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Kajian Eksperimental untuk Mengukur Kinerja *Ground Granulated Blast Furnace Slag* sebagai Pengganti Sebagian Semen terhadap Kekuatan Tekan dan Sorptivitas *Self-Compacting Mortar*

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ABSTRAK

Peningkatan pembangunan infrastruktur di Indonesia, berdampak pada permintaan semen yang semakin meningkat. Industri semen menyumbangkan sekitar 8% emisi karbondioksida di dunia yang signifikan memberikan dampak buruk bagi lingkungan. *Ground Granulated Blast Furnace Slag* (GGBFS), yang merupakan limbah indutri padat, dapat dimanfaatkan menjadi salah satu alternatif bahan substitusi sebagian semen untuk membuat material konstruksi yang ramah lingkungan. Penelitian ini bertujuan untuk mengetahui pemanfaatan limbah industri yaitu GGBFS sebagai substitusi semen pada mortar mutu tinggi untuk membuat *self-compacting mortar* (SCM). Variasi substitusi sebagian semen dengan GGBFS yang diambil untuk membuat SCM adalah sebesar 0%, 10% dan 20%. Tujuan dari penelitian ini adalah untuk mengetahui pengaruh dari sustitusi sebagian semen dengan GGBFS terhadap kekuatan tekan dan sorptivitas. Rasio air terhadap binder (w/b) diambil sebesar 0,3. Berdasarkan hasil yang telah diperoleh, kekuatan tekan SCM pada variasi 20% mencapai 61,8 MPa pada umur 28 hari. Pada campuran yang sama, diperoleh nilai *initial absorption* sebesar 0,0076 dan *secondary absorption* sebesar 0,0024 yang mengindikasikan campuran dengan substitusi sebagian semen dengan GGBFS sebesar 20% memiliki tingkat penyerapan air yang rendah dan memiliki durabilitas yang baik. Pemanfaatan GGBFS sebagai substitusi sebagian semen memiliki manfaat yang positif untuk menciptakan material konstruksi yang ramah lingkungan.

Kata kunci: *ground granulated blast furnace slag*, kekuatan tekan, *self-compacting mortar*, sorptivitas

1. PENDAHULUAN

Semen merupakan salah satu material konstruksi utama penyusun mortar dan beton pada pembangunan infrastruktur. Dimana, pada pembuatan semen dihasilkan emisi gas karbondioksida (CO_2) yang tinggi sehingga berdampak buruk bagi lingkungan, yang dapat menyebabkan terjadinya kenaikan suhu pada atmosfer yang dapat memicu pemanasan global. Proses pembuatan semen berkontribusi sebesar 8% dalam menyumbang emisi gas rumah kaca di dunia. Emisi CO_2 tersebut berasal dari proses pembakaran pada suhu yang tinggi dan konsumsi energi yang tinggi dalam pembuatan semen [1]. Dengan proyeksi bahwa pembangunan infrastruktur

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menggunakan semen akan terus semakin meningkat, maka akumulasi dari emisi CO_2 yang dihasilkan oleh industri semen dapat mencapai 470 GT dalam rentang 30 tahun ke depan [2].

Untuk mengurangi emisi gas rumah kaca yang signifikan yang diakibatkan dari produksi semen, maka diperlukan suatu material alternatif yang dapat menggantikan sebagian semen sebagai bahan pengikat. Terdapat beberapa material yang umumnya dapat digunakan sebagai bahan pengganti sebagian semen karena memiliki sifat yang sementitus dan pozzolanik, yaitu *ground granulated blast furnace slag* (GGBFS), *fly ash*, *silica fume*, dan metakaolin [3].

Pemanfaatan GGBFS sebagai material alternatif pengganti semen sudah dilakukan lebih dari 60 tahun lamanya. GGBFS merupakan bahan pengganti sebagian semen yang ramah lingkungan yang mampu meningkatkan sifat mekanik dan durabilitas dari dari beton/mortar [4]. GGBFS adalah produk sampingan dari pembuatan produk baja dan besi, yang terbentuk ketika limbah berupa slag cair didinginkan dengan cepat dengan air dengan menggunakan *water jets* sehingga terbentuk slag berbentuk butiran/granular. Selanjutnya, butiran slag diproses lebih lanjut dengan melalui proses penggilingan untuk membuat GGBFS. GGBFS dimanfaatkan sebagai karena mengandung senyawa silika (SiO_2), kapur (CaO), dan alumina (Al_2O_3) yang cukup tinggi, yaitu berkisar 35,09%, 37,79%, dan 17,54% secara berturut-turut [5]. Berdasarkan komposisi kimia yang dimiliki oleh GGBFS dapat mendukung terjadinya reaksi pozzolanik antara SiO_2 atau Al_2O_3 dengan kasium hidroksida ($Ca(OH)_2$) yang terbentuk pada proses hidrasi semen [6]. Oleh karena itu pemanfaatan GGBFS yang berpotensi untuk menciptakan material konstruksi yang ramah lingkungan.

Kemampuan beton segar untuk dapat mengalir dengan beratnya sendiri dan mempertahankan homogenitas yang memadai tanpa adanya segregasi dan *bleeding*, yang dikenal dengan istilah *self-compacting concrete* (SCC), telah dikembangkan oleh Okamura dari Jepang pada tahun 1986. Viskositas yang baik dari SCC akan mengakibatkan campuran beton segar dapat mengalir dan mengisi bekisting dan celah-celahnya yang terhalang oleh tulangan tanpa diperlukannya getaran. Pada perencanaan *SCC, Okamura dan Ouchi* mengusulkan perencanaan karakterisitik mortar pada SCC yang dikenal dengan *self-compacting mortar* (SCM) [7]. Sejalan, dengan perkembangan teknologi SCM juga telah dikembangkan sebagai mortar stuktural [8] maupun mortar perbaikan (*repair mortar*) [9].

Durabilitas merupakan salah satu parameter yang penting dalam perencanaan material konstruksi khususnya mortar. Durabilitas pada mortar dapat dinilai dari kemudahan masuknya zat cair kedalam matriks mortar melalui sistem pori-pori. Salah satu cara pengujian durabilitas adalah dengan mengukur tingkat penyerapan air (sorptivitas) [10]. Penggunaan material yang bersifat pozzolanik khususnya GGBFS dapat membantu meningkatkan durabilitas dengan mengurangi pori-pori kapiler akibat pembentukan kalsium silikat hidrat (CSH) tambahan yang terbentuk dari reaksi pozzolanik [11].

Penelitian ini bertujuan untuk melakukan kajian kinerja GGBFS sebagai material pengganti sebagian semen dengan variasi penggantian sebesar 0%, 10%, dan 20% terhadap kekuatan tekan dan sorptivitas SCM yang mempunyai potensi pemanfaatan sebagai material perbaikan struktur.

