan kekuatan dan kinerja struktur secara keseluruhan. Contoh penerapan *retrofitting* global meliputi pemasangan *shear wall*, *infill wall*, *base isolation*, dan sistem *bracing* [4, 14].

Concrete jacketing

Concrete jacketing merupakan salah satu metode perkuatan dengan menambahkan lapisan beton yang baru serta tulangan tambahan pada elemen struktur eksisting. Tujuan utama metode ini adalah meningkatkan kapasitas daya dukung, daktilitas, serta ketahanan terhadap beban gempa[4].



Gambar 3. *Concrete Jacketing* [4]

Berdasarkan standar [4],

a. Luas beton dan luas tulangan yang dibutuhkan untuk *jacketing* :

$$Ac = (3/2)Ac' \quad (1)$$

$$As = (4/3)As' \quad (2)$$

dengan Ac dan As menunjukkan luas beton dan luas tulangan yang diperlukan pada *jacketing* sedangkan Ac' dan As' menunjukkan luas beton dan luas tulangan eksisting.

b. Spasi kait pada *jacketing* :

$$s = \frac{f_y}{\sqrt{f_c'}} \frac{d_h^2}{t_j} \quad (3)$$

dengan s menunjukkan spasi kait, f_y menunjukkan tegangan leleh tulangan, f_c' menunjukkan kuat tekan beton, d_h menunjukkan diameter sengkang dan t_j menunjukkan ketebalan *jacketing*.

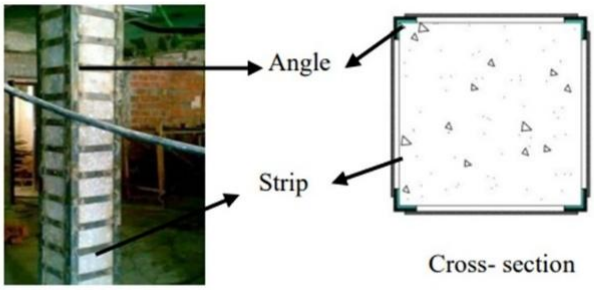
Tabel 1. Ketentuan *Concrete Jacketing* [16]

Spesifikasi *jacketing*	Kuat tekan beton jacketing sama atau lebih besar 5 N/mm^2 dari kuat tekan beton elemen eksisting
Tebal *jacketing*	Minimum 100 mm
Tulangan longitudinal	Spasi ≤ 6 tebal jacketing dan maksimum 600 mm Rasio tulangan jacketing 0,015-0,04 Di setiap sudut dipasang tulangan
Tulangan transversal	Spasi sesuai dengan peraturan ketahanan gempa Diametr minimum 10 mm atau 1/3 dari diameter maksimum tulangan longitudinal Kait dibengkokkan 135^0

Metode *concrete jacketing* memiliki sejumlah keunggulan dalam peningkatan kinerja struktur. Selain mampu meningkatkan kapasitas daya dukung, daktilitas, serta ketahanan terhadap beban gempa [4], metode ini juga terbukti efektif dalam memperbaiki atau memperkuat kolom dengan derajat kelangsingan tinggi maupun kolom yang telah mengalami degradasi [13]. Dari segi pelaksanaan, metode ini bersifat umum dan tidak memerlukan peralatan khusus, sehingga memudahkan penerapannya di lapangan. Namun demikian, metode ini juga memiliki beberapa keterbatasan. Penambahan lapisan beton mengakibatkan bertambahnya dimensi elemen struktur, sehingga meningkatkan beban mati bangunan. Selain itu, ikatan antara beton lama dengan beton baru tidak selalu homogen, yang akibatnya dapat mengurangi efektivitas *retrofit*. Proses pelaksanaan yang relatif memakan waktu juga menjadi salah satu tantangan dalam penerapan *concrete jacketing*.

Steel Jacketing

Steel jacketing adalah salah satu metode perkuatan kolom untuk meningkatkan daktilitas dan kapasitas geser dari kolom serta meningkatkan ketahanan seismik gedung dalam menahan beban gempa . *Steel jacketing* dapat menggunakan pelat baja dan profil baja siku yang dipasang pada keempat sisi kolom [5].



Gambar 4. *Steel Jacketing* [17]

Tabel 2. Ketentuan *Steel Jacketing* [5]

Dimensi profil / pelat baja	Profil baja siku tidak boleh kurang dari 50x50x5 Tebal pelat baja minimum 6 mm
Ketinggian Jacketing	1.2 - 1.5 dari panjang *splice* ,jika kolom lentur Sesuai tinggi kolom ,jika kolom geser
Ujung bebas pada *jacketing*	Dilas diseluruh ketinggian jacketing
Celah antara *steel jacket* dan kolom beton.	Diisi dengan *cement grouting* setebal 25 mm
Ukuran dan jumlah dari angkur	Diameter 25 mm dengan panjang 300 mm, yang tertanam pada kolom beton sedalam 200 mm. Angkur dipasang setelah melakukan pengeboran lubang pada *steel jacket* dan menggunakan *epoxy adhesive.* Dua angkur dibutuhkan untuk memperkaku *steel jacket*

Rekomendasi desain *steel jacketing* menurut L. Cirtek [18].

a. Panjang sisi dari pelat siku :

$$aan \geq 0.2\beta \quad (4)$$

$$\beta = 0.5(a+b) \quad (5)$$

dengan aan menunjukkan panjang sisi pelat siku, a menunjukkan panjang sisi kolom arah X dan b menunjukkan panjang sisi kolom arah Y.

b. Tebal dari pelat siku :

$$tan \geq 0.1aan \quad (6)$$

dengan tan menunjukkan tebal pelat siku.

c. Jarak antar strip :

$$0.40\beta \leq astr \leq 0.75\beta \quad (7)$$

dengan astr menunjukkan jarak antar strip

d. Luas dan tebal dari strip :

$$Astr \geq 0.004\beta^2 \quad (8)$$

$$tstr \leq tan \quad (9)$$

dengan Astr menunjukkan luas strip dan tstr menunjukkan tebal strip.

Steel jacketing memiliki sejumlah keunggulan dalam *retrofit* struktur beton bertulang. Metode ini mampu meningkatkan daktilitas, kapasitas geser, serta ketahanan seismik struktur terhadap beban gempa [5]. Selain itu, penambahan dimensi penampang akibat penerapan jaket baja relatif kecil, dan proses pelaksanaannya cenderung lebih cepat dibandingkan metode *concrete jacketing*. Namun demikian, *steel jacketing* juga memiliki beberapa keterbatasan. Salah satu kekurangannya adalah kerentanan terhadap korosi, terutama jika profil/ pelat baja tidak dilindungi dengan sistem pelapisan yang memadai. Di samping itu, dalam pemasangan material baja memerlukan tenaga kerja dengan keahlian khusus, khususnya dalam hal pengelasan dan penanganan material baja.

Soft Story

Suatu struktur dapat diklasifikasikan sebagai beraturan atau tidak beraturan berdasarkan kriteria yang tercantum dalam SNI 1727:2019 [19]. Ketidakberaturan dalam struktur dibagi menjadi dua jenis, yaitu ketidakberaturan horizontal dan ketidakberaturan vertikal. Salah satu ketidakberaturan vertikal adalah *soft story*, yang termasuk dalam kategori ketidakberaturan kekakuan tingkat lunak atau tipe 1a. Ketidakberaturan ini terjadi apabila suatu tingkat memiliki kekakuan lateral kurang dari 70% kekakuan lateral tingkat di atasnya atau kurang dari 80% dari kekakuan rata-rata tiga tingkat di atasnya [19].

3. METODOLOGI PENELITIAN

Penelitian ini menggunakan pendekatan kuantitatif dengan metode analisis numerik untuk mengevaluasi struktur gedung beton bertulang yang mengalami *soft story*. Metode analisis struktur yang dipergunakan analisis elastis linier respon spektrum.

Objek Penelitian

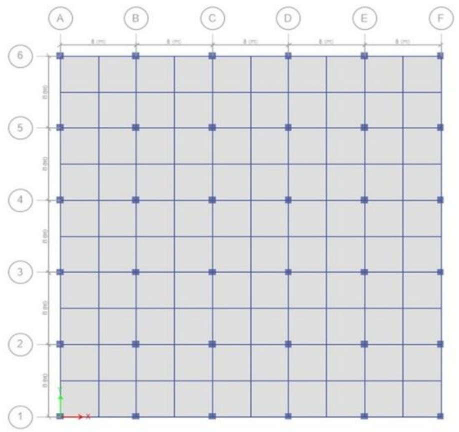
Objek penelitian berupa gedung beton bertulang 8 lantai yang berfungsi sebagai hotel dan berlokasi di Jakarta pada tanah lunak. Sistem struktur dipergunakan sistem Struktur Rangka Pemikul Momen Khusus (SRPMK).

Simulasi struktur dibagi menjadi tiga model sebagai berikut:

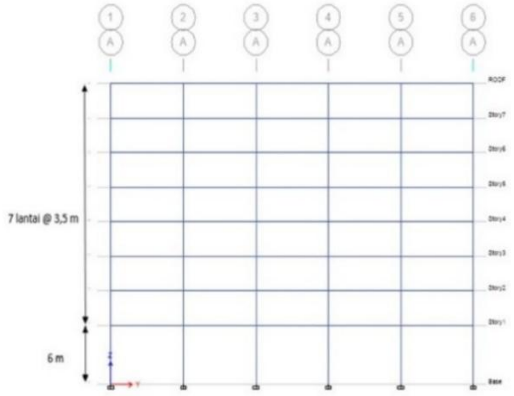
a. Model *eksisting*: bangunan *eksisting* dengan ketidakberaturan vertikal tingkat lunak (*soft story*) pada lantai 1.
b. Model 1: bangunan eksisting dengan *soft story* pada lantai 1 dan di-*retrofit* dengan *concrete jacketing*.
c. Model 2: bangunan eksisting dengan *soft story* pada lantai 1 dan di-*retrofit* dengan *steel jacketing*.

Dalam analisis Model 1 dan 2 tidak memperhitungkan deformasi pada Model *eksisting*. Sementara itu, gambar denah, potongan dan tampak 3D dari ketiga model ditampilkan pada Gambar 5 – 7.

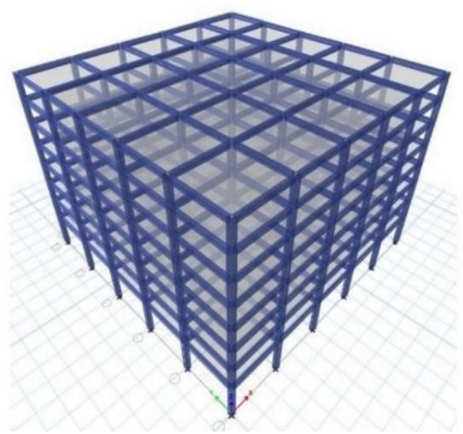
Dimensi balok untuk semua model sama, (1) Balok Induk (BI) 350 x 700 mm dan (2) Balok Anak (BA) 250 x 500 mm. Dimensi kolom model *eksisting* K1 750 x 750 mm dengan tulangan 16D25. Untuk model 1, kolom K1 pada lantai 1 di sisi terluar di-*retrofit* dengan *concrete jacketing* dan untuk model 2 kolom K1 pada posisi yang sama di-*retrofit* dengan *steel jacketing* [15], [16], [17], [18], [22]. Posisi kolom yang di-*retrofit* berada di sisi terluar yaitu yang diberi warna merah seperti pada Gambar 8. Diambil di sisi terluar dengan pertimbangan nilai D/C ratio yang mendekati nilai satu dan dari tampilan arsitektur.



Gambar 5. Denah Lantai Tipikal



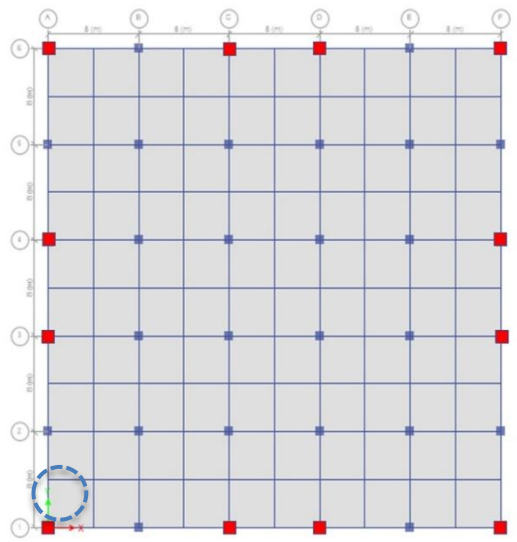
Gambar 6. Potongan pada As A



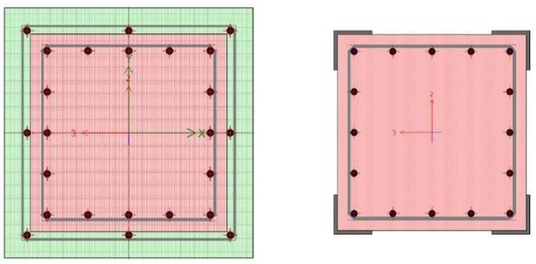
Gambar 7. Tampak 3D

Tabel 3. Data Material

Material	Mutu	Modulus Elastisitas (E)
Beton	fc' = 30 MPa	4700 √fc'
Baja Tulangan	fysr = 420 MPa	200000 MPa
Baja Profil	BJ-37, fy = 240MPa Fu = 370 MPa	200000 MPa



Gambar 8. Denah Kolom *Retrofit*



(a) *Concrete Jacketing* (b) *Steel Jacketing*

Gambar 9. Penampang Kolom *Retrofit*

Tabel 4. Kolom *Retrofit Concrete Jacketing*

Tipe	Dimensi (mm)	Mutu Beton Jacketing	Tul. Long. Tambahan	Tul. Trans. Tambahan
K-CJ	950 x 950	35 MPa	8 D25	D10

Tabel 5. Kolom *Retrofit Steel Jacketing*

Tipe	Dimensi (mm)	Profil Siku(mm)	Plat Strip (mm)
K-SJ	750 x 750	150 x 150 x 15	600 x 15

Pembebanan

Beban gravitasi terdiri dari beban mati (berat sendiri dan beban mati tambahan) serta beban hidup. Besarnya beban mati tambahan 1,25 kN/m^2, beban hidup lantai 1,72 kN/m^2 dan beban hidup lantai atap 0,96 kN/m^2. Beban dinding 7,875 kN/m. Standar yang dipergunakan adalah SNI 1727:2013 [20].

Beban gempa mengacu pada SNI 1727:2019 [19]. Untuk fungsi gedung sebagai hotel termasuk ke dalam kategori risiko II, faktor keutamaan,Ie=1 dengan kelas situs tanah lunak (SE). Percepatan Respons Spektral MCE Terpetakan Ss=0,68 & S1=0,29, Koefisien Situs Fa=1,412 & Fv=2,85. Percepatan Respons Spektral MCE SMS=0,96 & SM1=0,287. Percepatan Respons Spektral SDS=0,64 & SD1=0,551. Kategori Desain Seismik D, Sistem struktur SRPMK sehingga koefisien modifikasi respon , R = 8, Faktor Perbesaran Defleksi, Cd = 5,5, Faktor Kuat Lebih, Ω_0 = 3 dan Faktor Redudansi 1,3 [19].

Analisis Struktur

Untuk pemodelan dan analisis struktur menggunakan perangkat lunak ETABS [23]. Perangkat lunak lain yang dipergunakan adalah Excel dan Mathcad.

4. HASIL DAN PEMBAHASAN

Periode dan Gerak Dominan Struktur

Periode struktur pada model eksisting tercatat sebagai yang tertinggi, yaitu sebesar 1,535 detik. Setelah dilakukan *retrofit*, terjadi penurunan periode sebesar 4,10% pada Model 1 dan 1,75% pada Model 2. Dalam analisis struktur bangunan bertingkat, gerak dominan pada ragam pertama dan kedua seharusnya berupa translasi, sedangkan pada ragam ketiga berupa rotasi. Hasil analisis menunjukkan bahwa seluruh model telah memenuhi ketentuan tersebut. Informasi terkait periode struktur dan karakteristik gerakan pada masing-masing ragam disajikan pada Tabel 6.

Tabel 6. Periode & Gerak Dominan Struktur

Mode	Periode (sec)	UX	UY	RZ
Model Eksisting				
1	1,535	0,8718	0,0001	0
2	1,535	0,0001	0,8718	0
3	1,362	0	0	0,8727
Model 1				
1	1,472	0	0,8508	0
2	1,472	0,8508	0	0
3	1,287	0	0	0,8427
Model 2				
1	1,508	0,8633	0,0001	0
2	1,508	0,0001	0,8633	0
3	1,328	0	0	0,8605

Partisipasi Massa Ragam

Nilai partisipasi massa ragam yang disyaratkan adalah lebih besar dari 90 persen. Untuk semua model, pada mode ke-12 telah lebih dari 90%.