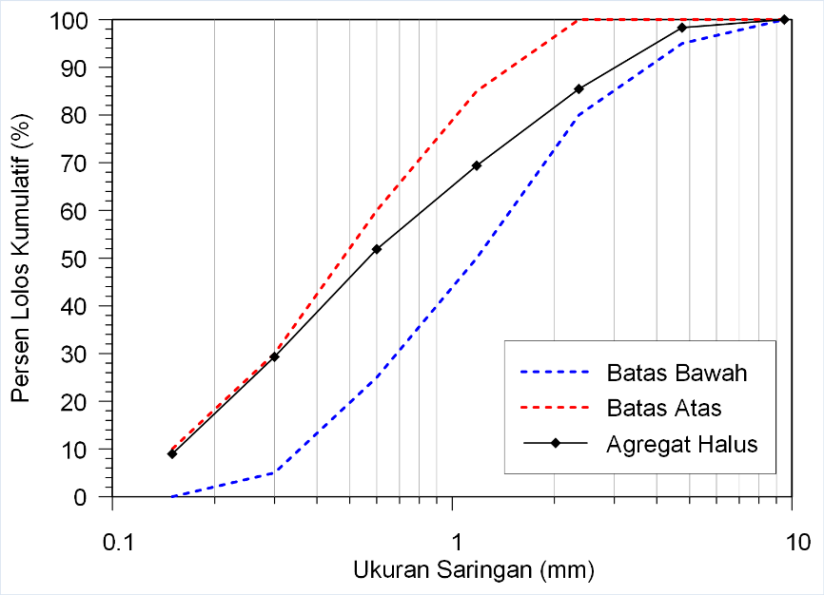
2. MATERIAL

Bahan pengikat yang digunakan dalam pembuatan SCM adalah ordinary Portland cement (OPC) dengan *specific gravity* sebesar 3,07 dan GGBFS *specific gravity* dengan specific gravity sebesar 2,83 yang diuji dengan acuan ASTM C188 [12]. Properti fisik dari kedua bahan pengikat tersebut dapat dilihat pada Gambar 1.

(a) OPC (b) GGBFS

Gambar 1. Bahan Pengikat SCM

Agregat halus yang digunakan dalam penelitian ini berasal dari dareah gunung Galunggung, Jawa Barat yang memiliki specific gravity sebesar 2,53 dan absorpsi sebesar 3,12% yang diuji berdasarkan ASTM C128 [13]. Pengujian gradasi agregat halus dilakukan sesuai dengan ASTM C136/C136M [14] dapat dilihat pada Gambar 2. Dimana agregat halus tersebut memenuhi batasan gradasi yang ditentukan oleh ASTM C33/33M [15] dengan besarnya modulus kehalusan sebesar 2,57.



Gambar 2. Analisis Saringan dari Agregat Halus

Superplasticizer digunakan untuk mengontrol properti segar dari SCM adalah berjenis *polycarboxyic ether* yang mempunyai kemampuan untuk mereduksi air dengan rentang yang tinggi dan meningkatkan kekuatan tekan awal.

3. METODOLOGI PENELITIAN

Pada penelitian ini perencanaan campuran SCM diformulasikan dengan menggunakan metode volume absolut dengan memformulasikan tiga buah campuran SCM dengan variasi penggantian sebagian semen dengan GGBFS sebesar 0%, 10%, dan 20%. Kebutuhan air pada campuran dihitung terhadap jumlah OPC dan GGBFS dengan menggunakan rasio air terhadap binder (w/b) [16]. Pada penelitian ini w/b ditetapkan sebesar 0,3 yang didapatkan berdasarkan *trial mix* yang dilakukan sebelumnya. Volume pasir ditetapkan sebesar 40% sesuai dengan rekomendasi EFNARC [17]. Detail proporsi campuran SCM dapat dilihat pada Tabel 1.

Tabel 1. Proporsi Campuran SCM

Kode	w/b	Air (kg/m³)	OPC (kg/m³)	GS (kg/m³)	AH (kg/m³)	SP (%)
SCM-GS0	0,3	287,89	959,63	0	1013,01	1,30
SCM-GS10		286,61	859,82	95,54	1013,01	1,37
SCM-GS20		285,33	760,89	190,22	1013,01	1,25

Keterangan: SCM-GGBFS = *self-compacting mortar* dengan penggantian sebagian semen dengan GGBFS; angka menunjukan besarnya persentase penggantian; OPC = *ordinary Portland cement*; GS = *ground granulated blast furnace slag*; AH = agregat halus; SP = *superplasticizer*

Properti segar dari SCM diuji dengan menggunakan peralatan *mini slump flow* dan *mini V-funnel* sesuai yang direkomendasikan oleh EFNARC [17]. Pengujian kekuatan tekan SCM dilakukan pada benda uji kubus berukuran 50 mm x 50 mm x 50 mm yang mengacu pada ASTM C109/C109M [18]. Pengujian dilakukan menggunakan alat Compression Testing Machine (CTM) yaitu dengan memberikan gaya vertikal pada satu permukaan kubus hingga benda uji mengalami kegagalan dan kekuatan tekan maksimum didapatkan. Pengujian kekuatan tekan dilakukan pada umur 7, 14, dan 28 hari. Pengujian sorptivitas merupakan salah satu metode untuk mengetahui tingkat penyerapan air yang dilakukan sesuai dengan acuan ASTM C1585 [19] dengan melakukan modifikasi benda uji berupa kubus berukuran 50 mm x 50 mm x 50 mm sesuai dengan penelitian yang dilakukan oleh Qureshi dan Ghosh (2014) [20]. Pengujian ini dilakukan untuk menentukan tingkat penyerapan air oleh benda uji yang dengan mengukur peningkatan massa spesimen (m_t) yang dihasilkan dari penyerapan air sebagai fungsi waktu (t) pada suatu luasan permukaan benda uji (a) yang bersentuhan dengan air dengan massa jenis d. Besarnya absorpsi (I) dapat dihitung dengan menggunakan Persamaan (1).

$$I = \frac{m_t}{a \times d} \tag{1}$$

Benda uji yang telah dikondisikan sesuai dengan ASTM C1585 [19], kemudian dilakukan perendaman didalam air, kemudian absorpsi dihitung pada saat benda uji mulai kontak dengan air dan yang dihitung pada interval 1, 5, 10, 20, 30, 60, 120, 180, 240, 300, and 360 menit untuk penentuan *initial absorption* dan pengujian setiap hari hingga hari ke-8 dilakukan untuk menentukan *secondary absorption*. Ilustrasi pengujian sorptivitas dapat dilihat pada Gambar 3.

Gambar 3. Pengujian Sorptivitas

4. HASIL DAN PEMBAHASAN

Properti Segar SCM

Pengujian *slump flow* dilakukan untuk mengetahui kemampuan SCM untuk dapat mengalir dan mengisi ke seluruh bagian dengan beratnya sendiri. Hasil pengujian *slump flow* dapat dilihat pada Tabel 2. Berdasarkan hasil pengujian tersebut, SCM dengan kadar GGBFS 20% memiliki nilai *slump flow* sebesar 275 mm. Dengan kadar superplasticizer yang hampir sama terlihat adanya

peningkatan diameter *slump flow* yang diakibatkan karena peningkatan kadar GGBFS. GGBFS memberikan pengaruh penurunan nilai kekentalan dalam campuran SCM.

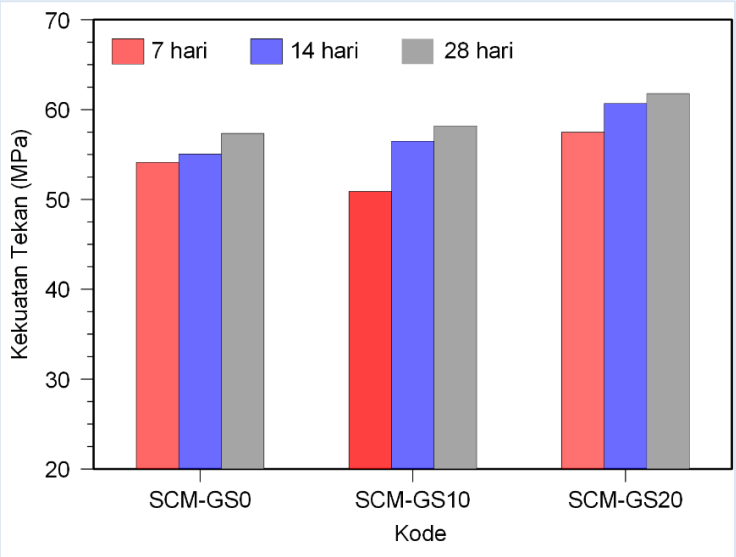
Pengujian *mini V-Funnel* dilakukan untuk menilai nilai kemampuan *filling ability* dari SCM, yaitu kemampuan untuk memastikan bahwa campuran SCM dapat mengalir dalam kondisi homogen. Hasil pengujian *mini V-Funnel* dapat dilihat pada Tabel 2. Berdasarkan hasil pengujian tersebut, SCM dengan kadar GGBFS 20% memiliki *V-Funnel time* sebesar 10 detik. Adanya penurunan *V-funnel time* campuran ini diakibatkan karena peningkatan kadar GGBFS.

Tabel 2. Properti Segar SCM

Parameter	SCM-GS0	SCM-GS10	SCM-GS20
Slump flow (mm)	260	270	275
V-funnel time (det)	11	10,5	10

Kekuatan Tekan

Gambar 4 menunjukkan hasil pengujian kuat tekan SCM yang diuji pada umur 7, 14, dan 28 hari dengan substitusi kadar GGBFS 0%, 10% dan 20% sebagai pengganti sebagian semen. Pada umur 7 hari memiliki nilai kuat tekan sebesar 54,1 MPa, 50,9 MPa, dan 57,5 MPa. Pada umur 14 hari memiliki nilai kuat tekan 55,1 MPa, 56,5 MPa dan 60,7 MPa, sedangkan pada umur 28 hari memiliki nilai kuat tekan 57,3 MPa, 58,2 MPa dan 61,8 MPa. Sehingga dapat disimpulkan bahwa semakin besar kadar SCM dengan persentase substitusi GGBFS sebesar 0%, 10% dan 20% menghasilkan nilai kuat tekan yang semakin tinggi. Hal tersebut disebabkan oleh aktivitas pozolanik dari GGBFS dimana SiO_2 dan Al_2O3 bereaksi dengan $Ca(OH)_2$ untuk membentuk C-S-H gel yang akan meningkatkan kekuatan tekan [21]. Berdasarkan hasil pengujian, kekuatan tekan tertinggi diperoleh pada variasi substitusi 20% pada umur 28 hari sebesar 61,8 MPa dapat dikategorikan sebagai mortar struktural karena memiliki kekuatan tekan yang lebih besar dari 45 MPa yang dapat dimanfaatkan sebagai *repair mortar* [22].



Gambar 4. Hasil Pengujian Kekuatan Tekan SCM

Sorptivitas

Pengujian sorptivitas dilakukan untuk mengetahui pengaruh variasi GGBFS terhadap tingkat penyerapan air pada mortar dengan mengukur peningkatan massa benda uji terhadap fungsi waktu yang diakibatkan karena terjadi penyerapan air pada satu permukaan benda uji yang bersentuhan dengan air. Pengujian sorptivitas mencatat pengukuran perubahan massa spesimen selama enam jam pertama, yang dihitung pada interval 1, 5, 10, 20, 30, 60, 120, 180, 240, 300,

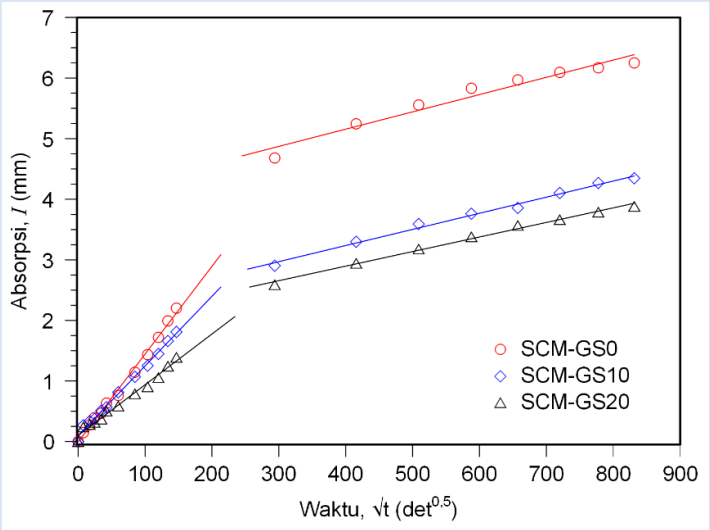
dan 360 menit setelah benda uji mulai kontak dengan air untuk penentuan *initial absorption* (S_i) dan pengujian setiap hari hingga hari ke-8 dilakukan untuk menentukan *secondary absorption* (S_s). Berdasarkan data pengujian dapat diperoleh hubungan antara tingkat penyerapan air (I) terhadap waktu ($\sqrt{t}$), kemudian regresi linier dibuat untuk menghitung S_i dan S_s yang merupakan gradien garis seperti terlihat pada Persamaan (2) dan (3).

$$I = S_i\sqrt{t} + b \quad (2)$$

$$I = S_s\sqrt{t} + b \quad (3)$$

Gambar 5 memperlihatkan bahwa pada *initial absorption*, kemiringan kurva lebih curam, hal ini menunjukan bahwa *initial absorption* lebih cepat, dimana air akan menyerap melalui pori-pori yang lebih besar pada kurun waktu enam jam pertama, sedangkan pada *secondary absorption* kemiringan kurva lebih landai, menandakan penyerapan mengisi pori-pori kapiler yang lebih kecil.