Tabel 7. Partisipasi Massa Ragam

Mode	Sum UX	Sum UY	Sum RX	Sum RY	Sum RZ
Model Eksisting					
1	0,8718	0,0001	0	0,1481	0
2	0,8719	0,8719	0,1481	0,1481	0
3	0,8719	0,8719	0,1481	0,1481	0,8727
11	0,9953	0,9953	0,9833	0,9833	0,9866

Mode	Sum UX	Sum UY	Sum RX	Sum RY	Sum RZ
12	0,9953	0,9953	0,9833	0,9833	0,9953
Model 1					
1	0	0,8508	0,1757	0	0
2	0,8508	0,8508	0,1757	0,1757	0
3	0,8508	0,8508	0,1757	0,1757	0,8427
11	0,993	0,993	0,9764	0,9764	0,9785
12	0,993	0,993	0,9764	0,9764	0,9918
Model 2					
1	0,8633	0,0001	0	0,1579	0
2	0,8634	0,8634	0,158	0,158	0
3	0,8634	0,8634	0,158	0,158	0,8605
11	0,9943	0,9943	0,9801	0,9801	0,9833
12	0,9943	0,9943	0,9801	0,9801	0,9939

Ketidakberaturan

Ketidakberaturan horizontal dari seluruh tipe tidak teridentifikasi pada semua model yang dianalisis. Sedangkan ketidakberaturan vertikal tipe 1a hanya muncul pada model eksisting, baik pada arah X maupun arah Y, sebagaimana ditunjukkan pada Tabel 8. Sementara itu, ketidakberaturan vertikal tipe 1a tidak ditemukan pada model 1 dan model 2, sesuai dengan hasil yang disajikan dalam Tabel 9 dan Tabel 10.

Kekakuan Tingkat

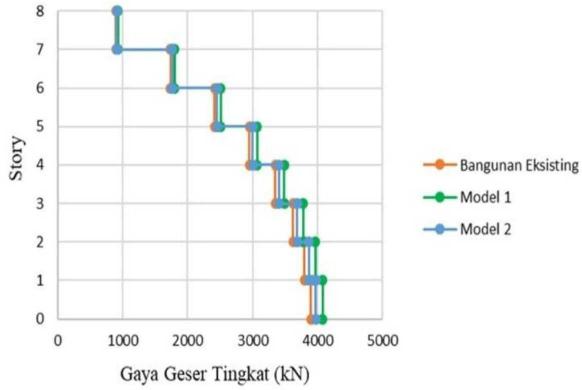
Pada model 1 dan model 2 terjadi peningkatan kekakuan pada lantai 1 masing-masing sebesar 26,12% dan 11,95%, sebagaimana ditunjukkan pada Tabel 9 dan Tabel 10. Peningkatan ini menyebabkan kekakuan lantai 1 pada kedua model tersebut telah memenuhi ambang batas minimum, yaitu 70% dari kekakuan lateral tingkat di atasnya atau 80% dari rata-rata kekakuan tiga tingkat di atasnya [19]. Dengan demikian, ketidakberaturan vertikal tipe 1a (*soft story*) yang sebelumnya teridentifikasi pada model 1 dan model 2 berhasil diatasi.

Gaya Geser Tingkat

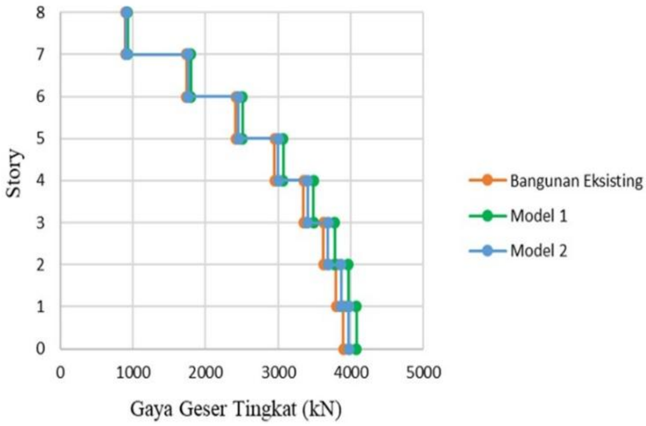
Peningkatan gaya geser tingkat terjadi pada semua arah untuk model yang telah dilakukan *retrofit*, yaitu Model 1 dan Model 2. Pada Model 1, gaya geser tingkat meningkat sebesar 4,62%, sedangkan pada Model 2 peningkatan tercatat sebesar 1,86%. Hasil tersebut dapat dilihat pada Gambar 10 dan Gambar 11.

Simpangan Lantai dan Simpangan Antar Lantai

Model 1 dan model 2 menunjukkan penurunan simpangan lantai sebesar 2,29% untuk Model 1 dan 1,05% untuk Model 2 pada kedua arah (arah X dan Y) jika dibandingkan dengan simpangan lantai pada model *eksisting*, sebagaimana ditunjukkan pada Gambar 12-13. Seluruh model yang dianalisis juga menunjukkan penurunan nilai simpangan antar lantai (*drift*) maksimum sebesar 17,26% pada Model 1 dan 7,91% pada Model 2. Pada semua model menunjukkan *drift* yang terjadi berada di bawah batas maksimum yang diizinkan, baik pada arah X maupun arah Y, sebagaimana ditampilkan pada Gambar 14-15.



Gambar 10. Gaya Geser Tingkat Arah X



Gambar 11. Gaya Geser Tingkat Arah Y

Tabel 8. Ketidakberaturan vertical tipe 1a Pada Model *Eksisting*

Lantai	hsx (mm)	Kekakuan kN/m	0.8 x Kekakuan (kN/m)	0.7 x Kekakuan (kN/m)	0.8 x Kekakuan 3 Story (kN/m)	Cek
Arah X						
Atap	3500	465574,65	-	-	0	-
7	3500	568771,18	372459,72	325902,26	0	TIDAK TERJADI
6	3500	581657,56	455016,94	398139,83	0	TIDAK TERJADI
5	3500	581440,04	465326,05	407160,29	430934,24	TIDAK TERJADI
4	3500	579447,6	465152,03	407008,03	461831,67	TIDAK TERJADI
3	3500	577467,51	463558,08	405613,32	464678,72	TIDAK TERJADI
2	3500	574918,68	461974,01	404227,26	463561,37	TIDAK TERJADI
1	6000	421532,12	459934,94	402443,08	461822,34	**TERJADI**
Arah Y						

Lantai	hsx (mm)	Kekakuan kN/m	0.8 x Kekakuan (kN/m)	0.7 x Kekakuan (kN/m)	0.8 x Kekakuan 3 Story (kN/m)	Cek
Atap	3500	465574,65	-	-	0	-
7	3500	568771,18	372459,72	325902,26	0	TIDAK TERJADI
6	3500	581657,56	455016,94	398139,83	0	TIDAK TERJADI
5	3500	581440,04	465326,05	407160,29	430934,24	TIDAK TERJADI
4	3500	579447,6	465152,03	407008,03	461831,67	TIDAK TERJADI
3	3500	577467,51	463558,08	405613,32	464678,72	TIDAK TERJADI
2	3500	574918,68	461974,01	404227,26	463561,37	TIDAK TERJADI
1	6000	421532,12	459934,94	402443,08	461822,34	**TERJADI**

Tabel 9. Ketidakberaturan vertical tipe 1a Pada Model 1

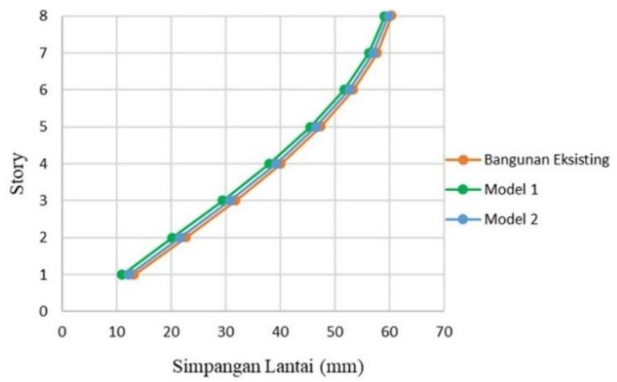
Lantai	hsx (mm)	Kekakuan kN/m	0.8 x Kekakuan (kN/m)	0.7 x Kekakuan (kN/m)	0.8 x Kekakuan 3 Story (kN/m)	Cek
Arah X						
Atap	3500	466425,74	-	-	0	-
7	3500	569611,95	373140,59	326498,02	0	TIDAK TERJADI
6	3500	582693,53	455689,56	398728,37	0	TIDAK TERJADI
5	3500	583277,42	466154,82	407885,47	431661,66	TIDAK TERJADI
4	3500	583775,95	466621,94	408294,19	462822,11	TIDAK TERJADI
3	3500	589742,19	467020,76	408643,17	466599,17	TIDAK TERJADI
2	3500	613950,59	471793,75	412819,53	468478,82	TIDAK TERJADI
1	6000	531632,74	491160,47	429765,41	476658,33	TIDAK TERJADI
Arah Y						
Atap	3500	466425,74	-	-	0	-
7	3500	569611,95	373140,59	326498,02	0	TIDAK TERJADI
6	3500	582693,53	455689,56	398728,37	0	TIDAK TERJADI
5	3500	583277,42	466154,82	407885,47	431661,66	TIDAK TERJADI
4	3500	583775,95	466621,94	408294,19	462822,11	TIDAK TERJADI
3	3500	589742,19	467020,76	408643,17	466599,17	TIDAK TERJADI
2	3500	613950,59	471793,75	412819,53	468478,82	TIDAK TERJADI
1	6000	531632,74	491160,47	429765,41	476658,33	TIDAK TERJADI

Tabel 10. Ketidakberaturan vertikal tipe 1a Pada Model 2

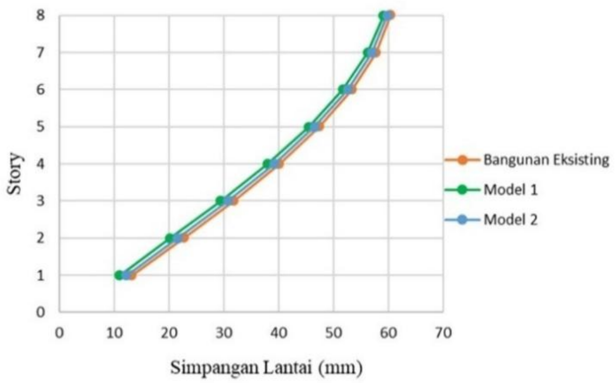
Lantai	hsx (mm)	Kekakuan kN/m	0.8 x Kekakuan (kN/m)	0.7 x Kekakuan (kN/m)	0.8 x Kekakuan 3 Story (kN/m)	Cek
Arah X						
Atap	3500	463581,35	-	-	0	-
7	3500	568941,24	370865,08	324506,95	0	TIDAK TERJADI
6	3500	581587,44	455152,99	398258,87	0	TIDAK TERJADI
5	3500	581864,48	465269,95	407111,21	430429,34	TIDAK TERJADI
4	3500	581763,07	465491,58	407305,14	461971,51	TIDAK TERJADI
3	3500	584497,20	465410,46	407234,15	465390,66	TIDAK TERJADI
2	3500	593992,04	467597,76	409148,04	466166,60	TIDAK TERJADI
1	6000	471920,54	475193,63	415794,43	469400,62	TIDAK TERJADI

Tabel 10. Ketidakberaturan vertikal tipe 1a Pada Model 2 (Lanjutan)

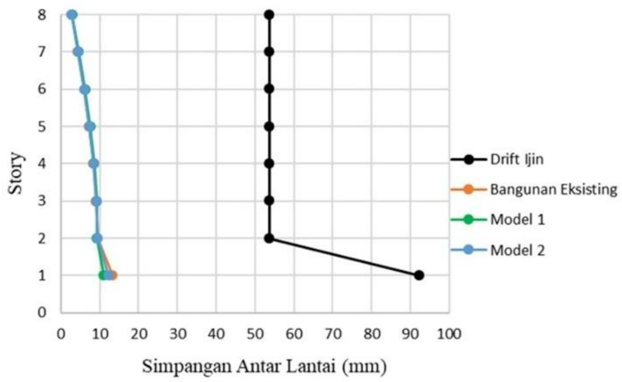
Lantai	hsx (mm)	Kekakuan kN/m	0.8 x Kekakuan (kN/m)	0.7 x Kekakuan (kN/m)	0.8 x Kekakuan 3 Story (kN/m)	Cek
Arah Y						
Atap	3500	463581,35	-	-	0	-
7	3500	568941,24	370865,08	324506,95	0	TIDAK TERJADI
6	3500	581587,44	455152,99	398258,87	0	TIDAK TERJADI
5	3500	581864,48	465269,95	407111,21	430429,34	TIDAK TERJADI
4	3500	581763,07	465491,58	407305,14	461971,51	TIDAK TERJADI
3	3500	584497,20	465410,46	407234,15	465390,66	TIDAK TERJADI
2	3500	593992,04	467597,76	409148,04	466166,60	TIDAK TERJADI
1	6000	471920,54	475193,63	415794,43	469400,62	TIDAK TERJADI



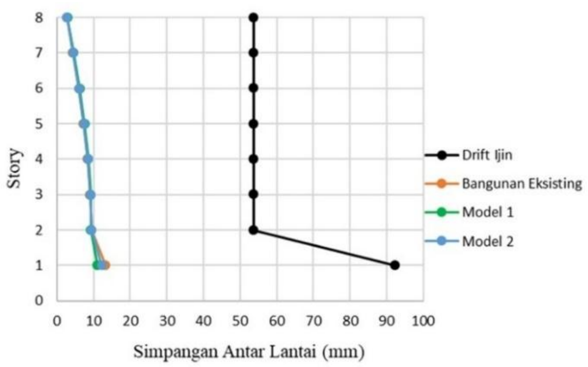
Gambar 12. Simpangan Lantai Arah X



Gambar 13. Simpangan Lantai Arah Y



Gambar 14. Simpangan Antar Lantai Arah X



Gambar 15. Simpangan Antar Lantai Arah Y

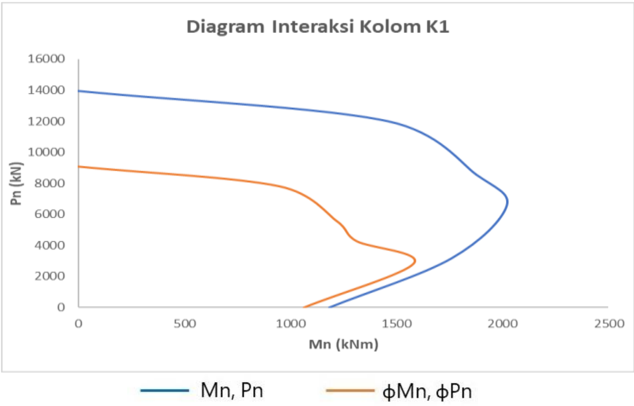
Demand to Capacity Ratio

Demand to Capacity Ratio merupakan perbandingan antara gaya yang harus dipikul terhadap kekuatan elemen struktur. Nilai Demand to Capacity (D/C) ratio untuk semua elemen struktur harus lebih kecil dari 1. Nilai maksimum D/C ratio pada model eksisting untuk kolom K1 adalah sebesar 0,948. Pada Model 1, kolom K-CJ memiliki nilai D/C maksimum sebesar 0,909, sedangkan pada Model 2, kolom K-SJ menunjukkan nilai D/C maksimum sebesar 0,884.

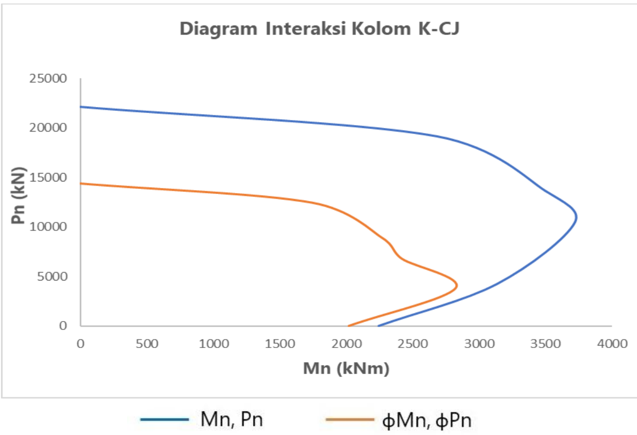
Dengan demikian, terjadi penurunan nilai D/C ratio masing-masing sebesar 4,11% pada Model 1 dan 6,75% pada Model 2 dibandingkan terhadap model *eksisting*.

Diagram Interaksi

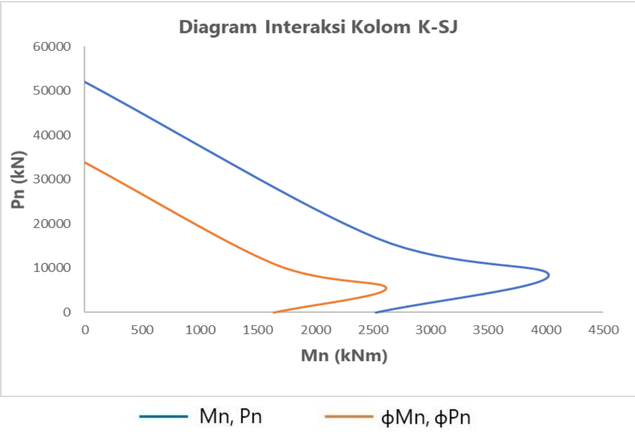
Kapasitas kolom dapat ditentukan melalui analisis diagram interaksi, yang menggambarkan hubungan antara momen lentur dan gaya aksial yang bekerja pada elemen struktur [24], [25]. Pada penelitian ini, kolom yang dianalisis terletak pada as A1 di lantai 1, sebagaimana ditunjukkan pada Gambar 8.



Gambar 16. Diagram Interaksi Kolom K1



Gambar 17. Diagram Interaksi Kolom K-CJ



Gambar 18. Diagram Interaksi Kolom K-SJ

Hasil analisis menunjukkan bahwa kapasitas kolom yang telah dilakukan *retrofit* (K-CJ pada Model 1 dan K-SJ pada Model 2) mengalami peningkatan yang signifikan dibandingkan dengan kolom tanpa *retrofit* (K1 pada model *eksisting*). Pada Model 1, kapasitas aksial meningkat sebesar 58,58%, sedangkan kapasitas momen meningkat sebesar 78,43%. Sementara itu, pada Model 2 tercatat peningkatan kapasitas aksial yang lebih tinggi, yaitu sebesar 273,11%, dengan peningkatan kapasitas momen sebesar 65,27%. Diagram interaksi setiap model ditampilkan pada Gambar 16 – 18.

5. KESIMPULAN

Penerapan *retrofit* dengan metode *concrete jacketing* dan *steel jacketing* pada kolom sisi terluar lantai 1 terbukti efektif dalam meningkatkan performa struktur bangunan eksisting. Efektivitas tersebut ditunjukkan melalui berbagai parameter analisis. Pertama, terjadi penurunan periode struktur sebesar 4,10% pada Model 1 dan 1,74% pada Model 2. Kedua, simpangan lantai mengalami penurunan masing-masing sebesar 2,29% dan 1,05%, sedangkan simpangan antar lantai (*drift*) menurun sebesar 17,26% pada Model 1 dan 7,91% pada Model 2. Selain itu, gaya geser tingkat meningkat sebesar 4,62% pada Model 1 dan 1,86% pada Model 2. Peningkatan kekakuan tingkat di lantai 1 masing-masing sebesar 26,12% dan 11,95% pada Model 1 dan Model 2 turut berkontribusi dalam mengatasi ketidakberaturan vertikal tipe *soft story*.

Dari sisi elemen struktur, terjadi peningkatan kapasitas kolom yang signifikan berdasarkan hasil analisis diagram interaksi. Kapasitas aksial meningkat sebesar 58,58% dan 273,11%, sedangkan kapasitas momen meningkat sebesar 78,43% dan 65,27% secara berturut-turut untuk Model 1 dan Model 2. Selain itu, nilai *Demand to Capacity (D/C) Ratio* menunjukkan penurunan sebesar 4,11% pada Model 1 dan 6,75% pada Model 2, yang mengindikasikan peningkatan kapasitas kolom setelah proses *retrofit* dilakukan.

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Life Cycle Assessment of Sustainable Building Materials in The Nigerian Construction Industry

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ABSTRACT

This study presents a comprehensive life cycle assessment (LCA) of sustainable building materials in the Nigerian construction industry, focusing on bamboo, recycled steel, and low-carbon concrete. It evaluates the environmental impacts of these materials across their entire life cycles—from raw material extraction to end-of-life disposal. A mixed-methods approach was employed: primary data were collected via interviews and surveys with industry professionals, while secondary data came from credible literature and databases. Results revealed bamboo as the most environmentally friendly, with the lowest impacts on global warming, ozone depletion, eutrophication, and resource depletion. Low-carbon concrete also offered significant environmental advantages, particularly in reducing greenhouse gas emissions. Recycled steel supported circular economy goals but had higher energy demands and emissions due to its intensive recycling process. Key barriers to adoption in Nigeria included high upfront costs, limited local availability, and inadequate regulatory support. The study recommends strengthening regulatory frameworks, offering financial incentives, boosting local production, and promoting awareness through education and training. These findings underscore the potential of sustainable materials to reduce the environmental footprint of construction in Nigeria and offer practical guidance for policymakers, industry stakeholders, and researchers committed to advancing sustainability in the built environment.

1. INTRODUCTION

The Nigerian construction industry is experiencing unprecedented expansion, driven by rapid urbanization, population growth, and national development policies. While this growth signals economic progress, it also introduces substantial environmental challenges such as elevated carbon emissions, excessive energy use, and the accelerated depletion of natural resources [1]. Conventional construction practices in Nigeria heavily rely on materials like cement, concrete, and steel—resources known for their high environmental burdens across their life cycles. In the face of global climate change and Nigeria's commitments to the Sustainable Development Goals (SDGs), this reliance is increasingly unsustainable.

Sustainable building materials—such as bamboo, recycled steel, and low-carbon concrete—have emerged as viable alternatives due to their lower environmental impacts, renewability, and compatibility with circular economy models [2, 3]. Globally, the adoption of these materials is being driven by regulatory support, technological advancements, and a growing emphasis on the environmental performance of the built environment [4, 5]. However, in Nigeria, their uptake remains limited due to infrastructural bottlenecks, high initial investment costs, weak local manufacturing capacity, and inadequate regulatory enforcement [6, 7].

A critical tool for quantifying the environmental implications of material choices is Life Cycle Assessment (LCA), which evaluates impacts across all stages of a material's life—from raw material extraction through to end-of-life disposal. Although LCA has become standard in sustainability evaluations globally [8], its application within the Nigerian context remains limited, particularly with respect to empirical, material-specific comparisons. Existing studies have explored the principles of green construction and sustainable building design, but few have rigorously applied LCA to compare sustainable and conventional materials under Nigeria's unique environmental and socio-economic conditions [9, 10].

To address this gap, the present study undertakes a comprehensive LCA of sustainable building materials in the Nigerian construction industry. Specifically, it assesses bamboo, recycled steel, and low-carbon concrete, evaluating their life cycle performance across key environmental impact categories such as global warming potential, ozone depletion, eutrophication, and resource depletion. The study is guided by three primary objectives: [1] to quantify the environmental impacts associated with these materials across their life cycles; [2] to compare their sustainability performance with that of conventional alternatives commonly used in Nigeria; and [3] to provide policy and practice-oriented recommendations for enhancing the adoption of sustainable materials in Nigerian construction.

2. LITERATURE REVIEW

Systematic Review Framework

This literature review was developed through a systematic methodology inspired by the PRISMA framework, ensuring methodological transparency and academic rigor in the selection, screening, and synthesis of sources. A structured search strategy was executed using major academic databases including Scopus, Web of Science, and Google Scholar. The search combined terms such as "sustainable building materials," "life cycle assessment," "green construction," and "Nigeria," using Boolean operators to refine scope. Only peer-reviewed literature published between 2020 and 2024 was considered. Inclusion criteria prioritized studies focusing on environmental performance, application within construction, and empirical analysis via life cycle assessment (LCA) or comparable evaluative frameworks.

Following the application of inclusion and exclusion filters, a final dataset of 76 articles was selected. These articles were systematically reviewed and thematically categorized into three primary focus areas: [1] classification and performance metrics of sustainable building materials; [2] evolution and implementation of LCA methodologies; and [3] contextual challenges and advancements in Nigeria's construction sector.

Sustainable Building Materials: Definitions, Characteristics, and Classifications

Sustainable building materials are recognized as essential for reducing the ecological footprint of the built environment. Defined by their reduced environmental impact across all life cycle stages, these materials are characterized by low embodied energy, high durability, reusability, recyclability, and non-toxicity. Renewable materials such as bamboo, cork, and sustainably harvested timber have gained attention due to their regenerative capacity and ability to minimize long-term environmental disruption. Bamboo, in particular, has been widely examined for its superior compressive strength, high carbon sequestration potential, and rapid regrowth cycle, rendering it a highly viable substitute for conventional hardwoods in both structural and non-structural applications [11, 12].

Recycled materials also provide substantial sustainability benefits by closing resource loops and minimizing extraction-related emissions. Recycled steel, which maintains full structural performance, consumes significantly less energy during processing than virgin steel and has been shown to reduce greenhouse gas emissions by up to 70% [13, 14]. Similarly, aggregates derived from construction and demolition waste have demonstrated effectiveness in non-load-bearing concrete applications, reducing landfill loads and conserving finite natural resources [15]. Reclaimed wood continues to offer environmental, aesthetic, and economic value, particularly in adaptive reuse projects, contributing to circularity while mitigating deforestation.

A rapidly expanding category of innovative sustainable materials has emerged to address the inherent limitations of conventional alternatives. Low-carbon concrete, produced through the incorporation of supplementary cementitious materials (SCMs) such as fly ash, slag, and silica fume, significantly reduces the embodied carbon of concrete. Studies show that these formulations can reduce lifecycle CO_2 emissions by up to 30–40% while improving material durability and resilience [16, 17]. Complementary to these advances are eco-insulation solutions made from cellulose, sheep's wool, and agricultural by-products, which are valued for their biodegradability, low thermal conductivity, and enhancement of indoor air quality [18, 19].

The performance of sustainable materials is increasingly evaluated not only in environmental terms but also in relation to lifecycle cost efficiency, structural adaptability, energy performance, and integration ease within conventional construction systems. The rise in environmental product declarations (EPDs) and certifications such as Forest Stewardship Council (FSC) and Cradle to Cradle has improved supply chain traceability and stakeholder confidence (Table 1). Recent comparative assessments suggest that many sustainable materials, when lifecycle energy savings and maintenance costs are considered, can achieve cost parity with or even outperform conventional materials [20, 21].

Life Cycle Assessment (LCA): Framework and Applications in Construction

Life Cycle Assessment (LCA) is a standardized methodology used to evaluate the environmental impacts of building materials across all life stages—from resource extraction and manufacturing to use and end-of-life management. Guided by ISO 14040 and ISO 14044, LCA encompasses four critical phases: goal and scope definition, inventory analysis, impact assessment, and interpretation [22]. Within the construction sector, LCA has become indispensable for identifying environmental

Table 1. Sustainable Building Materials and LCA Findings

Material Category	Examples	Life Cycle Benefits	Recent LCA Insights (2020–2024)
Renewable	Bamboo, Cork, Sustainably harvested timber	Low embodied energy, carbon sequestration, biodegradability	Bamboo shows 60–70% lower GWP than concrete [12].
Recycled	Recycled steel, Reclaimed wood, Crushed concrete	Energy savings, reduced landfill use, conservation of natural resources	Recycled steel reduces energy use by 70% vs virgin steel [14].
Innovative	Low-carbon concrete, Cellulose insulation, Sheep's wool	CO_2 reduction, improved thermal performance, low VOC emissions	Low-carbon concrete cuts CO_2 by 30–40% with SCMs [17]

hotspots, evaluating material alternatives, and supporting sustainable design decisions [23].

Recent applications of LCA in construction highlight its relevance in assessing embodied carbon, energy intensity, and environmental toxicity. For instance, bamboo-based composites have been shown to exhibit significantly lower global warming potential (GWP) and ozone depletion potential than reinforced concrete of similar structural performance [12]. Recycled steel, although energy-intensive during reprocessing, still presents a lower GWP and eutrophication potential relative to virgin steel, owing to the environmental benefits of closed-loop material cycles [13, 14]. Low-carbon concrete—especially blends incorporating fly ash and slag—provides added durability while lowering emissions, offering enhanced resistance to sulfate attack and alkali-silica reactions [16, 17].

With growing access to regional databases and improvements in LCA modeling software, assessments are now more context-sensitive, incorporating local parameters such as transportation logistics, grid energy mixes, and climatic conditions. This regionalization is crucial in countries like Nigeria, where infrastructural limitations and environmental contexts differ considerably from high-income regions. Moreover, the integration of LCA into Building Information Modeling (BIM) platforms is facilitating real-time environmental assessments during the early design stages, a trend gaining momentum globally [15].

Nonetheless, challenges persist in terms of data accessibility, methodological standardization, and technical expertise—especially in developing markets. Despite these limitations, LCA continues to serve as a core criterion in green certification frameworks like LEED, BREEAM, and Green Star, reaffirming its role as a benchmark for performance-based evaluation [24].

Sustainable Construction Trends and Material Adoption in Nigeria

Nigeria's construction industry, while integral to economic growth and infrastructure development, remains heavily reliant on environmentally intensive materials such as cement and steel. Cement production alone contributes significantly to greenhouse gas emissions due to its calcination and high-temperature processing [1]. Although awareness of sustainable construction practices is increasing, the adoption of environmentally preferable materials remains constrained by several systemic barriers. These include high upfront costs, limited domestic manufacturing capacity, inconsistent regulatory enforcement, and low public and professional awareness [6, 25].

Nonetheless, emerging studies underscore the feasibility and advantages of transitioning to sustainable materials within the Nigerian context. For example, locally sourced bamboo has been recognized for its structural adequacy in low-rise buildings and its cost-effectiveness in furniture and prefabricated applications. Similarly, the integration of fly ash into concrete mixtures under Nigerian climatic conditions has demonstrated a potential to reduce cement use by up to 30%, thereby lowering both cost and emissions [12].

Despite these opportunities, current initiatives are fragmented and under-resourced. Institutional backing and strategic investments remain essential to mainstream sustainable material use. To improve communication and clarity, it is recommended that the manuscript include a summary visual labeled: "Key Socio-Economic Barriers to Sustainable Material Adoption in Nigeria." This figure can present a concise overview of regulatory, economic, and infrastructural challenges while also identifying leverage points for policy reform and industry engagement.

Life Cycle Assessment of Building Materials: Insights from Recent Studies

Over the past decade, a growing body of scholarly work has applied LCA methodologies to assess the environmental performance of building materials. These studies consistently validate LCA as an effective instrument for comparing environmental impacts across material types, supply chains, and regional markets. Reviews such as those by Shad et al. [26] and Geng et al. [3] emphasize the environmental advantages of materials like bamboo, recycled steel, and low-carbon concrete over conventional alternatives.

Zhang and Xiao [14] demonstrated that low-carbon concrete containing fly ash or blast furnace slag achieves significant reductions in CO_2 emissions while maintaining mechanical performance. Similarly, Fufa et al. [13] reported that recycled steel, despite its reprocessing energy demands, offers net environmental benefits through its alignment with circular economy principles.

Wood-based materials sourced from responsibly managed forests also offer environmental advantages through carbon sequestration. Ortiz-Rodriguez et al. [19] showed that engineered timber products such as cross-laminated timber (CLT) not only reduce embodied carbon but also contribute positively to indoor air quality. In the West African context, Adewumi et al. [12] reported that construction with bamboo and laterite blocks achieves lower embodied energy and reduced waste generation compared to traditional cement blocks, especially when material sourcing occurs locally.

Additionally, LCA has been instrumental in optimizing design strategies and enhancing material selection. Ahmad et al. [17] conducted a comparative analysis of insulation materials, concluding that bio-based options such as cellulose and sheep's wool surpass conventional mineral wool in categories like resource depletion and GWP. As LCA methodologies continue to evolve, emphasis is shifting toward integrating health impacts, user comfort, and lifecycle economics, with increased demand for regional datasets and stakeholder-informed models.

Sustainability Challenges and Institutional Responses in the Nigerian Construction Industry

The ongoing expansion of Nigeria's construction sector, fueled by rapid urbanization and infrastructure investments, has amplified the industry's environmental footprint. The persistent reliance on conventional materials—such as Portland cement, steel, and virgin aggregates—has raised serious concerns about sustainability. Cement production, in particular, is among the largest contributors to construction-related carbon emissions in Nigeria due to its energy-intensive nature and greenhouse gas output [27, 1].

Despite the well-documented environmental costs, the transition toward sustainable building practices in Nigeria has been slow and fragmented. A primary obstacle is the limited availability and market penetration of environmentally sustainable materials. Although local alternatives such as bamboo, laterite, and agricultural waste products offer promising environmental and structural properties, they remain underutilized due to underdeveloped supply chains, insufficient processing infrastructure, and resistance to innovation within the construction market [12].

Knowledge and technical gaps further impede the shift toward sustainability. Many practitioners—including architects, engineers, and contractors—lack exposure to life cycle assessment (LCA) methodologies and have limited familiarity with sustainable materials. This knowledge deficit has reinforced a preference for conventional design practices [6, 18]. Without focused investments in training and professional development, regulatory policies may struggle to achieve the desired uptake among industry stakeholders.

Institutionally, Nigeria has initiated several important steps. The Nigerian Building and Road Research Institute (NBRRI) has led efforts in developing and promoting indigenous sustainable materials. However, challenges related to funding continuity, project implementation, and technology commercialization have limited its impact [28]. The Green Building Council of Nigeria (GBCN) has introduced a voluntary certification program inspired by the LEED framework, offering a potential platform for recognizing environmentally responsible projects. Nevertheless, its effectiveness has been curtailed by a lack of national legislative support, minimal financial incentives, and limited industry engagement [7, 26].

Fragmented policy environments and poor alignment between public and private stakeholders continue to undermine systemic transformation. Zhang and Xiao [14] advocate for comprehensive fiscal and regulatory measures—including green tax incentives, subsidies for sustainable construction, and mandatory environmental assessments for public infrastructure tenders—to catalyze adoption. Additionally, the potential of international collaborations through climate finance, multilateral technical assistance, and sustainable technology transfer remains largely untapped in Nigeria's construction policy landscape.