Tabel 3 memperlihatkan bahwa semakin besar persentase substitusi GGBFS maka besarnya S_i dan S_s semakin kecil, yang bermakna bahwa tingkat penyerapan air semakin berkurang, karena terjadi porositas yang lebih sehingga dapat disimpulkan dengan penambahan GGBFS, mempunyai kemampuan untuk meningkatkan durabilitas mortar.



Gambar 5. Hasil Pengujian Sorptivitas SCM

Tabel 3. Persamaan Regresi *Initial Absorption* dan *Secondary Absorption*

Kode	***Initial Absorption*** $I = S_i\sqrt{t} + b$	***Secondary Absorption*** $I = S_s\sqrt{t} + b$
SCM-GS0	$I = 0{,}0145\sqrt{t} - 0{,}0062$ $R^2 = 0{,}994$	$I = 0{,}0029\sqrt{t} + 4{,}0164$ $R^2 = 0{,}956$
SCM-GS10	$I = 0{,}0115\sqrt{t} + 0{,}0989$ $R^2 = 0{,}994$	$I = 0{,}0027\sqrt{t} + 2{,}1709$ $R^2 = 0{,}992$
SCM-GS20	$I = 0{,}0076\sqrt{t} + 0{,}1214$ $R^2 = 0{,}983$	$I = 0{,}0024\sqrt{t} + 1{,}9339$ $R^2 = 0{,}993$

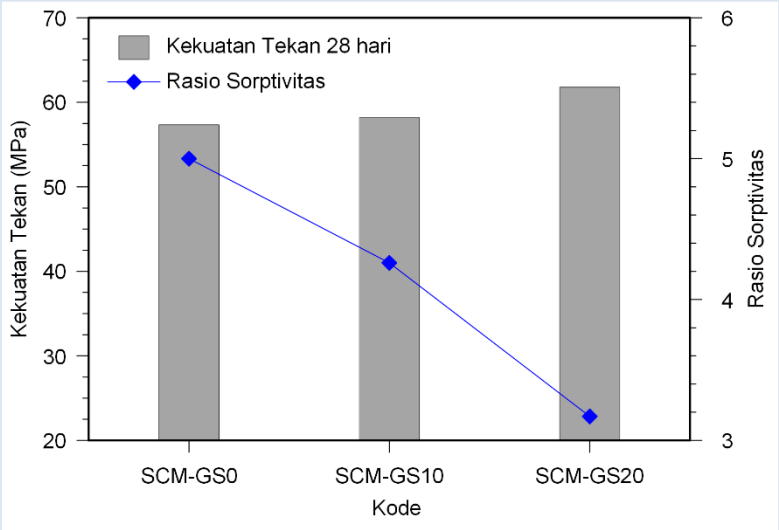
Hubungan Kekuatan Tekan dan Rasio Sorptivitas

Rasio *initial absorption* terhadap *secondary absorption* dikenal dengan rasio sorptivitas (S_i / S_s) merupakan salah satu parameter yang penting dapat digunakan untuk memberi penilaian pada durabilitas [20]. Berdasarkan hasil yang diperoleh dari pengujan sorptivitas diperoleh bahwa SCM dengan persentase substitusi GGBFS sebesar 0%, 10%, dan 20% menghasilkan nilai rasio sorptivitas sebesar 5,00; 4,26; dan 3,17 dengan data yang terlihat pada Tabel 4. Seperti terlihat

pada Gambar 6 bahwa nilai sorptivitas yang lebih rendah, menghasilkan kekuatan tekan yang lebih tinggi. Sehingga, nilai rasio sorptivitas dapat digunakan untuk menilai durabilitas dari SCM yang menandakan bahwa pemanfaatan GGBFS sebagai pengganti sebagian semen mampu meningkatkan durabilitas. Substitusi yang paling optimum adalah SCM dengan persentase substitusi GGBFS sebesar 20%, karena menghasilkan nilai rasio sorptivitas yang paling kecil yaitu sebesar 3,17 disebabkan oleh struktur pori yang lebih padat dari SCM dengan persentase substitusi GGBFS lainnya. Ratio sorptivitas yang paling kecil menghasilkan nilai kuat tekan terbesar yaitu 61,8 MPa, sehingga dapat disimpulkan substitusi GGBFS sebesar 20%, memiliki tingkat durabilitas yang baik.

Tabel 4. Rasio Sorptivitas pada SCM

Kode	*Initial Absorption* (S_i)	*Secondary Absorption* (S_s)	Rasio Sorptivitas (S_i / S_s)
SCM-GS0	0,0145	0,0029	5,00
SCM-GS10	0,0115	0,0027	4,26
SCM-GS20	0,0076	0,0024	3,17



Gambar 6 Hubungan Kekuatan Tekan dan Rasio Sorptivitas

5. KESIMPULAN

Berdasarkan kajian yang telah dilakukan, dapat disimpulkan bahwa SCM dengan persentase substitusi GGBFS yang lebih besar menghasilkan nilai kekuatan tekan semakin besar. Dimana, berdasarkan kekuatan tekan pada 28 hari, pada substitusi GGBFS sebesar 10% terjadi peningkatan kekuatan tekan sebesar 1,5% dan pada substitusi GGBFS sebesar 20% terjadi peningkatan kekuatan tekan sebesar 7,76 % apabila hasil-hasil tersebut dibandingkan dengan kekuatan tekan pada substitusi kadar GGBFS sebesar 0%. SCM dengan kadar substitusi GGBFS 0%, 10% dan 20% menghasilkan nilai rasio sorptivitas sebesar 5,00; 4,26; dan 3,17. Dapat disimpulkan bahwa SCM dengan persentase substitusi GGBFS yang lebih lebih besar menghasilkan nilai rasio sorptivitas yang semakin rendah, dimana rasio sorptivitas yang rendah menunjukkan tingkat durabilitas SCM yang lebih tinggi. Nilai kekuatan tekan optimum didapatkan pada SCM pada persentase substitusi GGBFS sebesar 20%, yaitu sebesar 61,8 MPa, dengan ratio sorptivitas terkecil sebesar 3,17 yang menghasilkan tingkat durabilitas yang terbaik. Pemanfaatan GGBFS sebagai pengganti sebagian semen memiliki manfaat yang positif untuk menciptakan material konstruksi yang ramah lingkungan dan yang mempunyai potensi pemanfaatan sebagai mortar struktural sebagai material perbaikan struktur.

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Investigation of Community Engagement in Sustainable Construction Projects: Case Studies from Nigeria

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ABSTRACT
This study investigates the role of community engagement in sustainable construction projects in Nigeria, focusing on three case studies: a green residential building in Lagos, an eco-friendly community center in Abuja, and a sustainable water infrastructure project in rural Kano. Using a mixed-methods approach, data were collected through interviews, surveys, and document analysis. The research identifies significant variations in engagement practices, with Lagos showing high engagement levels, leading to greater community acceptance and better environmental outcomes. Key success factors include strong leadership, adequate funding, and effective communication, while challenges such as socio-cultural barriers and political interference were noted. The findings emphasize the importance of sustained, tailored engagement strategies to enhance project sustainability and community support. This study contributes to the literature by providing empirical data on the long-term impacts of community engagement, offering insights for policy makers and project managers to improve community participation in sustainable construction.

Keywords: case study, community engagement, environmental sustainability, green building, social cohesion, sustainable construction, sustainability

1. INTRODUCTION

The construction industry is a cornerstone of global economic development, contributing significantly to national economies through infrastructure development, job creation, and the enhancement of living standards [1]. In Nigeria, the construction sector is one of the largest industries, playing a vital role in urban development and economic growth [2]. However, this sector is also a major contributor to environmental degradation, resource depletion, and greenhouse gas emissions, which poses significant challenges to achieving environmental sustainability [3][4]. The environmental issues associated with construction activities include deforestation, loss of biodiversity, and pollution of air, water, and soil, all of which adversely affect ecosystems and human health [5]. In response to these concerns, the concept of sustainable construction has gained prominence, aiming to balance economic growth, social equity, and environmental protection by integrating practices that promote resource efficiency, waste reduction, and improved living conditions [6].

Sustainable construction practices encompass the use of renewable and recyclable materials, energy-efficient building designs, water conservation techniques, and the implementation of green building standards [7]. These practices not only mitigate the negative environmental impacts of building activities but also contribute to the economic and social well-being of communities [8]. A critical component of sustainable construction is community engagement, which involves the active participation of local communities in the planning,

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execution, and monitoring of construction projects [9]. Effective community engagement ensures that projects align with the actual needs and priorities of the people they are intended to serve, leading to smoother implementation and reduced conflicts [10]. By fostering a sense of ownership and responsibility among local stakeholders, community engagement is crucial for the long-term sustainability and maintenance of projects [11].

In Nigeria, where diverse socio-economic and cultural landscapes exist, effective community engagement can bridge cultural gaps, ensure the inclusion of marginalized groups, and harness local knowledge and resources [12]. This approach not only enhances the relevance and effectiveness of construction projects but also empowers communities by giving them a voice in the development process [13]. Moreover, community engagement can result in innovative solutions that are culturally and environmentally appropriate, thereby contributing to the overall sustainability of construction projects [14].

Community engagement is essential in sustainable construction for several reasons. Firstly, it promotes transparency and accountability within the construction process, allowing projects to address local concerns and preferences, leading to more inclusive decision-making [15]. This approach helps to identify and address potential social and environmental issues early in the project lifecycle, preventing costly modifications and fostering trust between stakeholders and project developers [16]. Secondly, community engagement fosters a sense of ownership and responsibility among local stakeholders, which is vital for the long-term success and maintenance of construction projects [17]. When communities are actively involved in the planning and implementation phases, they are more likely to take pride in the outcomes and ensure that the infrastructure is maintained properly [18].

Additionally, involving the community helps harness local knowledge and resources, which can lead to more culturally and environmentally appropriate solutions [19]. Local communities possess invaluable insights into their environment, cultural practices, and needs, which can inform more sustainable and acceptable construction practices [20]. For instance, community members might suggest the use of locally available materials that are more sustainable and cost-effective or highlight cultural practices that could influence the design and use of the infrastructure [21]. In the context of Nigeria, where diverse socio-economic and cultural landscapes exist, effective community engagement can significantly contribute to the success and sustainability of construction projects [22]. Nigeria's diverse population includes numerous ethnic groups with distinct traditions and needs. Engaging these communities ensures that construction projects are tailored to fit the specific requirements and preferences of different groups, thereby enhancing their acceptance and utility [23].

Moreover, community engagement can help mitigate conflicts that often arise in construction projects. In many cases, construction projects can lead to displacement or disruption of local communities. By engaging these communities from the outset, project developers can negotiate and mitigate such impacts, ensuring that the benefits of the project are equitably distributed and that negative consequences are minimized [24]. This proactive approach can prevent delays and resistance, leading to smoother project implementation [25]. Furthermore, effective community engagement can enhance the social sustainability of construction projects by ensuring that they contribute to the well-being and quality of life of the local population [26]. Participatory approaches allow projects to be designed with features that enhance social cohesion, such as community centers, green spaces, and public amenities, which can have lasting positive impacts on the community [27].

The primary objective of this study is to explore the role of community engagement in sustainable construction projects in Nigeria. Specifically, the study aims to investigate the current practices of community engagement in sustainable construction projects, identify the success factors and challenges associated with community engagement, assess the impact of community engagement on the sustainability outcomes of construction projects, and provide recommendations for improving community engagement practices [28]. Through a

comprehensive analysis, this study seeks to contribute valuable insights into how community involvement can enhance the sustainability and success of construction projects, particularly within the diverse socio-economic and cultural context of Nigeria [29].

This study is guided by several critical research questions aimed at understanding the role and impact of community engagement in sustainable construction projects in Nigeria. The research seeks to investigate the current practices of community engagement, identify success factors for effective community involvement, and address the challenges faced during the process [30]. These challenges can range from socio-cultural barriers to logistical and communication issues, all of which can significantly affect the efficacy of community engagement [31]. Additionally, the study examines how community engagement impacts the sustainability outcomes of construction projects in Nigeria, including assessing long-term benefits and potential drawbacks [32].

The paper is structured to provide a comprehensive analysis of community engagement in sustainable construction projects. Following this introduction, the literature review will explore existing studies and theoretical frameworks related to sustainable construction and community engagement. The methodology section outlines the research design, data collection methods, and data analysis techniques used in this study. The results and discussion section will present and interpret the findings from the case studies, highlighting key insights and implications. Finally, the conclusion will summarize the main findings, discuss their implications for policy and practice, and offer recommendations for future research [33].

2. LITERATURE REVIEW

Definition and Scope of Sustainable Construction

Sustainable construction refers to the creation and responsible management of a healthy built environment through the application of resource-efficient and ecological principles [11]. This holistic approach encompasses every stage of a building's lifecycle, from initial planning and design to construction, operation, maintenance, renovation, and eventual deconstruction [12]. The goal of sustainable construction is to minimize the environmental impact of buildings by enhancing energy efficiency, reducing waste, conserving water, and utilizing sustainable materials [13]. The scope of sustainable construction is broad and multifaceted, integrating strategies and practices designed to achieve sustainability goals. During the planning and design stages, sustainable construction practices include site selection that minimizes environmental disruption, orientation that maximizes natural lighting and ventilation, and the incorporation of green roofs and walls that enhance biodiversity and reduce urban heat island effects [14]. Additionally, the use of Building Information Modeling (BIM) is emphasized to optimize resource use and reduce waste [15].