Figure 1 visualizes the main challenges—such as weak regulatory enforcement, lack of incentives, and fragmented supply chains—alongside their severity levels, derived from thematic synthesis of literature [6, 12].

Synthesis of Findings from Previous Studies

A synthesis of contemporary and foundational LCA studies confirms the significant role that sustainable materials play in reducing the environmental footprint of buildings. Research by Dodoo et al. [29] and Bilec et al. [30] found that timber-framed and low-energy buildings consistently demonstrate lower lifecycle emissions when compared to conventional structures. Penna et al. [31] illustrated that retrofitting buildings with sustainable materials can yield considerable energy savings and environmental benefits, although they emphasized the need for life cycle costing to fully capture long-term value.

End-of-life strategies have also gained prominence in sustainability discourse. Vieira and Horvath [32] advocated for greater focus on closed-loop recycling and material reuse as critical to achieving full environmental value. Expanding on this, Hellweg and Milà i Canals [33] and Liu et al. [15] highlighted the need to integrate social and economic dimensions into LCA assessments to ensure alignment with evolving global sustainability frameworks.

Within the Nigerian context, Adebayo [34], Akinola and Okunola [35], and Fapohunda and Stephenson [36] have explored structural barriers to sustainable construction, identifying fragmented policy, financial uncertainty, insufficient awareness, and skills shortages as key impediments. Tetteh and King [18] emphasized institutional training and leadership development as essential interventions, while Adewumi et al. [12] argued for the transformative potential of pilot projects to de-risk sustainable innovations and build stakeholder confidence.

Overall, while technical feasibility for sustainable material adoption exists, successful implementation in Nigeria will require a multi-pronged strategy encompassing evidence-based policymaking, financial incentives, public-private partnerships, and institutional innovation.

3. RESEARCH METHODOLOGY

Research Design

This study adopted a mixed-methods research design, integrating qualitative and quantitative approaches to provide a robust evaluation of the environmental impacts associated with sustainable building materials in Nigeria. Mixed-methods research has gained acceptance for its capacity to triangulate data, enhance construct validity, and yield richer insights compared to mono-method designs [37, 38].

The qualitative strand of the study investigated stakeholder perceptions, professional practices, and institutional challenges via in-depth interviews. Simultaneously, the quantitative strand employed standardized Life Cycle Assessment (LCA) methodologies to empirically quantify environmental impacts. This dual approach ensured that the analysis was both empirically grounded and context-sensitive, aligning with methodological best practices in construction sustainability research [39, 40].

Through this integrative framework, the study produced findings that are not only technically rigorous but also actionable within policy, industry, and research domains. The approach ensured a comprehensive understanding of both environmental metrics and the socio-technical systems that influence material selection and sustainability practices.

Data Collection

Data were collected using a combination of primary and secondary sources to ensure methodological triangulation and contextual depth. Primary data collection involved semi-structured interviews and structured surveys targeting professionals in architecture, civil engineering, construction management, urban planning, and environmental policy. A purposive sampling strategy was used to ensure representation across expertise, geographic distribution, and sectoral affiliation.

Thirty professionals participated in the interview phase, a sample deemed sufficient for achieving thematic saturation—a benchmark commonly employed in qualitative research [41]. Interviews were conducted using a thematic guide that explored material selection behavior, awareness of LCA, perceived barriers to sustainable material adoption, and the effectiveness of regulatory instruments. This approach reflects methodologies used in comparable studies of sustainability transitions in emerging economies [42, 43].

Secondary data comprised peer-reviewed academic literature, environmental product declarations (EPDs), national technical reports, and international LCA databases. These were used to support the construction of LCA models and contextual interpretation. This mixed-source approach reinforced both internal and external validity and is consistent with leading practices in contemporary sustainability assessment research [44, 45].

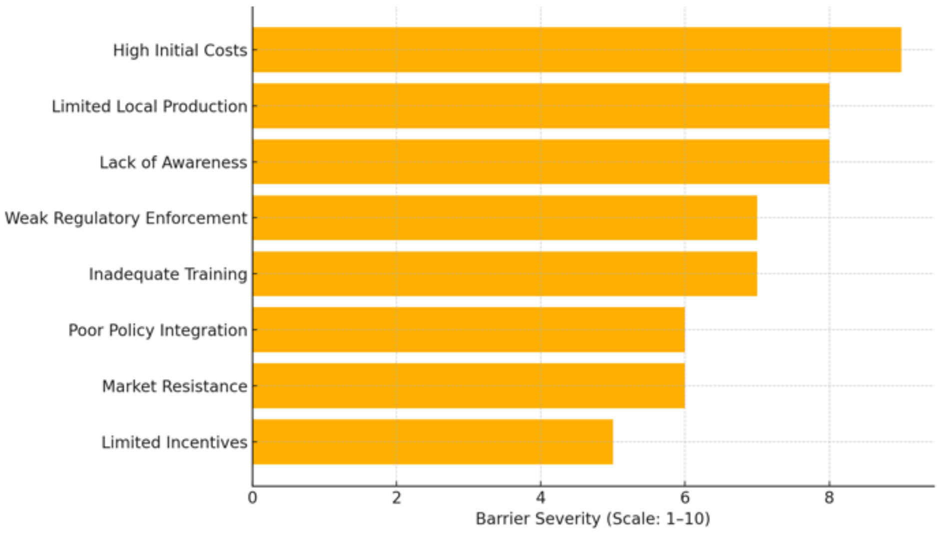

Figure 1. Barriers to Adoption of Sustainable Materials in Nigeria

Table 2. Interview Questions and Sources

No.	Category	Interview Questions	Citation
1	General Information	Can you provide a brief overview of your role and experience in the construction industry?	[46]
2		How familiar are you with the concept of sustainable building materials?	[47]
3	Sustainable Building Materials	What types of sustainable building materials are commonly used in your projects?	[48]
4		What are the main benefits and challenges associated with using sustainable building materials?	[49]
5		How do you source sustainable building materials for your projects?	[46]
6	Life Cycle Assessment (LCA)	Are you familiar with the concept of Life Cycle Assessment (LCA)? If so, how do you apply it in your projects?	[50]
7		What are the key stages you consider in the life cycle of building materials?	[51]
8		How do you collect and analyze data for conducting an LCA in your projects?	[52]
9	Environmental Impacts	What are the primary environmental impacts you have observed from using conventional building materials?	[53]
10		How do sustainable building materials compare in terms of environmental impacts?	[47]
11	Challenges and Barriers	What challenges do you face in adopting sustainable building materials in your projects?	[6]
12		How do cost and availability influence your choice of building materials?	[46]
13	Policy and Regulation	Are there any specific policies or regulations that promote the use of sustainable building materials in Nigeria?	[6]
14		How effective are these policies in encouraging the adoption of sustainable practices?	[46]
15	Recommendations	What strategies do you recommend enhancing the adoption of sustainable building materials in the Nigerian construction industry?	[53

Table 3. Demography

No.	Demographic Category	Options
1	Gender	- Male
		- Female
		- Prefer not to say
2	Age	- 43
		- 61
		- 81
		- 101
		- 56 and above
3	Educational Level	- Diploma
		- Bachelor’s Degree
		- Master’s Degree
		- Doctorate
		- Other
4	Years of Experience in Construction Industry	- 0-5 years
		- 6-10 years
		- 11-15 years
		- 16-20 years
		- More than 20 years
5	Professional Role	- Architect
		- Engineer

No.	Demographic Category	Options
		- Contractor
		- Policy Maker
		- Other

Table 4. Questionnaire Survey

No	Category	Question	Citation
1	General Information	I am familiar with the concept of sustainable building materials.	[46]
2		I have used sustainable building materials in my projects.	[47]
3		Sustainable building materials are widely available in Nigeria.	[48]
4		The cost of sustainable building materials is a barrier to their adoption.	[6]
5		I believe sustainable building materials can significantly reduce environmental impacts.	[47]
6		I am aware of the environmental benefits of using sustainable building materials.	[46]
7		I have received training or education on sustainable building materials.	[49]
8		My organization encourages the use of sustainable building materials.	[6]
9		Sustainable building materials are durable and perform well over time.	[47]
10		The use of sustainable building materials is increasing in the Nigerian construction industry.	[46]
11	Sustainable Building Materials	I am knowledgeable about different types of sustainable building materials.	[48]
12		I believe bamboo is a viable sustainable building material.	[49]
13		Recycled steel is commonly used in sustainable construction projects.	[47]
14		Low-carbon concrete is an effective sustainable building material.	[46]
15		Eco-friendly insulation materials are important for sustainable construction.	[48]
16		I have used recycled glass in my construction projects.	[53]
17		Using reclaimed wood is a sustainable practice in the construction industry.	[46]
18		I consider the embodied energy of materials when selecting sustainable building materials.	[49]
19		Sustainable building materials enhance indoor environmental quality.	[47]
20		I believe the use of sustainable building materials can lead to cost savings over the building's lifecycle.	[53]
21	Life Cycle Assessment (LCA)	I am familiar with the Life Cycle Assessment (LCA) methodology.	[50]
22		I have applied LCA in evaluating the environmental impacts of building materials.	[51]
23		LCA is a useful tool for assessing the sustainability of building materials.	[52]
24		I consider all stages of the life cycle (cradle to grave) when conducting LCA.	[50]
25		Data collection for LCA is challenging in the Nigerian context.	[53]
26		The functional unit is crucial in LCA for consistent comparisons.	[54]
27		I believe that LCA results should guide material selection in construction projects.	[51]
28		LCA helps in identifying the environmental hotspots of building materials.	[47]
29		I consider the environmental impacts of transportation in the LCA of building materials.	[52]
30		LCA should be integrated into the early design phase of construction projects.	[51]
31	Environmental Impacts	The use of conventional building materials has significant environmental impacts.	[53]
32		Sustainable building materials help in reducing greenhouse gas emissions.	[47]
33		I believe that using sustainable building materials contributes to resource conservation.	[49]

No	Category	Question	Citation
34		The production of sustainable building materials consumes less energy than conventional ones.	[46]
35		Sustainable building materials are less polluting than conventional materials.	[53]
36		I consider the waste generation potential of materials in construction projects.	[47]
37		Sustainable building materials improve indoor air quality.	[49]
38		I am aware of the impact of building materials on biodiversity and ecosystem services.	[46]
39		(duplicate of 38) I am aware of the impact of building materials on biodiversity and ecosystems.	[46]
40		Using locally sourced sustainable materials reduces transportation-related impacts.	[53]
41		The end-of-life disposal of conventional building materials has major environmental impacts.	[47]
42		Reusing and recycling building materials can significantly reduce environmental impacts.	[49]
43		Sustainable building materials contribute to the circular economy.	[46]
44		The construction industry plays a major role in mitigating climate change.	[53]
45		I consider reuse and recycling potential when selecting building materials.	[47]
46		The environmental benefits of sustainable materials outweigh their initial cost.	[49]
47		Sustainable materials are essential for achieving green building certifications.	[46]

Survey and Secondary Data Collection

In this study, survey instruments (Tables 3 and 4) were distributed across a broad segment of the Nigerian construction sector to gather insights into sustainable material usage, professional awareness, and perceived barriers to adoption. The respondent pool included members of recognized professional organizations such as the Nigerian Institute of Architects (NIA) and the Nigerian Society of Engineers (NSE). A stratified random sampling method was adopted to ensure representative coverage across regional zones, disciplines, and organizational roles within the industry. A total sample size of 200 was targeted, ensuring a sufficiently powered dataset for quantitative interpretation, consistent with recommended practices in social science sampling frameworks [55].

The primary data collected from the surveys were supported by qualitative insights obtained through semi-structured interviews, as previously detailed. These data were further enriched by an extensive review of secondary sources, including scholarly journal articles, environmental product declarations (EPDs), technical bulletins, and relevant policy documents. These materials provided the foundational basis for Life Cycle Assessment (LCA) modeling and contextual analysis. The secondary literature focused on key themes such as material performance in tropical climates, energy intensity of local production systems, and the evolution of sustainable design regulations in Nigeria. Peer-reviewed sources such as [15] and [14] were particularly instrumental in identifying methodological benchmarks and contextual challenges relevant to developing countries.

The combination of structured survey responses and literature-driven insights enabled a robust triangulation of perspectives, enhancing the internal validity of the findings and aligning with best practices in mixed-method sustainability research.

Data Analysis Methods

The data analysis approach was anchored in a standardized Life Cycle Assessment (LCA) methodology, following the principles and procedural guidelines set forth in ISO 14040 and ISO 14044 [50, 54]. The application of this framework was tailored to reflect the specific conditions of Nigeria's construction sector, including variations in transportation infrastructure, energy supply chains, and regulatory enforcement.

The Life Cycle Inventory (LCI) phase constituted the first step in the analysis. This phase involved the systematic collection and organization of quantitative input-output data related to material production, energy usage, emissions, and end-of-life disposal. A triangulated approach was adopted to develop the LCI, combining primary data from interviews with local material suppliers and manufacturers, national industry averages, and global databases such as Ecoinvent and GaBi. Peer-reviewed literature also supplemented the inventory where empirical gaps were identified [56]. This hybrid approach enhanced the comprehensiveness and credibility of the LCI dataset, particularly in areas where local data were scarce or inconsistently reported.

Localization was a critical feature of this phase. Transport distances were calculated based on major inter-regional routes between material production centres and urban construction hubs. Emission coefficients were recalibrated to reflect Nigeria's grid energy profile, which is heavily reliant on fossil fuels. Construction practices such as manual labor intensity and hybrid equipment use were validated through stakeholder interviews and site visits, as suggested by. [57] and [14]. The overall data flow and contextual adjustment process is represented in Figure 2, which illustrates the methodological sequence from raw data acquisition to impact modelling.

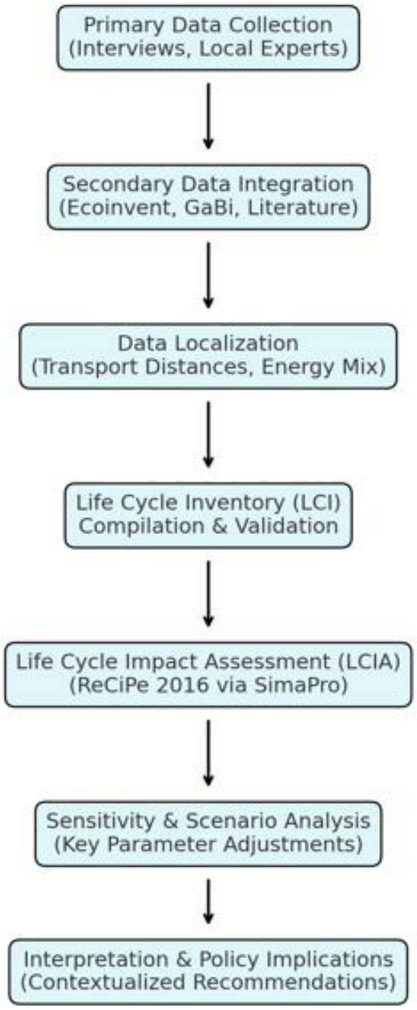

Figure 2. LCI and LCIA Workflow Adapted for Nigerian Context

The Life Cycle Impact Assessment (LCIA) was performed using the ReCiPe 2016 methodology implemented within the SimaPro software environment. This method was selected due to its dual-level characterization system, which offers midpoint indicators such as global warming potential, eutrophication, and acidification, as well as endpoint indicators covering ecosystem quality, human health, and resource scarcity [58]. This integrative framework as shown in Figure 2 enabled a multifaceted evaluation of material sustainability that was well-suited to the varied ecological and human health contexts of Nigerian construction.

Each environmental impact category included in the LCIA was selected based on its relevance to local conditions. Global warming potential was prioritized due to the carbon-intensive nature of Nigerian cement and steel production. Ozone depletion was considered considering the prevalent use of chlorofluorocarbon-based refrigerants in construction-related HVAC systems. Eutrophication and acidification were deemed critical due to poorly regulated runoff and combustion emissions. Fossil resource depletion reflected the country's reliance on non-renewable fuel sources, while human toxicity and freshwater ecotoxicity were added to capture the health impacts of informal construction and waste mismanagement. These categories are summarized with contextual justifications in Table 5.

To evaluate the robustness of the LCIA results, a sensitivity analysis was conducted. This involved systematic variation of key parameters such as energy sources, transport distances, and material lifespan assumptions. The results of this analysis identified transportation logistics and energy mix as the most influential variables in lifecycle emissions, aligning with similar findings in low- and middle-income country contexts [59]. This procedure enabled the identification of environmental hotspots within the building material supply chain, highlighting critical areas for future policy intervention and infrastructure investment.

Scenario analysis was also applied to simulate the environmental performance of alternative material compositions and energy sources. For instance, scenarios involving the substitution of Portland cement with fly ash or the use of solar-powered processing systems were modelled and compared to baseline values. These scenarios revealed potential reductions in global warming potential and fossil fuel depletion by up to 30%, reinforcing the case for renewable energy integration and industrial symbiosis strategies in Nigerian construction [56].