During the construction phase, sustainable practices include the use of recycled and locally sourced materials, implementation of waste management plans to recycle and reuse construction debris, and employment of energy-efficient machinery and construction techniques [16]. Moreover, managing the construction site to minimize dust, noise, and water pollution is crucial to reducing the project's environmental footprint [17]. In the operation and maintenance phase, sustainable construction focuses on energy-efficient building systems, such as advanced HVAC (heating, ventilation, and air conditioning) systems, high-performance glazing, and renewable energy sources like solar panels and wind turbines [18]. Water conservation measures, including rainwater harvesting and greywater recycling, are also integral components of sustainable construction [19]. Smart building technologies that monitor and optimize energy and water use contribute to ongoing sustainability [20].

Renovation and deconstruction represent the final stages of a building's lifecycle in sustainable construction. Renovation practices prioritize upgrading existing structures to improve energy efficiency and extend the building’s life, thereby reducing the need for new construction and conserving resources [21]. Deconstruction, as opposed to traditional demolition, focuses on systematically disassembling buildings to recover and reuse materials, minimizing waste sent to

landfills and reducing the need for virgin materials [22]. Sustainable construction integrates economic, social, and environmental objectives to create structures that not only benefit the environment but also enhance the quality of life and economic viability [23]. Economically, sustainable buildings often result in lower operating costs through reduced energy and water consumption, while also potentially increasing property values and marketability [24]. Socially, these buildings provide healthier indoor environments, improving occupant health and productivity, and can also foster community engagement and social equity through inclusive design processes and accessible spaces [25].

The Role of Community Engagement in Sustainable Development

Community engagement is fundamental to the success of sustainable development initiatives, ensuring that development projects are not only environmentally and economically viable but also socially inclusive and responsive to the needs and aspirations of the local populace [26]. This participatory approach involves the active involvement of community members in decision-making processes, which allows for the incorporation of local knowledge, cultural values, and preferences into the planning and execution of projects [27]. In the context of sustainable construction, community engagement plays several critical roles. Firstly, it enhances project acceptance by fostering a sense of ownership and responsibility among community members [28]. When people feel that their voices are heard and their contributions are valued, they are more likely to support and take pride in the project, leading to higher levels of community buy-in and long-term commitment [29]. This is particularly important in construction projects, where the involvement of the local community can significantly impact the maintenance and sustainability of the built environment [30].

Secondly, community engagement improves the relevance and appropriateness of design solutions [31]. Local residents possess unique insights into their environment and lifestyle that external developers might overlook [32]. By integrating these insights into the design phase, projects can better address the real needs and challenges faced by the community, resulting in more practical and sustainable solutions [33]. For instance, local knowledge about seasonal weather patterns, traditional building materials, and construction techniques can lead to the development of structures that are more resilient and environmentally friendly [34]. Furthermore, effective community engagement helps identify potential environmental and social impacts early in the project lifecycle [35]. By involving community members in environmental assessments and planning processes, developers can gain a comprehensive understanding of the potential consequences of their projects [36]. This proactive approach allows for the development of mitigation strategies that address the concerns and priorities of those most affected, thereby reducing negative impacts and enhancing the overall sustainability of the project [37].

Community engagement also fosters transparency and accountability in sustainable development projects [38]. Open communication and participatory decision-making processes help build trust between developers and community members, which is essential for the successful implementation of projects [39]. When stakeholders are involved in every stage of the project, from planning to execution and monitoring, they can hold developers accountable for their commitments and ensure that project goals align with community needs and values [40]. In Nigeria, the importance of community engagement in sustainable construction is particularly pronounced due to the diverse socio-economic and cultural landscapes [41]. Engaging local communities in the planning and execution of construction projects can help bridge cultural gaps, ensure equitable resource distribution, and promote social cohesion [42]. Effective engagement strategies in Nigeria often include community meetings, focus group discussions, participatory mapping, and collaborative planning sessions, all aimed at empowering communities and fostering a sense of collective responsibility [43].

Theoretical Frameworks on Community Engagement

Several theoretical frameworks underpin the concept of community engagement, each offering unique insights into the processes and outcomes of involving communities in decision-making and development projects. Arnstein's (1969) Ladder of Citizen Participation provides a foundational model for understanding the varying degrees of citizen involvement [44]. This model categorizes participation into eight levels, arranged in a ladder format, ranging from non-participation to full citizen control. The bottom rungs of the ladder, labeled as manipulation and therapy, represent non-participation, where the aim is to cure or educate the participants rather than genuinely engage them [45]. The next levels include informing, consulting, and placation, which involve some degree of participant feedback but still retain decision-making power primarily with the authorities [46]. Higher up the ladder are partnership, delegated power, and citizen control, where citizens have increasing degrees of influence and control over decision-making processes [47]. This model highlights the importance of moving beyond tokenism to genuine empowerment in community engagement [48].

The International Association for Public Participation (IAP2) Spectrum further refines the concept of community engagement by outlining a continuum of participation. This spectrum includes five levels: inform, consult, involve, collaborate, and empower [49]. At the inform level, the objective is to provide the public with balanced and objective information to assist them in understanding the problem, alternatives, and solutions [50]. Consulting involves obtaining public feedback on analysis, alternatives, and decisions [51]. Involving ensures that public concerns and aspirations are consistently understood and considered throughout the decision-making process [52]. Collaborating entails partnering with the public in each aspect of the decision, including the development of alternatives and the identification of the preferred solution [53]. Empowering places the final decision-making in the hands of the public [54]. This model emphasizes the need for a strategic approach to public participation that matches the level of engagement to the specific context and objectives of the project [55].

Social capital theory, as articulated by [23], emphasizes the importance of social networks, norms, and trust in facilitating collective action [56]. Social capital is the collective value of social networks and the inclinations that arise from these networks to do things for each other [57]. High levels of social capital can enhance community engagement by fostering collaboration, mutual support, and trust among community members [58]. Putnam distinguishes between bonding social capital, which refers to the relationships within a homogenous group, and bridging social capital, which connects diverse groups [59]. Both forms of social capital are crucial for successful community engagement in sustainable projects, as they can help build strong, cohesive communities that are capable of working together towards common goals [60].

In addition to these models, participatory action research (PAR) offers another valuable framework for community engagement. PAR is a collaborative research approach that involves community members as active participants in the research process [61]. This approach is grounded in the principles of co-learning, mutual respect, and the co-creation of knowledge [62]. By involving community members in identifying research questions, collecting data, and analyzing results, PAR aims to produce actionable knowledge that directly benefits the community [63]. This approach is particularly relevant for sustainable construction projects, as it ensures that the research addresses the real needs and priorities of the community [64].

Previous Studies on Community Engagement in Construction Projects

A substantial body of research underscores the significance and impact of community engagement in construction projects. These studies collectively highlight that community participation is a critical factor in achieving project success and sustainability. One notable study by [65] examined community participation in public housing projects in Ogun State, Nigeria. The study found that involving community members in the planning and implementation phases significantly increased resident satisfaction. This involvement ensured that the housing projects were tailored to meet the specific needs and preferences of the community, leading to enhanced

acceptability and utility of the housing units. Ibem's research emphasized that community engagement is not merely a procedural formality but a strategic approach that can improve project outcomes and stakeholder satisfaction.

Another important study by [66] explored the role of participatory approaches in environmental management projects across several African countries. The study revealed that projects which actively involved local communities were more likely to achieve sustainable and widely accepted results. This was attributed to the inclusion of local knowledge and practices, which often provided more effective and culturally appropriate solutions to environmental challenges. The researchers found that community engagement facilitated better project planning and implementation, as it allowed for the early identification and mitigation of potential issues. This proactive approach not only reduced project risks but also built stronger community support and ownership. Further research by [67] delved into the specific mechanisms through which community engagement enhances project sustainability. Their study on urban development projects in Germany found that active community participation led to more innovative and adaptable project designs. By incorporating community feedback and ideas, project planners were able to develop solutions that were more resilient to changing social and environmental conditions. The study highlighted that community engagement can act as a catalyst for creativity and innovation, driving projects towards more sustainable outcomes.

In addition, a comprehensive review by [68] synthesized findings from various urban planning and construction projects globally. The review identified several key benefits of community engagement, including improved transparency, greater accountability, and enhanced social cohesion. The authors noted that when community members are involved in decision-making processes, there is a greater likelihood of trust and cooperation between stakeholders. This collaborative environment can lead to more efficient project execution and higher levels of community satisfaction and support. Moreover, a study by. [69] focused on post-disaster reconstruction projects in Sri Lanka, underscoring the importance of community engagement in ensuring the relevance and sustainability of such projects. The researchers found that involving the affected communities in reconstruction efforts led to more effective and contextually appropriate solutions. This engagement helped to address the specific needs of the disaster-affected populations, thereby enhancing the resilience and long-term success of the reconstruction projects.

Barriers to Effective Community Engagement in Nigeria

Despite its critical importance, several barriers hinder effective community engagement in sustainable construction projects in Nigeria. One significant barrier is the presence of socio-cultural factors, such as hierarchical social structures and entrenched gender roles, which can limit participation from certain segments of the population. In many Nigerian communities, decision-making power is often concentrated in the hands of traditional leaders or elder male figures, marginalizing women and younger community members [70]. This hierarchical structure can stifle diverse voices and inhibit comprehensive community involvement. Political and economic constraints also pose substantial challenges to effective community engagement. The lack of adequate funding for community engagement activities can severely limit the extent and quality of participation efforts. Many sustainable construction projects operate on tight budgets, and community engagement often becomes a secondary priority [71]. Additionally, inadequate policy frameworks that fail to mandate or incentivize community involvement can lead to insufficient or superficial engagement practices [72]. Political interference and corruption further exacerbate these issues, as project decisions can be influenced by political agendas rather than community needs.

Communication barriers significantly complicate the engagement process. Nigeria is a linguistically diverse country with over 500 languages spoken, leading to potential misunderstandings and miscommunications during engagement activities [73]. Language differences can create significant hurdles in ensuring that all community members fully

understand and participate in the discussions. Low literacy levels in some regions further exacerbate this problem, making it challenging to disseminate information and collect meaningful feedback from community members [74]. Moreover, there is often a general lack of awareness and understanding of the benefits of sustainable construction among community members. This lack of awareness can lead to resistance or indifference towards participation in such projects. Community members may prioritize immediate economic gains over long-term sustainability benefits, leading to conflicts and disengagement [75]. Additionally, previous negative experiences with construction projects, where promises were unfulfilled or the community was negatively impacted, can lead to skepticism and mistrust towards new projects [76].

Institutional barriers also play a significant role in hindering effective community engagement. Many local governments and construction companies lack the institutional capacity and expertise to effectively facilitate community engagement. There is often an absence of trained personnel who can manage and execute community engagement activities proficiently [77]. Furthermore, bureaucratic red tape can delay or complicate the engagement process, leading to frustration among community members and project stakeholders.

Benefits of Community Engagement in Sustainable Construction

Engaging communities in sustainable construction projects offers numerous benefits that extend beyond the immediate project outcomes, fostering long-term sustainability and community development. One of the primary advantages is the promotion of transparency and accountability. When project details and decision-making processes are openly shared with stakeholders, it ensures that the community is well-informed and involved at every stage [78]. This transparency is crucial in building trust between the project developers and the community, as it demonstrates a commitment to addressing local concerns and priorities. Trust, in turn, fosters a sense of ownership among community members, making them more likely to support and maintain the project over its lifecycle.

Furthermore, community engagement leverages local knowledge and resources, which can significantly enhance the contextual appropriateness and innovation of the project solutions. Local knowledge includes an understanding of the environmental, cultural, and social dynamics that external experts might overlook [79]. For example, community members can provide insights into traditional construction methods that are sustainable and cost-effective, or identify locally available materials that reduce the project's environmental footprint. This collaboration can lead to innovative approaches that are tailored to the specific needs and conditions of the community, enhancing the overall effectiveness and sustainability of the project.

Involving the community also plays a critical role in identifying and mitigating potential social and environmental impacts. Early and continuous engagement allows for the timely identification of issues that could affect the project's success, such as land use conflicts, cultural sensitivities, or environmental concerns [80]. Addressing these issues proactively, with input from those who are directly affected, ensures that the project can adapt and respond to potential challenges, making it more resilient and sustainable in the long term. This inclusive approach not only mitigates risks but also enhances the legitimacy and acceptance of the project, as community members feel that their voices are heard and their interests are considered. Additionally, community engagement contributes to capacity building within the community. By involving local people in the planning, implementation, and monitoring of the project, they acquire new skills and knowledge that can be applied to future initiatives [81]. This empowerment fosters a culture of continuous improvement and innovation, where communities are better equipped to manage and sustain their development projects. For instance, training programs on sustainable practices or participatory monitoring can leave a lasting impact, enabling communities to take greater control over their development trajectory.

Gaps in the Existing Literature

While there is substantial literature on the benefits and practices of community engagement, several gaps remain that warrant further investigation. Firstly, there is a notable lack of comprehensive studies focusing specifically on sustainable construction projects in Nigeria. Much of the existing research tends to address general construction projects or focus on other regions, particularly developed countries where the socio-economic and cultural contexts differ significantly from those in Nigeria [82]. This geographical and contextual gap limits the applicability of existing findings to the Nigerian setting, where unique challenges and opportunities exist.

Additionally, there is limited empirical data on the long-term impacts of community engagement on the sustainability of construction projects. Most studies provide a snapshot of community engagement practices and their immediate outcomes, but few track these impacts over extended periods to assess how they influence the durability and adaptability of sustainable construction efforts [83]. Understanding these long-term effects is crucial for developing strategies that not only initiate but also sustain community involvement throughout the lifecycle of a construction project. Another significant gap lies in the exploration of specific barriers and success factors related to community engagement in Nigeria. While general barriers such as socio-cultural factors, political and economic constraints, and communication issues are acknowledged [84], there is a lack of detailed, context-specific research that delves into how these barriers manifest in different regions and project types within Nigeria. Similarly, the success factors identified in the literature are often broad and generalized, lacking the nuanced understanding needed to tailor engagement strategies to local conditions effectively.