The final interpretative stage of the LCA extended beyond technical metrics to incorporate a socio-economic and regulatory perspective. This holistic interpretation aligned the LCA findings with observed market behaviours, policy gaps, and infrastructural realities. It also provided the basis for formulating strategic recommendations targeting government regulators, industry stakeholders, and academic institutions. These recommendations emphasized the need for institutional support, localized data development, and structured incentives to promote the adoption of sustainable materials at scale in Nigeria. These categories are summarized with contextual justifications in Table 5.

Table 5. Summary of Life Cycle Impact Categories (ReCiPe 2016)

Impact Category	Relevance in Nigerian Context
Global Warming Potential (GWP)	Critical due to high emissions from cement and diesel-powered machinery.
Ozone Depletion	Relevant for refrigerant management in cooling systems.
Eutrophication	Linked to construction runoff and sewage mismanagement.
Acidification	Driven by sulphur/nitrogen oxides from fuel combustion.
Fossil Resource Depletion	Tied to Nigeria's dependency on non-renewable energy sources.
Human Toxicity	Exposure risks from poorly regulated industrial emissions.
Freshwater Ecotoxicity	Impacts from construction waste near aquatic systems.

4. RESULTS AND DISCUSSION

Response Rate and Demographic Profile

Out of 200 distributed questionnaires, 180 responses were received, resulting in a 90% response rate. This high level of participation demonstrates strong engagement among professionals in the Nigerian construction sector regarding sustainability issues. The demographics of the respondents are presented in Figure 3, which shows diversity in gender, age, education, professional roles, and industry experience.

This table summarizes gender distribution, age brackets, highest educational qualifications, professional experience, and roles. The dominance of engineers (38.9%) and individuals with a Bachelor's or Master's degree (a combined 75%) provides a knowledgeable and experienced respondent base for evaluating sustainable construction materials.

Life Cycle Inventory Results

The life cycle inventory analysis spanned five major phases: material extraction and processing, transportation, construction, operational use and maintenance, and end-of-life disposal. Primary and secondary data sources were harmonized to ensure consistency and local relevance. Tables 6 to 10 present detailed LCI metrics for each material. Bamboo consistently demonstrated the lowest values across all phases, particularly in energy consumption and CO_2 emissions, affirming its environmental advantage. Recycled steel, although circular in concept, exhibited higher environmental loads due to intensive reprocessing and transportation. Low-carbon concrete displayed moderate impacts and presented a compelling case for cement replacement strategies.

Life Cycle Impact Assessment Results

The life cycle impact assessment, conducted using the ReCiPe 2016 method in SimaPro, offered quantifiable environmental performance metrics. Table 11 summarizes the results across five key categories: global warming potential, ozone depletion, eutrophication, acidification, and resource depletion. Bamboo outperformed both recycled steel and low-carbon concrete in every category. These findings confirm the viability of bamboo as a low-emission, low-impact material well-suited to the Nigerian context.

Sensitivity Analysis

A sensitivity analysis was performed by increasing bamboo’s transportation distance to 500 km, aligning it with recycled steel. Despite the increase, bamboo still maintained a lower emissions profile, highlighting its environmental resilience under varying logistics scenarios.

Scenario Analysis

Scenario modeling assessed three interventions: local sourcing, renewable energy in production, and extended lifespan. Each yielded substantial environmental improvements. Table 12 outlines the relative reductions achieved across these scenarios. Renewable energy use during production achieved the highest reduction in emissions (30%). Local sourcing followed with a 25% decrease, and extending lifespan provided a 20% improvement. These strategies demonstrate viable policy options for optimizing material sustainability

Comparison of Sustainable Building Materials

The comparative Life Cycle Assessment (LCA) of bamboo, recycled steel, and low-carbon concrete revealed distinct variations in environmental performance across all assessed life cycle stages. Among the three, bamboo emerged as the most environmentally advantageous material. Its extraction requires only 2.5 MJ/kg of energy, and its associated carbon emissions are minimal at 0.15 kg CO_2 per kilogram of material produced. These values are among the lowest for building materials assessed in tropical construction environments. The primary factors contributing to bamboo's superior performance include its rapid growth rate, renewability, low embodied energy, and limited need for industrial processing. Furthermore, bamboo actively sequesters carbon during its growth phase, which enhances its role as a negative-emission material when harvested responsibly. This makes it exceptionally suited for integration into sustainable design frameworks in Nigeria, where renewable resource availability is crucial.

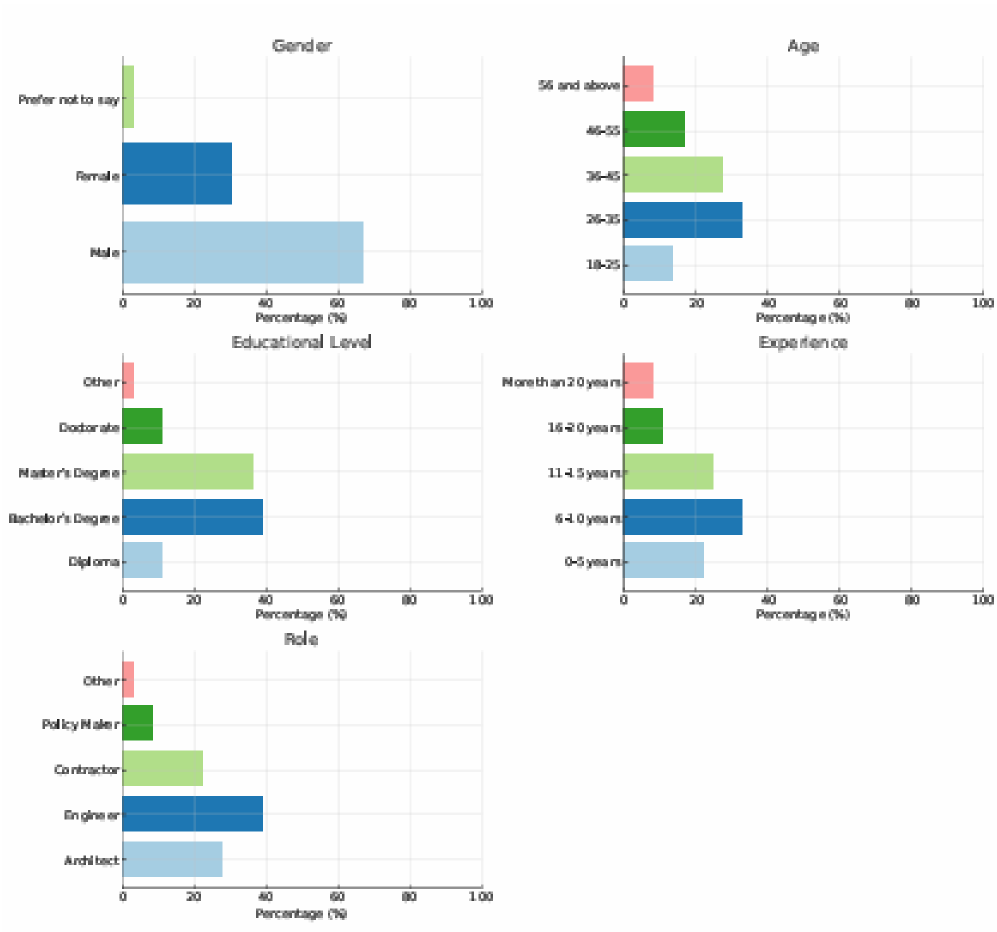

Figure 3. Demographic Profile of Respondents

Table 6. Energy Consumption and Emissions during Material Extraction and Processing

Material	Energy Consumption (MJ/kg)	CO_2 Emissions (kg CO_2/kg)	Other Emissions (kg/kg)
Bamboo	2.5	0.15	0.02 (Particulate Matter)
Recycled Steel	5.0	0.50	0.05 (SO_x, NO_x)
Low-Carbon Concrete	1.8	0.12	0.01 (Particulate Matter)

Table 7. Fuel Consumption and Emissions during Transportation

Material	Distance (km)	Fuel Consumption (L/km)	CO_2 Emissions (kg CO_2/km)
Bamboo	200	0.05	0.12
Recycled Steel	500	0.08	0.20
Low-Carbon Concrete	100	0.04	0.10

Table 8. Energy Consumption and Emissions during Construction

Material	Energy Consumption (MJ/m^2)	CO_2 Emissions (kg CO_2/m^2)	Other Emissions (kg/m^2)
Bamboo	15	1.0	0.1 (Particulate Matter)
Recycled Steel	25	2.0	0.2 (SO_x, NO_x)
Low-Carbon Concrete	20	1.5	0.1 (Particulate Matter)

Table 9. Energy Consumption and Emissions during Use and Maintenance

Material	Energy Consumption (MJ/m^2/year)	CO_2 Emissions (kg CO_2/m^2/year)	Other Emissions (kg/m^2/year)
Bamboo	5	0.3	0.02 (Particulate Matter)
Recycled Steel	8	0.5	0.04 (SO_x, NO_x)
Low-Carbon Concrete	6	0.4	0.03 (Particulate Matter)

Table 10. Energy Consumption and Emissions during End-of-Life Disposal

Material	Energy Consumption (MJ/m^2)	CO_2 Emissions (kg CO_2/m^2)	Other Emissions (kg/m^2)
Bamboo	10	0.7	0.05 (Particulate Matter)
Recycled Steel	12	1.0	0.08 (SO_x, NO_x)
Low-Carbon Concrete	8	0.6	0.04 (Particulate Matter)

Table 11. Environmental Impact Categories (ReCiPe 2016)

Impact Category	Bamboo	Recycled Steel	Low-Carbon Concrete
Global Warming Potential (kg CO_2-eq/m^2)	2.25	4.5	3.12
Ozone Depletion (kg CFC-11-eq/m^2)	0.0001	0.0002	0.00015
Eutrophication (kg PO_4-eq/m^2)	0.01	0.03	0.02
Acidification (kg SO_2-eq/m^2)	0.05	0.1	0.07
Resource Depletion (MJ/m^2)	33	55	40

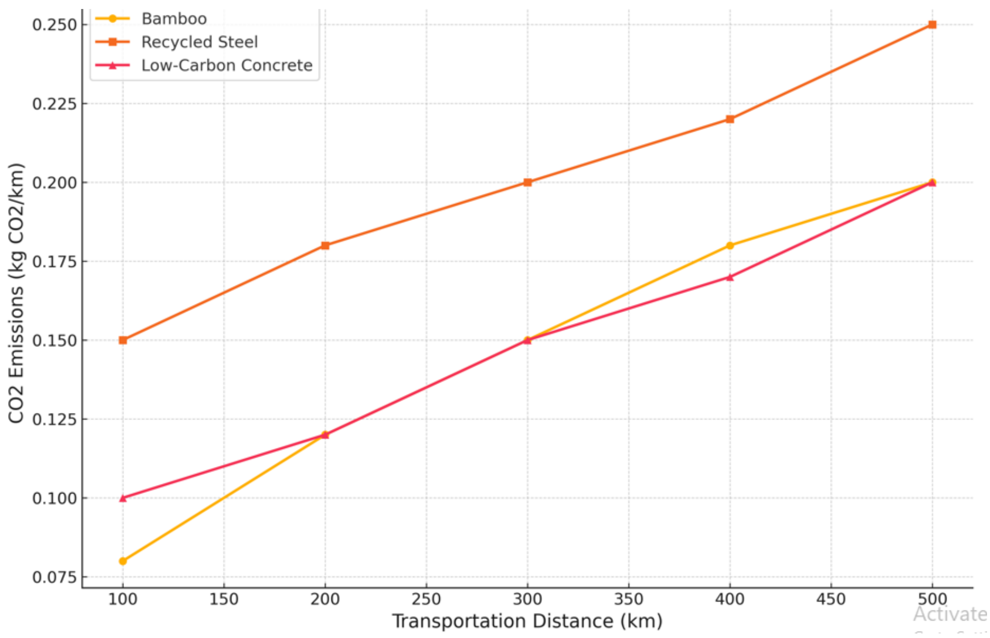

Figure 4. Sensitivity of CO_2 Emissions to Transportation Distance

Table 12. Environmental Benefits of Strategic Scenarios

Scenario	Key Findings	Environmental Impact (Relative to Baseline)
Local Sourcing	Significant reduction in transportation emissions	-25%
Renewable Energy Use	Substantial reduction in CO_2 emissions during production	-30%
Extended Lifespan	Further reduction in life cycle impacts	-20%

Low-carbon concrete also demonstrated notable environmental advantages, primarily attributed to the incorporation of supplementary cementitious materials (SCMs) such as fly ash, slag, or silica fume. These industrial by-products replace a significant portion of energy-intensive Portland cement, reducing emissions to 0.12 kg CO_2/kg and energy consumption to 1.8 MJ/kg. While not as low-impact as bamboo, low-carbon concrete offers significant improvements over traditional concrete formulations and retains structural and durability benefits required in commercial-scale applications. This balance of performance and reduced environmental burden establishes low-carbon concrete as a transitional material in green building innovation.

In contrast, recycled steel showed the highest environmental impacts among the three materials, with a life cycle energy requirement of 5.0 MJ/kg and carbon emissions of 0.50 kg CO_2/kg. These elevated figures are largely due to the high energy inputs required during the melting and reprocessing stages of steel recycling. However, despite its relatively high embodied energy, recycled steel contributes positively to resource efficiency by mitigating the need for virgin steel extraction and by promoting closed-loop material cycles. Its role in circular economy applications positions it as a sustainable alternative within structural systems where non-renewable materials are otherwise unavoidable.

Discussion of Findings in Relation to Research Questions

This study was structured around three central research questions: the environmental impacts associated with the life cycles of sustainable building materials used in Nigeria; how these materials compare with conventional alternatives; and what strategies could facilitate their broader adoption within the construction sector. The findings provide empirically grounded answers to each of these questions, supported by both quantitative LCA modelling and qualitative insights from industry professionals.

In addressing the first research question, the results clearly demonstrate that bamboo possesses the lowest environmental impact across key indicators, including global warming potential, resource depletion, acidification, and eutrophication. Bamboo's rapid renewability, combined with low processing demands and its capacity to act as a carbon sink during cultivation, solidifies its standing as the most sustainable of the materials studied. Moreover, the advantages of bamboo are further amplified when sourced locally, which minimizes transport emissions and supports regional economies. These findings underscore the critical importance of renewable bio-based materials in low-carbon construction strategies and suggest a clear priority area for material substitution in Nigerian buildings.

The second research question concerned the comparative performance of these sustainable materials relative to conventional counterparts and to each other. The findings show that while recycled steel incurs higher energy and emissions burdens during processing, it provides notable advantages in terms of landfill reduction, material reuse, and alignment with circular economy principles. Its performance, though less favourable than bamboo or low-carbon concrete in direct emissions, is superior to that of virgin steel, particularly when accounting for end-of-life recyclability. Low-carbon concrete presented a mid-range environmental profile, offering substantial emission reductions over conventional Portland cement concrete while meeting structural performance standards. These outcomes reflect broader global trends in sustainable construction, where hybrid material strategies—particularly cementitious substitutions—are becoming increasingly mainstream.

In response to the third research question, which explored pathways for promoting the use of sustainable building materials in Nigeria, several actionable strategies emerged from both the LCA findings and the qualitative stakeholder feedback. First, there is a pressing need for the Nigerian government to strengthen regulatory frameworks and enforce compliance through building codes that mandate or incentivize the use of sustainable materials. Regulatory tools such as green certification standards, environmental impact thresholds, and minimum content requirements for recycled or bio-based materials could help institutionalize sustainable practices across the industry.

Financial mechanisms must also play a role. Subsidies, tax relief programs, and green procurement policies can lower the economic barriers that currently limit the adoption of sustainable materials. In addition, expanding access to low-interest financing for green construction projects—particularly those that incorporate bamboo, low-carbon concrete, or recycled content—would encourage developers to prioritize environmental performance without compromising economic viability.

Education and capacity building are equally essential. Training programs aimed at architects, engineers, contractors, and policymakers should emphasize life cycle thinking, material innovation, and sustainable design methodologies. These initiatives can foster a more sustainability-literate workforce capable of implementing and advocating for greener construction methods. Enhancing local production capacity is another strategic imperative. Investment in domestic manufacturing facilities for eco-materials, coupled with targeted support for small- and medium-sized enterprises (SMEs), can ensure that materials like bamboo and low-carbon concrete are available, affordable, and scalable. Encouraging public-private partnerships for research and development will be critical in tailoring material solutions to the unique climatic and socio-economic conditions of Nigeria.

Overall, this study demonstrates that sustainable building materials—when selected based on localized LCA results and integrated into broader policy, economic, and educational frameworks—can significantly reduce the environmental footprint of Nigeria's construction industry. The findings confirm the viability of bamboo as an optimal low-impact material, support the adoption of low-carbon concrete as a transitional strategy, and validate recycled steel's role in advancing circular construction models. The strategic recommendations offered herein provide a roadmap for policymakers and industry stakeholders seeking to align construction practices with Nigeria's sustainable development goals.

5. CONCLUSION

This study employed a life cycle assessment (LCA) approach to evaluate the environmental impacts of three sustainable building materials—bamboo, recycled steel, and low-carbon concrete—within the Nigerian construction industry. The analysis revealed that bamboo consistently outperforms the other materials across all impact categories, including global warming potential, resource depletion, acidification, and eutrophication. Its rapid renewability, low embodied energy, and minimal emissions profile highlight its promise as a cornerstone of sustainable construction in Nigeria. Even when subjected to sensitivity and scenario modeling, bamboo's environmental superiority remained evident.

Low-carbon concrete emerged as a valuable intermediary solution. Its partial substitution of Portland cement with supplementary cementitious materials reduced both its carbon footprint and resource intensity. Although not as environmentally efficient as bamboo, its structural versatility and durability justify its inclusion in green construction practices. Recycled steel, while supportive of circular economy principles, was associated with the highest environmental burdens due to its energy-intensive recycling process and long transport distances. The study's findings underscore a critical opportunity for Nigeria to reduce construction-sector emissions and resource consumption by embracing sustainable materials. However, the path to adoption is hindered by systemic challenges including high initial costs, limited market availability, and inadequate production infrastructure. Strategic interventions are essential to overcome these barriers

Policy frameworks must be strengthened to embed sustainability into national construction codes, supported by incentives such as tax credits, low-interest loans, and subsidies for green projects. Regulatory mandates can accelerate the market transition by setting minimum environmental performance benchmarks for building materials. Capacity building through professional training and public education campaigns will also be pivotal in shifting industry mindsets and practices. Enhancing local production capabilities is a strategic imperative. Investing in domestic manufacturing, particularly for bamboo-based composites and alternative binders for low-carbon concrete, will reduce costs, enhance supply reliability, and stimulate local economies. Partnerships between government, academia, and the private sector will be key in driving innovation and developing scalable technologies tailored to regional needs.

Future research should expand the LCA database with region-specific inputs to improve the accuracy and applicability of sustainability assessments. Longitudinal studies assessing the in-use performance, durability, and cost-effectiveness of sustainable materials under Nigerian climatic and operational conditions are also recommended. Moreover, integrated assessments that combine environmental, economic, and social dimensions will offer a more holistic understanding of sustainability trade-offs in the built environment.

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Pemanfaatan *Slag* Feronikel dan *Silica Fume* sebagai Pengganti Sebagian Semen terhadap Kekuatan Tekan dan Tarik Belah Mortar Struktural

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INFORMASI ARTIKEL

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ABSTRAK

Pembangunan infrastruktur yang semakin meningkat akan menyebabkan bertambahnya konsumsi semen secara global. Penggunaan semen sebagai material konstruksi utama menyebabkan peningkatan emisi karbon dioksida (CO_2) sekitar 5-10% dari total emisi global. Emisi ini berdampak negatif terhadap lingkungan, termasuk penipisan lapisan ozon. Untuk mengurangi dampak negatif tersebut, perlu diupayakan material alternatif untuk dimanfaatkan sebagai bahan penggantian sebagian dari semen. Kajian ini mengevaluasi pengaruh penggantian sebagian semen dengan *slag* feronikel (SFN) dengan variasi sebesar 0 wt% hingga 30 wt% terhadap kekuatan tekan dan tarik belah mortar struktural. Hasil pengujian kekuatan tekan pada 28 hari menunjukkan bahwa mortar dengan substitusi SFN sebesar 0, 10, 20 dan 30 wt% memiliki kekuatan tekan sebesar 43,4 MPa, 51,5 MPa, 43,8 MPa, dan 29 MPa. Sedangkan, pada pengujian kuat tarik belah diperoleh nilai substitusi masing-masing adalah 1,4 MPa, 1,7 MPa, 1,6 MPa, dan 1,4 MPa untuk substitusi SFN sebesar 0, 10, 20 dan 30 wt%. Substitusi SFN sebesar 10 wt% memiliki kinerja terbaik yang dapat meningkatkan kekuatan tekan dan tarik belah sebesar 18,7% dan 25,4% apabila dibandingkan dengan campuran tanpa penggantian dengan SFN. Fenomena ini menunjukkan potensi pemanfaatan SFN dapat memberikan dampak positif sebagai material alternatif yang efektif untuk meningkatkan properti mekanis mortar yang lebih ramah lingkungan.

1. PENDAHULUAN

Pembangunan infrastruktur di Indonesia semakin meningkat, dimana penggunaan semen menjadi salah satu material konstruksi utama yang digunakan dalam keperluan pembangunan infrastruktur. Pertumbuhan infrastruktur yang masif turut mendorong peningkatan konsumsi semen sebagai bahan utama dalam material konstruksi, yang pada gilirannya menyebabkan peningkatan emisi karbon dioksida (CO_2) secara global, diperkirakan mencapai 7% hingga 8% dari total emisi akibat proses produksi semen [1]. Selain itu, pada pembuatan semen dihasilkan emisi gas rumah kaca (GRK) sekitar satu ton dan 1,5 hingga 10 kg NO_x yang dilepaskan pada setiap produksi satu ton semen [2]. Kondisi tersebut dapat memberikan dampak merugikan terhadap lingkungan, terutama melalui peningkatan suhu atmosfer yang berkontribusi terhadap percepatan fenomena pemanasan global.

Dalam dunia konstruksi, telah dilakukan berbagai upaya untuk mengurangi emisi CO_2 dan GRK dengan mencari material alternatif untuk menggantikan penggunaan semen. Para peneliti telah banyak melakukan riset terkait penggunaan material yang bersifat *pozzolanic* dan bersifat sementitus untuk menjadi bahan pengikat pada pembuatan beton dan mortar yaitu dengan memanfaatkan *fly ash*, *ground granulated blast furnace slag* (GGBFS), *slag* feronikel, dan, *silica fume* [3-6].

Tingkat produksi feronikel dari industri baja tahan karat menghasilkan limbah pertambangan yang tinggi yaitu *slag* feronikel (SFN) merupakan produk sampingan dari proses peleburan bijih nikel. Apabila tidak dikelola secara tepat, limbah tersebut berpotensi menimbulkan dampak lingkungan yang signifikan. Kandungan unsur-unsur berbahaya dalam SFN dapat mencemari sumber air dan tanah, yang pada akhirnya dapat menimbulkan masalah ekologis serta risiko terhadap kesehatan masyarakat. Oleh karena itu, para peneliti mengupayakan untuk dapat memanfaatkan SFN yang memiliki sifat *pozzolanic* untuk dijadikan sebagai bahan alternatif pengganti semen dalam produksi mortar dan beton [7, 8]. Upaya tersebut dapat menjadi suatu solusi yang menjanjikan dalam mendukung praktik konstruksi berkelanjutan serta mengurangi dampak negatif terhadap lingkungan.

Penelitian yang dilakukan oleh Djayaprabha dan Fatharani (2024) menunjukkan bahwa penggantian sebagian semen dengan SFN sebesar 20 wt% pada pasta semen dapat meningkatkan kekuatan tekan sebesar 5,43% dan 21,17% pada umur 28 dan 56 hari, dibandingkan dengan pasta semen tanpa penambahan SFN. Namun, penggantian SFN dengan kadar yang lebih besar dari 30 wt% berpotensi menurunkan kekuatan tekan yang signifikan [5]. Huang *et al.* (2017) juga menemukan hal yang sama bahwa penggantian sebagian semen dengan SFN di atas 30 wt% dapat menurunkan kekuatan tekan yang disebabkan oleh rendahnya reaktifitas FNS yang menyebabkan derajat hidrasi menjadi lebih rendah [9]. Sementara itu, Guan *et al*. (2021) memanfaatkan SFN sebagai pengganti sebagian semen putih pada pembuatan mortar arsitektural. Hasil penelitian menunjukkan bahwa penggantian sebagian semen dengan SFN sebesar 0 hingga 20 wt% hanya mampu mempertahankan kekuatan tekan dengan kisaran 0,3 hingga 2,32%. Namun demikian, penggantian sebagian semen dengan SFN dapat menurunkan porositas mortar, sehingga dapat meningkatkan durabilitasnya [10].

Silica fume (SF) merupakan produk sampingan dari industri peleburan silikon dan ferrosilikon, dengan partikel sangat halus yang kaya akan silika (SiO_2). Sifat *pozzolanic* pada SF memungkinkannya terjadinya reaksi dengan $Ca(OH)_2$, sebagai produk hidrasi dari semen, untuk membentuk lebih banyak senyawa kalsium silikat hidrat (C-S-H). Dengan terbentuknya C-S-H tambahan pada hidrasi semen dapat membantu meningkatkan ikatan yang baik antara matriks semen dan pasir pada mortar [11]. Penggunaan SF dapat membantu untuk meningkatkan kekuatan tekan untuk mendapatkan kriteria mortar struktural. Beberapa kriteria mortar struktural untuk diaplikasikan sebagai pekerjaan pasangan dinding maupun sebagai material perbaikan struktur adalah memiliki kekuatan tekan minimum pada hari ke-28 pada rentang 17,2 hingga 45 MPa [12].

Pada penelitian ini, mortar struktural dipersiapkan dengan menggunakan bahan dasar semen Portland komposit (PCC) dan SF. Selanjutnya, kajian pemanfaatan SFN untuk menggantikan sebagian semen dilakukan dengan mengganti sebagian semen dengan SFN dengan variasi sebesar 0, 10, 20, dan 30 wt%, variasi tersebut ditentukan berdasarkan rekomendasi dari kajian literatur yang telah dilakukan [5, 9]. Pengaruh penggantian sebagian semen dengan SFN dikaji terhadap densitas semu, kekuatan tekan, dan kekuatan tarik belah pada mortar struktural yang lebih ramah lingkungan.

2. MATERIAL

Semen Portland Komposit (PCC)

Semen yang digunakan adalah PCC yang dapat diperoleh secara komersial di Indonesia. PCC yang digunakan memiliki massa jenis sebesar 2,93 g/cm^3 yang diuji mengaju pada ASTM C188 [13]. Properti fisik dari PCC dapat dilihat pada Gambar 1(a).

***Silica Fume* (SF)**

SF yang digunakan adalah MAPEPLAST SF yang berasal dari PT Mapei Indonesia seperti terlihat pada Gambar 1(b). Standar ASTM C1240 [14] digunakan untuk menentukan massa jenis dari SF. Berdasarkan pengujian yang telah dilakukan, diperoleh besarnya massa jenis SF sebesar 2,13 g/cm^3.

***Slag* Feronikel (SFN)**

SFN diperoleh dalam bentuk bubuk halus dari PT Growth Java Industry seperti terlihat pada Gambar 1(c). Dengan menggunakan standar pengujian ASTM C188 [13] diperoleh besarnya massa jenis dari SFN sebesar 2,76 g/cm^3.

(a) PCC

(b) SF

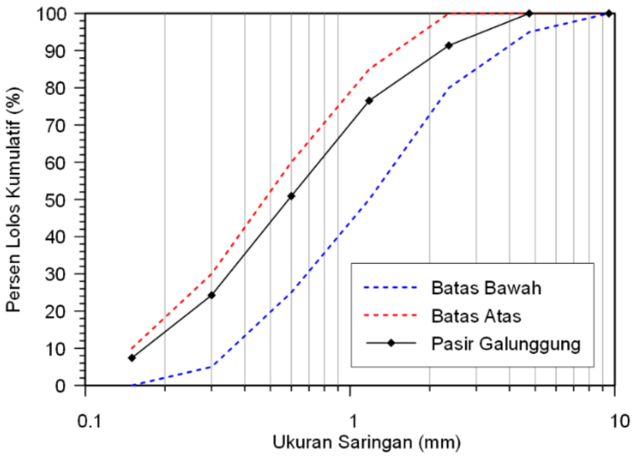
(c) SFN

Gambar 1. Bahan Pengikat Mortar Struktural

Tabel 1. Proporsi Campuran Mortar Struktural

Kode	w/cm	Air (kg/m³)	PCC (kg/m³)	SF (kg/m³)	SFN (kg/m³)	PG (kg/m³)	SP (%)
MS-SFN00	0,4	230,7	524,3	52,4	-	1441,8	1,21
MS-SFN10		230,4	471,3	52,4	52,4	1440,1	1,57
MS-SFN20		230,2	418,5	52,3	104,6	1438,6	1,78
MS-SFN30		229,9	365,8	52,3	156,8	1436,9	1,22

Keterangan: MS-SFN = mortar struktural dengan variasi penggantian PCC dengan SFN, angka menunjukkan persentase penggantian



Gambar 2. Kurva Gradasi Pasir Galunggung

Pasir Galunggung (PG)

Pasir Galunggung (PG) dengan *specific gravity* sebesar 2,55 dan absorpsi sebesar 4,57% dengan prosedur pengujian sesuai dengan ASTM C128 [15] digunakan untuk membuat mortar struktural. Kurva gradasi PG yang diuji dengan acuan ASTM C136/C136M [16] dapat dilihat pada Gambar 2. Terlihat pada kurva tersebut bahwa PG masuk dalam batasan gradasi yang ditentukan oleh ASTM C33/33M [17], dengan *fineness modulus sebesar* 2,49.

***Superplasticizer* (SP)**

Superplasticizer (SP) yang digunakan pada penelitian ini adalah Dynamon NRG 1030 yang memiliki massa jenis sebesar 1,04 g/cm³ dimana mempunyai fungsi utama SP adalah untuk mengontrol kelecakan dan mempercepat perkembangan kekuatan mekanis. Berdasarkan ASTM C494 [18] SP yang digunakan termasuk tipe C dan F.

3. METODOLOGI PENELITIAN

Pada penelitian ini, empat buah proporsi campuran mortar struktural dihitung berdasarkan metode volume absolut. Persentase penggantian sebagian semen dengan SFN dihitung berdasarkan rasio massa dari SFN:(PCC+SFN) pada variasi persentase sebesar 0:100, 10:90, 20:80, dan 30:70. Sedangkan persentase SF ditentukan berdasarkan rasio SF:(PCC+SFN) yang diambil dengan persentase sebesar 10:100. Pada penelitian ini rasio air terhadap material sementitus (w/cm) ditetapkan sebesar 0,4 berdasarkan *trial mix* yang dilakukan sebelumnya. Besarnya rasio pasir terhadap material sementitius, yaitu PCC, SF, dan SFN, ditetapkan sebesar 2,5 sesuai dengan penelitian sebelumnya [19]. Proporsi campuran mortar struktural dapat dilihat pada Tabel 1

Properti segar dari mortar struktural ditentukan dengan melakukan pengujian dengan menggunakan *flow table* dengan pengujian sesuai dengan acuan ASTM C1437 [20]. SP dipergunakan untuk mengontrol nilai *flow* sebesar 110±5% diperoleh sesuai dengan ketentuan ASTM C109/109M [21]. Kekuatan tekan mortar struktural diuji pada benda uji kubus 50-mm sesuai ketentuan ASTM C109/C109M [21]. Sedangan pengujian kekuatan tarik belah pada mortar struktural dilakukan dilakukan dengan mengadopsi prosedur pengujian dari ASTM C496 [22] yang diterapkan pada benda uji silinder mini dengan diameter 50 mm dengan tinggi 100 mm [19, 23]. Alat pengujian tekan dengan kapasitas 2000kN digunakan untuk memberikan gaya tekan untuk melakukan pengujian kekuatan tekan dan tarik belah pada umur 7, 14, dan 28 hari, dengan setting pengujian seperti terlihat pada Gambar 3.

4. HASIL DAN PEMBAHASAN

Properti Segar Mortar Struktural

Segera setelah proses pengadukan mortar selesai dilakukan, properti segar dari mortar struktural diuji dengan menggunakan *flow table*. Dimana campuran mortar segar yang sudah diketuk sebanyak 25 kali menggunakan *flow table* diukur diameter sebarannya sebanyak dua kali dengan mengambil dua buah diameter yang saling tegak lurus, kemudian dihitung diameter rata-ratanya (D_{avg}). Besarnya *flow* (F), yaitu dinyatakan sebagai besarnya peningkatan D_{avg} yang dinyatakan sebagai persentase pertambahan diameter awal mortar (D_0) yaitu sebesar 100 mm, sesuai dengan Persamaan (1). Data hasil pengujian properti segar mortar struktural dapat dilihat pada Tabel 2, terlihat bahwa semua campuran memiliki kelecakan yang telah memenuhi persyaratan dengan nilai *flow* sebesar 110±5%.

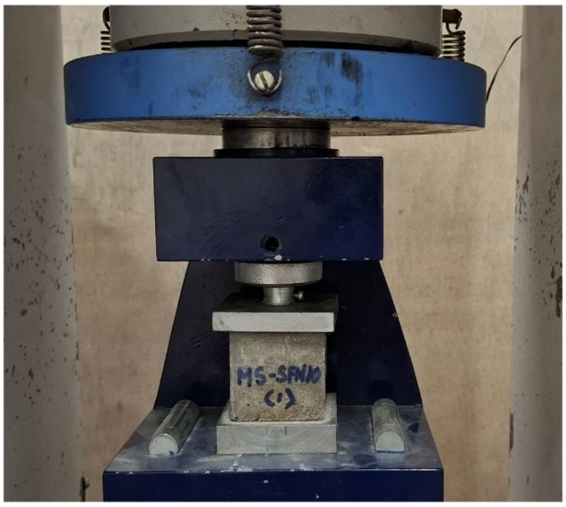
Densitas Semu

Densitas semu (*apparent density*) pada mortar struktural diperiksa pada dengan menimbang massa (m) dan volume aktual (V) benda uji. *Apparent density* (ρ_{app}) dihitung dengan menggunakan Persamaan (2) pada setiap umur pengujian 7, 14 dan 28 hari.

$$F = \left(D_{avg} - D_0 / D_0\right) \times 100\% \quad (1)$$

Tabel 2. Properti Segar Mortar Struktural

Kode	D_0 (mm)	D_{avg} (mm)	F (%)
MS-FNS00	100	208	108
MS-FNS10	100	205	105
MS-FNS20	100	215	115
MS-FNS30	100	205	105



(a) Pengujian Kekuatan Tekan

(b) Pengujian Kekuatan Tarik Belah

Gambar 3. *Setting* Pengujian

Berdasarkan data yang disajikan pada Tabel 3, *apparent density* dari mortar struktural menunjukkan peningkatan seiring dengan bertambahnya umur pengujian. Hal ini disebabkan oleh terbentuknya produk hidrasi C-S-H yang berkembang seiring waktu. Selain itu, kehadiran SF dan FNS dalam campuran mortar struktural turut mendorong terjadinya reaksi *pozzolanic* dimana $Ca(OH)_2$ terkonsumsi dan terbentuknya C-S-H tambahan [24]. Selanjutnya, terlihat bahwa *apparent density* mortar struktural mengalami penurunan seiring dengan peningkatan persentase penggantian sebagian semen dengan FNS. Penurunan ini disebabkan oleh nilai *specific gravity* dari FNS lebih kecil dari *specific gravity* PCC. Pada umur 28 hari, *apparent density* mortar struktural berada pada kisaran 2140,87 hingga 2164,36 kg/m^3.

$$\rho_{app} = m/V \quad (2)$$

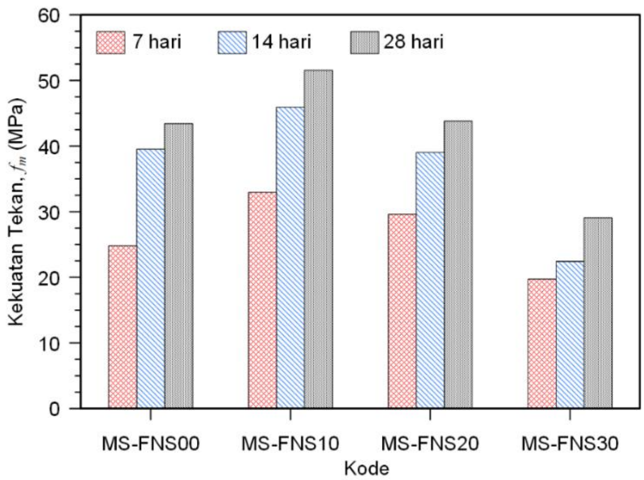
Tabel 3. Properti Segar Mortar Struktural

Kode	ρ_{app} (kg/m^3)		
	7 hari	14 hari	28 hari
MS-FNS00	2151,20	2159,33	2164,36
MS-FNS10	2142,91	2144,01	2156,79
MS-FNS20	2138,38	2145,26	2147,29
MS-FNS30	2085,74	2113,82	2140,87

Kekuatan Tekan

Pengujian kekuatan tekan mortar struktural (f_m) dihitung berdasarkan beban tekan maksimum (*P*) yang dapat dipikul oleh benda uji kubus 50-mm dengan luas penampang sebesar *A*. Kekuatan tekan mortar dapat dihitung menggunakan Persamaan (3)

$$f_m = P/A \quad (3)$$



Gambar 4. Kekuatan Tekan Mortar Struktural

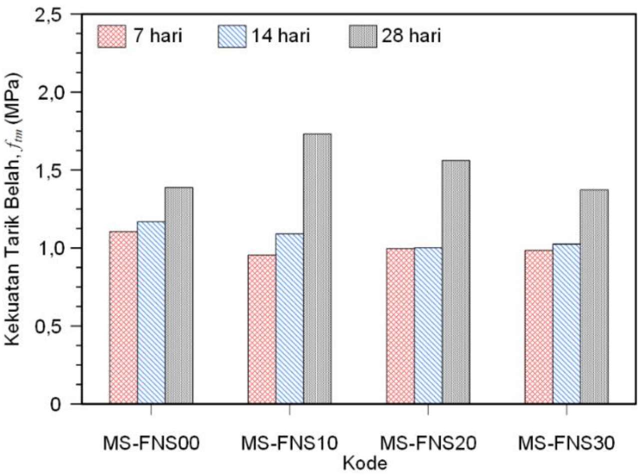
Hasil pengujian kekuatan tekan mortar struktural pada umur 7, 14 dan 28 hari dengan persentase penggantian sebagian semen dengan SFN sebesar 0 wt% (MS-SFN00), 10 wt% (MS-SFN10), 20 wt% (MS-SFN20), dan 30 wt% (MS-SFN30) dapat dilihat pada Gambar 4. Kekuatan tekan yang diperoleh pada umur 28 hari memiliki nilai kuat tekan sebesar 43,4 MPa, 51,5 MPa, 43,8 MPa, dan 29,0 MPa berturutan untuk MS-SFN00, MS-SFN10, MS-SFN20, dan MS-SFN30.

Hasil tersebut menunjukan bahwa campuran MS-SFN10 mempunyai hasil kekuatan tekan yang optimum dan dapat dikategorikan sebagai mortar struktural yang dapat dimanfaatkan sebagai mortar pada perbaikan struktur dengan kekuatan tekan yang melebihi 45,0 MPa [12]. Pengantian sebagian semen dengan SFN sebesar 10 wt% menunjukkan manfaat yang baik dengan ditunjukkannya peningkatan kekuatan tekan pada hari ke-28 sebesar 18,7%, apabila dibandingkan dengan kekuatan tekan mortar struktural tanpa menggunakan SFN. Penggantian semen dengan SFN yang terlampau banyak tidak mampu memberikan manfaat yang ditunjukkan dengan persentase penggantian sebesar 20% hanya dapat meningkatkan kekuatan tekan sebesar 0,9%, sedangkan penggantian sebesar 30% menurunkan kekuatan tekan sebesar 33,2%.

Kekuatan Tarik Belah

Uji kekuatan tarik belah dilakukan untuk mengetahui karakteristik tarik dari mortar struktural yang bermanfaat untuk menilai ketahanan terhadap retak yang dapat dipengaruhi oleh beban siklik, kadar air, dan pengaruh lingkungan [25, 26]. Kekuatan tarik belah (f_{tm}) dihitung dengan menggunakan Persamaan (4) dengan menghitung beban tekan maksimum (P_{max}) yang diaplikasikan pada silinder dengan tinggi (L) dan diameter (D) dan dengan rasio 2:1.

$$f_{tm} = 2P_{\max} / \pi LD \tag{4}$$



Gambar 5. Kekuatan Tarik Belah Mortar Struktural

Gambar 5 menunjukkan perkembangan kekuatan tarik belah dari mortar struktural pada umur 7, 14 dan 28 hari dengan variasi penggantian sebesar 0 wt%, 10 wt%, 20 wt%, dan 30 wt%. Hasil eksperimen menunjukkan bahwa kekuatan tarik belah 28 hari dari MS-SFA00, MS-SFA10, MS-SFA20, dan MS-SFA30 masing-masing secara berturutan adalah 1,4 MPa, 1,7 MPa, 1,6 MPa, dan 1,4 MPa. Sejalan dengan hasil kekuatan tekan, diperoleh pula bahwa MS-SFN10 memiliki kekuatan tarik belah yang optimum dan mampu meningkatkan kekuatan tarik belah pada hari ke-28 sebesar 25,36%, apabila dibandingkan dengan MS-SFN00. Produk hidrasi yang diperoleh dari hasil reaksi antara mineral amorf yang terkandung oleh SFN dengan *portlandite* yang akan menghasilkan C-S-H [9] yang dapat menambah ikatan matriks pada matriks mortar [11] yang dapat berpotensi untuk meningkatkan kekuatan tarik belah mortar.

5. KESIMPULAN

Berdasarkan kajian yang telah dilakukan, dapat disimpulkan bahwa pemanfaatan SF dan SFN dalam pembuatan mortar struktural memberikan manfaat signifikan dalam menciptakan material konstruksi yang lebih ramah lingkungan. Hasil pengujian menunjukkan bahwa substitusi sebagian semen dengan SFN sebesar 10 wt% menghasilkan kekuatan tekan optimum pada hari ke-28 sebesar 51,5 MPa, yang telah memenuhi kriteria mortar struktural. Kekuatan tekan ini meningkat sebesar 18,7% dibandingkan dengan mortar tanpa substitusi SFN. Selain itu, penggantian sebagian semen dengan SFN sebesar 10 wt% juga menghasilkan kekuatan tarik belah optimum sebesar 1,7 MPa, atau 24,7% lebih tinggi dibandingkan dengan mortar tanpa substitusi SFN. Dengan demikian, pemanfaatan SFN sebagai pengganti sebagian semen tidak hanya memberikan kontribusi positif terhadap keberlanjutan lingkungan, tetapi juga memiliki potensi besar untuk dimanfaatkan sebagai mortar struktural.

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Pemanfaatan Serbuk Cangkang Kerang sebagai Substitusi *Binder* pada Campuran Mortar Geopolimer

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ABSTRAK

Serbuk cangkang kerang dapat dijadikan material substitusi *binder* dalam campuran mortar geopolimer karena memiliki kandungan senyawa kimia pozzolan yaitu kapur (CaO), alumunium oksida (Al) dan silika (Si). Penelitian ini bertujuan untuk menganalisis pengaruh serbuk cangkang kerang sebagai substitusi *binder* terhadap kuat tekan mortar geopolimer. Persentase substitusi serbuk cangkang kerang terhadap *fly ash* sebesar 0%, 20%, 40% dan 60%. Sampel uji mortar geopolimer berbentuk kubus 5 cm x 5 cm x 5 cm. Uji kuat tekan mortar geopolimer dilakukan pada umur 7, 14, dan 28 hari. Dari hasil uji kuat tekan rata-rata mortar geopolimer diperoleh nilai maksimal sebesar 30,86 MPa pada subsitusi serbuk cangkang kerang dengan persentase 20% pada umur 28 hari. Semakin tinggi persentase substitusi cangkang kerang dalam campuran mortar geopolimer, maka kuat tekan rata-rata mortar geopolimer akan mengalami penurunan. Akan tetapi kuat tekan rata-rata seluruh variasi masih mencapai kuat tekan mortar tipe M di atas 17,16 MPa sesuai ASTM C270, sehingga serbuk cangkang kerang dapat direkomendasikan sebagai alternatif material konstruksi ramah lingkungan dan berkelanjutan serta diaplikasikan pada bangunan sebagai elemen dinding bata bertulang.

1. PENDAHULUAN

Beton merupakan material konstruksi bangunan yang seringkali digunakan di Indonesia, karena kelebihannya dibandingkan material lainnya yaitu sifat mekanis yang sangat baik serta dapat dirancang dalam berbagai ukuran dan bentuk [1]. Namun ada juga kekurangannya yaitu beton yang terbuat dari semen ternyata tidak ramah lingkungan. Industri semen memiliki dampak negatif terhadap lingkungan global, terutama karbon dioksida hasil pemrosesan bahan baku semen membuat lingkungan tercemar dan perubahan iklim buruk. Oleh karena itu, diperlukan resolusi untuk mengatasi permasalahan tersebut. Salah satu resolusinya yaitu penggunaan beton bebas semen, seperti beton geopolimer.

Beton geopolimer menggunakan material limbah industri, salah satunya *fly ash* (FA) sebagai material pengikat dalam komposisi penyusunnya. FA limbah hasil pembakaran batu bara di Pembangkit Listrik Tenaga Uap (PLTU), halmana jumlahnya akan bertambah seiring dengan berproduksinya industri. FA dikenal sebagai salah satu alternatif *binder* yang digunakan dalam pembuatan beton geopolimer, karena kandungan silikanya [37-38][40].

Selain menggunakan material FA, beton geopolimer pun dapat berinovasi dengan menggunakan material limbah cangkang kerang. Limbah cangkang kerang biasanya hanya digunakan kembali sebagai hiasan, pakan ternak dan campuran kosmetik sedangkan jumlah limbah cangkang kerang semakin bertambah seiring dengan berkurangnya proses pengolahan.

Limbah serbuk cangkang kerang (SCK) dapat dimanfaatkan sebagai material pengganti FA pada beton geopolimer. Hal ini dikarenakan kandungan kalsium karbonat ($CaCO_3$) dalam limbah SCK tergolong tinggi yaitu 95% hingga 99%, terutama pada kerang dara [2-5]. Kalsium karbonat ini yang dapat dikalsinasi menjadi kalsium oksida (CaO, atau yang umum dikenal dengan kapur) setelah dipanaskan pada suhu 800°C [3-7]. Kandungan kapur yang berasal dari kerang dapat digolongkan menjadi limbah biomaterial, dan berpotensi dapat dimanfaatkan menjadi material subtitusi semen dengan proses hidrasi yang tepat [4-5].

Beberapa tahun belakangan, penelitian mengenai campuran senyawa kapur hasil limbah batu kapur sangat populer terutama sebagai bahan dasar pembuatan *paving block*. Kuat tekan *paving block* dapat meningkat 17% ketika menggunakan kapur sebagai bahan tambahan [32]. Hal ini mengundang perhatian beberapa peneliti untuk melanjutkan penelitian tersebut, dan mengadopsinya pada beton struktural. Senyawa kapur merupakan senyawa pozzolan yang berpotensi untuk meningkatkan karakteristik beton. Namun, belum banyak penelitian mengenai variasi dan komposisi SCK sebagai substitusi FA, serta pengaruhnya terhadap kuat tekan. Penelitian mengenai variasi dan komposisi penggunaan limbah biomaterial cangkang kerang sangat penting untuk memperdalam pemahaman terhadap karakter geopolimer. Pemahaman dan pengetahuan ini diperlukan sabagai dasar pembentukan acuan spesifikasi mengenai pembuatan beton atau mortar geopolimer. Oleh karena itu, perlu adanya penelitian terhadap rancangan atau *mix design* terhadap variasi komposisi kandungan kapur dari hasil pengolahan limbah cangkang kerang.

2. TINJAUAN PUSTAKA

Komposisi mortar geopolimer terdiri dari 3 (tiga) material utama, yaitu material alam non-organik yang mengandung silika dan alumina (seperti FA), alkali aktivator, dan agregat halus [5]. FA dapat disubtitusikan dengan abu sekam padi (ASP) dari pembakaran sekam padi [6], limbah bata ringan [24], ataupun limbah kaca [34]. Hal ini dikarenakan material alam non-organik tersebut bersifat pozzolanik. Namun, pada penelitian ini, FA akan disubtitusikan dengan limbah SCK digunakan sehingga diharapkan dapat meningkatkan kemampuan ikat serta kekuatan tekan.

SCK mengandung unsur kimia pozzolan yaitu zat kapur (CaO), alumina (Al), dan *s*ilika (Si) sehingga berpotensi untuk meningkatkan sifat karakteristik beton geopolimer. Proses *pre-treatment* cangkang kerang melibatkan pembersihan, pembakaran pada suhu 700°C selama 2 jam, dan penghalusan menggunakan alat mortar hingga menghasilkan serbuk kerang yang homogen, yang akan menjadikan campuran beton lebih reaktif [34]. SCK memiliki potensi sebagai material substitusi kapur dalam pembuatan semen karena komposisi limbah SCK yang telah mengalami pembakaran pada suhu 700°C menghasilkan CaO sebesar 55,10% [4]. Kandungan CaO pada material prekursor ternyata memiliki pengaruh besar terhadap hasil pengerasan pada beton geopolimer.

Berbagai penelitian telah menunjukkan bahwa persentase penambahan cangkang kerang memiliki pengaruh signifikan terhadap kekuatan tekan, baik beton normal [2][7-8][10-12][15-23][26-31][35-38][40] maupun beton geopolimer [11][14]. Kekuatan tekan optimal beton geopolimer diperoleh dengan penambahan 10% cangkang kerang laut, sedangkan penggantian cangkang kerang melebihi 10% justru menurunkan kekuatan tekannya [39]. Pola serupa juga diamati dalam penelitian dengan menggunakan serbuk cangkang telur ayam sebagai substitusi parsial abu terbang, halmana hasil optimal dicapai pada substitusi 10% dengan kuat tekan beton mencapai 25,25 MPa [23].

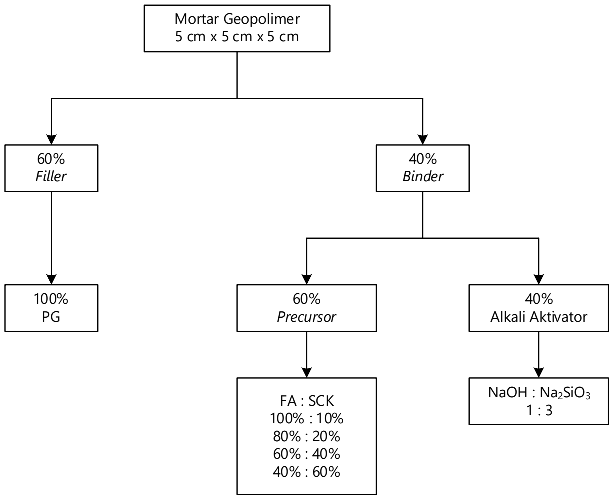
Meski cangkang kerang terbukti meningkatkan kuat tekan, namun beberapa penelitian juga menunjukkan adanya penurunan signifikan pada jumlah persentase tertentu. Studi komprehensif menunjukkan penurunan kekuatan yang signifikan pada spesimen dengan penambahan cangkang kerang melebihi 10% [24]. Pada spesimen dengan 30% cangkang kerang terjadi penurunan kekuatan sebesar 12,4%, kekuatan tekan semula 23,91 MPa (dengan 10% cangkang kerang) berubah menjadi 20,94 Mpa [7]. Penambahan 50% cangkang kerang bahkan menurunkan kinerja kekuatan spesimen lebih jauh menjadi 19,51 MPa, dengan total pengurangan 18,4% pada usia 28 hari [8-9]. Data ini menunjukkan adanya ambang batas optimal untuk penambahan cangkang kerang dalam campuran beton geopolimer.

Penambahan cangkang kerang dalam jumlah berlebihan pada sistem geopolimer berbasis abu terbang dapat menyebabkan reaksi ekspansif yang merugikan. Penambahan cangkang kerang (dengan kandungan senyawa Ca lebih dari 90%) pada abu terbang dengan kandungan Ca tinggi (abu terbang Kelas C) cenderung menghasilkan senyawa Ca yang tidak bereaksi [1]. Reaksi polimerisasi antara Si dan Al menggunakan sebagian besar senyawa Si dalam spesimen geopolimer untuk membentuk matriks geopolimer dan meninggalkan kelebihan Ca yang tidak bereaksi [1][3][16]. Ca yang tidak bereaksi ini kemudian menjalani reaksi hidrasi untuk membentuk senyawa kalsium hidroksida, yang dapat menyebabkan ekspansi beton dan menciptakan retakan dalam spesimen geopolimer [2][7]. Oleh karena itu, diperlukan adanya penelitian baru terkait justifikasi terhadap batas optimal penggunaan serbuk cangkang kerang untuk beton geopolimer.

3. METODOLOGI PENELITIAN

Penelitian diawali dengan pengujian kualitas material penyusun campuran mortar geopolimer, baik material pengikat (*binder*) maupun material pengisi (*filler*). Pengujian kualitas material ini bertujuan untuk mengetahui mutu materialnya sudah memenuhi persyaratan berdasarkan SNI 03-1968-1990, SNI 03-4804-1998, SNI 03-6825-2002, SNI 1970:2008, SNI 1971:2011 dan SNI 2861:2014. Pengujian yang dilakukan meliputi uji berat jenis dan kadar penyerapan baik material pengikat maupun material pengisi, serta modulus kehalusan material pengisi.

Selanjutnya, hasil uji berat jenis material penyusun menjadi tolak ukur untuk menentukan *trial and error mix design* campuran mortar geopolimer. Komposisi material penyusun mortar geopolimer yang digunakan pada penelitian ini merupakan hasil dari *trial and error mix design* penelitian-penelitian terdahulu [5-6][9][23][33], yang tersusun atas 60% material pengisi dan 40% material pengikat. Material pengikat tersusun atas 60% *precursor* (FA dan/atau SCK) dan 40% alkali aktivator berkonsentrasi 10M. Alkali aktivator tersusun atas Natrium Hidroksida (NaOH) dan Natrium Silikat (Na_2SiO_3) dengan rasio 1:3. Komposisi material penyusun mortar geopolimer disajikan pada Gambar 1. Persentase substitusi SCK sebesar 0%, 20%, 40% dan 60% terhadap FA. Jenis cangkang kerang yang digunakan pada penelitian ini adalah jenis limbah SCK yang paling mudah diperoleh yaitu cangkang kerang dara. Material lainnya yang digunakan yaitu agregat halus berupa Pasir Galunggung, FA kelas F dari Pembangkit Listrik Tenaga Uap (PLTU) Paiton.

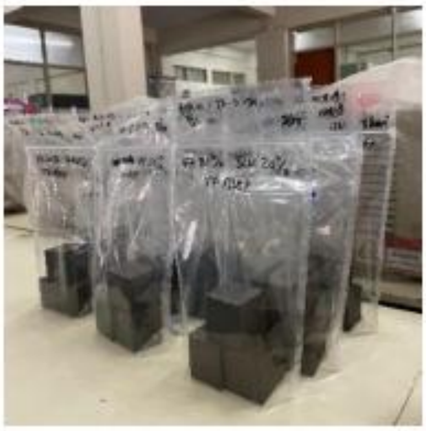


Gambar 1. Komposisi Campuran Mortar Geopolimer

Uji waktu ikat mortar geopolimer dilakukan sebelum uji kuat tekan dengan menggunakan alat CTM (*Compression Testing Machine*). Sampel uji mortar geopolimer berbentuk kubus 5 cm x 5 cm x 5 cm sesuai dengan SNI 03-6825-2002. Uji kuat tekan dilakukan pada usia 7, 14 dan 28 hari. Total sampel uji mortar geopolimer disajikan pada Tabel 1. Metode perawatan yang diaplikasikan pada mortar geopolimer yaitu *membrane curing*, halmana sampel uji dibungkus dengan menggunakan plastik kedap air supaya menghasilkan mutu sampel uji sesuai dengan ASTM C270. Gambar 2 memperlihatkan metode perawatan pada sampel uji mortar geopolimer.

Tabel 1. Jumlah Sampel Uji Mortar Geopolimer per Usia

Variasi	**Jumlah Sampel untuk Usia [hari]**		
	7	**14**	**28**
1(100%FA:0%SCK)	3	3	3
2(80%FA:20%SCK)	3	3	3
3(60%FA:40%SCK)	3	3	3
4(40%FA:60%SCK)	3	3	3



Gambar 2. Metode *Curing Membrane* Pada Sampel Uji Mortar Geopolimer

4. HASIL DAN PEMBAHASAN

Hasil Uji Kualitas Material Pengisi

Material pengisi yaitu agregat halus, Pasir Galunggung (PG) yang berasal dari Tasikmalaya. PG biasanya lolos saringan no. 4 ukuran 4,75 mm. Sifat fisik material pengisi seperti berat jenis, berat isi kadar air, kadar lumpur dan modulus kehalusan diketahui setelah dilakukan uji kualitas material. Data hasil uji kualitas material pengisi (agregat halus) bertujuan untuk memastikan terpenuhinya standar kualitas material yang ditetapkan. Tabel 3 menyajikan hasil uji kualitas PG yang digunakan.

Tabel 3. Hasil Uji Kualitas Material Pengisi

Uji	**Material Pengisi**	**Standar Kualitas**	**Keterangan**
Berat Jenis [gr/cm^3]	2,53	2,1-2,19	Memenuhi
Absorpsi [%]	2,49	<5	Memenuhi
Berat Isi [gr/cm^3]			
- padat	1,61	1,2-1,75	Memenuhi
- gembur	1,57	1,2-1,75	Memenuhi
Kadar Air [%]	2,25	<5	Memenuhi
Kadar Lumpur [%]	4,90	<5	Memenuhi
Modulus Kehalusan [%]	2,89	1,5-3,8	Memenuhi

Dari Tabel 3, seluruh parameter yang diuji sudah memenuhi standar kualitas yang ditetapkan.

Hasil Uji Kualitas Material Pengikat

Material pengikat yaitu *Fly Ash* (FA) tipe F berasal dari PLTU Paiton, serta Serbuk Cangkang Kerang (SCK) berasal dari Kabupaten Pasuruan. SCK lolos saringan no. 200. Sifat fisik material pengikat yang diuji kualitas materialnya, hanya berat jenis saja. Data hasil uji kualitas material pengikat, terutama *fly ash*, bertujuan untuk memastikan terpenuhinya standar kualitas material yang ditetapkan dan keakuratan data sebagai acuan dalam *trial and error mix design*. Tabel 4 menyajikan hasil uji kualitas FA dan SCK yang digunakan.

Tabel 4. Hasil Uji Kualitas Material Pengikat

Uji	**Material Pengisi**	**Standar Kualitas**	**Keterangan**
Fly Ash Berat Jenis [gr/cm^3]	2,56	2,1-2,9	Memenuhi
Serbuk Cangkang Kerang Berat Jenis [gr/cm^3]	2,20	2,1-2,9	Memenuhi

Dari Tabel 4, seluruh parameter yang diuji sudah memenuhi standar kualitas yang ditetapkan.

Hasil *Mix Design* Mortar Geopolimer

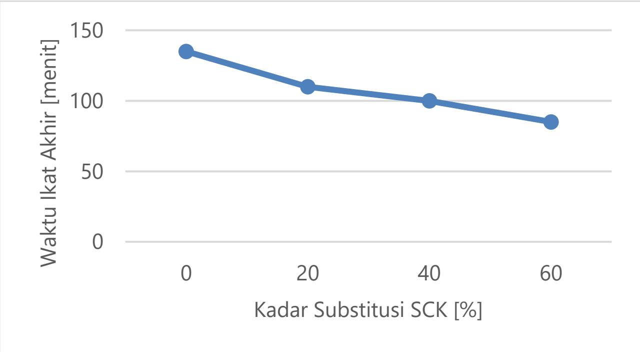
Kadar maksimal dari SCK yang digunakan sebagai substitusi FA yaitu 40%, walaupun juga dicoba kadar SCK sebesar 100% dan tidak menggunakan FA sama sekali namun campuran mortar geopolimer tidak dapat tercampur dengan baik. Kuat tekan rencana mortar geopolimer dirancang berdasarkan SNI 2847:2019 untuk kegunaan SRPMK dan SDK sebesar 21 MPa. Proporsi campuran mortar geopolimer terkoreksi disajikan pada Tabel 5. Variasi 1 100%FA:0%SCK (mortar geopolimer kontrol), variasi 2 80%FA:20%SCK, variasi 3 60%FA:40%SCK dan variasi 4 40%FA:60%SCK.

Tabel 5. Hasil *Mix-design* Mortar Geopolimer

Material	**Variasi *Mix-Design***			
	1	**2**	**3**	**4**
FA [gr]	80,77	64,61	48,61	32,31
SCK [gr]	0,00	13,86	27,72	41,58
PG [gr]	198,92	198,92	198,92	198,92
NaOH [gr]	11,18	11,18	11,18	11,18
Na_2SiO_3 [gr]	37,80	37,80	37,80	37,30

Hasil Uji Waktu Ikat Mortar Geopolimer

Reaksi kimia polimerisasi antara prekursor (FA dan/atau SCK) dengan larutan alkali activator ternyata sangat berpengaruh terhadap hasil uji waktu ikat. Nilai waktu ikat akhir diperoleh dari lamanya waktu pengerasan antara pasta FA dan/atau SCK pada campuran mortar geopolimer. Nilai waktu ikat akhir yang optimal akan menghasilkan sampel uji mortar geopolimer dengan kuat tekan maksimum. Hasil uji waktu ikat akhir seluruh variasi campuran mortar geopolimer disajikan pada Gambar 3.

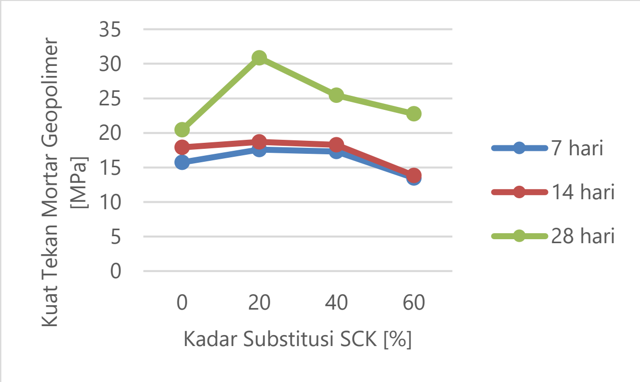


Gambar 3. Hasil Uji Waktu Ikat Akhir Mortar Geopolimer

Gambar 3 memperlihatkan semakin besar kadar substitusi SCK terhadap FA maka semakin cepat waktu ikat akhirnya. Hal ini dikarenakan kandungan unsur silika yang terdapat pada SCK sangat kecil sebesar 0,15%. Mortar geopolimer mengalami pengerasan tercepat pada variasi 4 (40%FA:60%SCK) selama ±85 menit, sedangkan waktu ikat akhir paling lama terdapat pada variasi 1 (100%FA:0%SCK) selama ±135 menit. Oleh karena itu, komposisi material pengikat (FA dan/atau SCK) dalam campuran mortar geopolimer ternyata sangat berpengaruh terhadap nilai waktu ikat akhir sehingga diperlukan material tambahan lainnya seperti retarder untuk memperlambat waktu ikat akhir mortar geopolimer jika ingin menggunakan SCK sebagai substitusi FA.

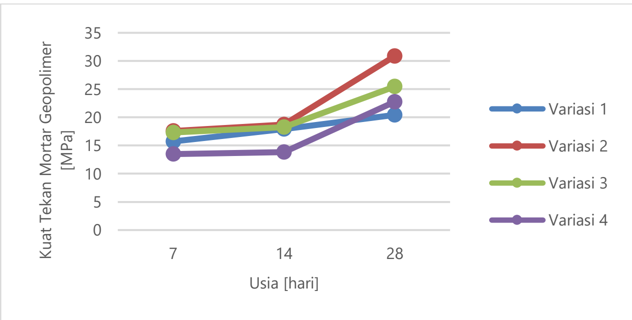
Hasil Uji Kuat Tekan Mortar Geopolimer

Kuat tekan mortar geopolimer ternyata mengalami penurunan seiring dengan peningkatan kadar substitusi SCK terhadap FA. Kuat tekan rerata mortar geopolimer pada variasi 1, variasi 2, variasi 3 dan variasi 4 berturut-turut pada usia 28 hari sebesar 20,43 MPa; 30,86 MPa; 25,45 MPa dan 22,76 MPa. Nilai kuat tekan rerata ini ternyata melebihi kuat tekan mortar tipe M yaitu 17,16 MPa untuk kegunaan dinding bata bertulang seperti pada ASTM C270. Gambar 4 menyajikan pola peningkatan kuat tekan rerata mortar geopolimer.



Gambar 4. Kadar Substitusi SCK Terhadap Kuat Tekan Mortar Geopolimer

Kuat tekan rerata untuk seluruh variasi menunjukkan peningkatan seiring bertambahnya usia mortar geopolimer. Namun hal ini berbanding terbalik dengan kadar substitusi SCK-nya, semakin besar kadar substitusi SCK terhadap FA maka semakin kecil kuat tekan reratanya sehingga SCK memberikan pengaruh yang kurang baik terhadap reaksi kimia polimerisasi antara *precursor* dan alkali activator. Mortar geopolimer yang memiliki kuat tekan rerata tertinggi yaitu pada variasi 2, dengan kadar substitusi SCK sebesar 20% terhadap FA. Hasil pengujian kekuatan tekan mortar struktural pada umur 7, 14, dan 28 hari dengan persentase substitusi FA dengan SCK sebesar 0% (Variasi 1), 20% (Variasi 2), 40% (Variasi 3), dan 60% (Variasi 4) dapat disajikan pada Gambar 5. Dari Gambar 5 tersaji bahwa kadar optimum penggunaan SCK sebagai subtitusi FA dalam campuran mortar geopolimer yaitu 20%.



Gambar 5. Hubungan Usia Sampel Uji Terhadap Kuat Tekan Mortar Geopolimer

Hasil tersebut menunjukan bahwa campuran variasi 2 mempunyai hasil kekuatan tekan yang optimum dan dapat diaplikasikan dan dimanfaatkan elemen struktural pada bangunan gedung SRPMK ataupun SDK dengan kekuatan tekan yang melebihi 21 MPa. Substitusi FA dengan SCK sebesar 20% menunjukkan potensi dan manfaat yang sangat baik dengan ditunjukkannya peningkatan kekuatan tekan pada hari ke-28 sebesar 51,05%; apabila dibandingkan dengan kekuatan tekan mortar geopolymer tanpa SCK. Substitusi FA dengan SCK yang banyak tidak juga mampu memberikan potensi dan manfaat yang ditunjukkan dengan kadar substitusi SCK sebesar 40% hanya dapat meningkatkan kekuatan tekan sebesar 24,57%; sedangkan penggantian sebesar 60% menurunkan kekuatan tekan sebesar 11,40%.

5. KESIMPULAN

Berdasarkan hasil analisis yang telah dilakukan dapat disimpulkan bahwa pemanfaatan SCK dalam pembuatan mortar geopolimer ternyata mampu menciptakan alternatif material konstruksi berkelanjutan dan ramah lingkungan. Hasil uji menunjukkan bahwa kadar substitusi SCK sebesar 20% terhadap FA (variasi 2) ternyata mampu menghasilkan kekuatan tekan mortar tertinggi pada usia 28 hari yaitu sebesar 30,86 MPa yang tercapainya kekuatan tekan mortar tipe M yang disyaratkan ASTM C270. Kekuatan tekan ini meningkat sebesar 51,05% dibandingkan dengan mortar geopolimer normal. Oleh karena itu, pemanfaatan SCK sebagai substitusi FA berpotensi untuk diaplikasikan dan dimanfaatkan sebagai elemen dinding bata bertulang.

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