Moreover, there is a need for research that develops and tests innovative community engagement strategies tailored to the Nigerian context. Current literature predominantly discusses traditional engagement methods, which may not fully capture the potential of new technologies and participatory approaches that could enhance engagement effectiveness [85]. For example, the use of digital platforms for community consultations and feedback in remote or underserved areas remains underexplored. Research into these innovative methods could provide valuable insights into scalable and adaptable engagement strategies. Lastly, there is a paucity of interdisciplinary studies that integrate insights from social sciences, environmental sciences, and engineering to provide a holistic understanding of community engagement in sustainable construction. Such interdisciplinary approaches could offer more comprehensive solutions that address the multifaceted nature of sustainability challenges [86]. By bridging these disciplinary gaps, future research can develop more robust frameworks for community engagement that are both theoretically sound and practically applicable.

3. METHODOLOGY

Research Design

This study employed a mixed-methods research design, which integrated both qualitative and quantitative approaches to provide a more comprehensive understanding of community engagement in sustainable construction projects. The mixed-methods approach was specifically chosen for its ability to capture the complexity of social phenomena by combining the depth of qualitative insights with the generalizability of quantitative data. This approach was instrumental in triangulating data from various sources, thereby increasing the validity and reliability of the findings [87].

Within the mixed-methods framework, a multiple case study approach was utilized. This approach allowed the research to focus on multiple sustainable construction projects across different regions of Nigeria, thereby providing a comparative analysis of community engagement practices in varied contexts. By examining multiple cases, the study was able to identify patterns, variances, and contextual factors that influence community engagement in sustainable construction. Each case study offered unique insights into how community engagement was approached, executed, and perceived in different geographical and socio-cultural settings. The

multiple case study approach was crucial for developing a nuanced understanding of the research questions and capturing the diverse experiences of stakeholders involved in these projects.

The mixed-methods design further incorporated qualitative methods (e.g., semi-structured interviews and document analysis) and quantitative methods (e.g., surveys). The qualitative component provided rich, in-depth data on the subjective experiences and perspectives of stakeholders, while the quantitative component enabled the measurement of engagement levels and other variables of interest. The integration of these methods allowed for a more holistic exploration of community engagement practices and their outcomes, offering a robust foundation for the study's conclusions.

Case Study Selection Criteria

The selection of case studies was guided by purposive sampling to ensure that the chosen projects were representative of diverse contexts within Nigeria. This sampling strategy was employed to maximize the variability and depth of the data, allowing the research to cover a broad spectrum of community engagement practices across different project types and regions. The selection criteria were as follows:

1) Sustainability Focus: The project must be a sustainable construction initiative that emphasizes environmentally friendly practices, resource efficiency, and social responsibility. This criterion ensured that the selected projects were aligned with the study's objective of exploring community engagement in the context of sustainable development.
2) Community Engagement: The project should demonstrate a significant level of community engagement, indicating active involvement of local communities in various aspects of the project. This criterion ensured that the selected cases were suitable for examining the dynamics and effectiveness of community participation.
3) Project Lifecycle Stage: The selected projects should be at different stages of the construction lifecycle, including planning, implementation, and post-construction phases. This variation enabled the study to capture community engagement practices across all stages of project development, providing a comprehensive view of how engagement evolves over time.
4) Geographical and Socio-cultural Diversity: The selected projects should be geographically diverse, capturing both urban and rural settings across different regions of Nigeria. This criterion ensured that the findings reflected the diversity of socio-economic and cultural contexts in the country, thereby enhancing the generalizability of the results.

Based on these criteria, three projects were selected for the study: (1) a green residential building project in Lagos, representing an urban, implementation-phase project with high levels of community engagement; (2) an eco-friendly community center in Abuja, representing a planning-phase project in a semi-urban setting with moderate community involvement; and (3) a sustainable water infrastructure project in rural Kano, representing a post-construction project with lower levels of community engagement. These projects varied in scale, purpose, and community engagement strategies, providing a rich basis for comparative analysis and offering valuable insights into the factors influencing community engagement across different contexts [88].

Data Collection Methods

To ensure a comprehensive understanding of community engagement practices, a triangulated data collection approach was adopted, incorporating interviews, surveys, and document analysis. This multi-method approach allowed the research to collect data from multiple sources, enhancing the depth and breadth of the findings. Each data collection method contributed unique insights, making it possible to cross-validate the information obtained and ensure the robustness of the study's conclusions.

1) Interviews

Semi-structured interviews were conducted with key stakeholders, including project managers, community leaders, local government officials, and residents. A total of 30 interviews were planned, with 10 interviews conducted for each case study. The semi-structured format provided flexibility, allowing the interviewer to probe deeper into specific issues while maintaining consistency across interviews. This approach facilitated the exploration of stakeholders' experiences, perceptions, and opinions regarding community engagement practices, challenges faced, and perceived impacts on project sustainability [89]. The interview questions were designed to elicit detailed and nuanced information, covering themes such as the effectiveness of engagement strategies, barriers to participation, and the role of community members in decision-making processes.

The qualitative data obtained from these interviews were analyzed using thematic analysis, which involved coding and categorizing the responses to identify recurring themes and patterns. This analysis enabled the research to capture the diversity of experiences and perspectives across the different case studies, providing a rich and contextualized understanding of community engagement.

2) Surveys

A survey was administered to a broader sample of community members involved in or affected by the selected projects. A sample size of 150 respondents was targeted, with 50 respondents for each case study. The survey was designed using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree) to quantitatively assess community engagement practices, levels of satisfaction, and perceived project impacts.

The survey instrument included questions related to current community engagement practices, success factors, challenges, and impacts on sustainability outcomes. The instrument was pre-tested to ensure the clarity and relevance of the questions, and adjustments were made based on the feedback received. The quantitative data collected through the survey were analyzed using descriptive and inferential statistics, allowing the study to measure and compare engagement levels across different projects. This method provided a numerical representation of engagement practices and their outcomes, which could be correlated with qualitative findings to offer a more complete picture of community engagement.

3) Document Analysis

Document analysis was conducted to supplement the data obtained from interviews and surveys. Relevant project documents, including project plans, meeting minutes, progress reports, and community feedback forms, were analyzed to provide historical and contextual information about each project. This method helped trace the evolution of community engagement practices over time, verify the accuracy of information provided by interviewees and survey respondents, and identify any discrepancies or inconsistencies.

The use of multiple data collection methods—interviews, surveys, and document analysis—facilitated the triangulation of data, enhancing the credibility and validity of the study’s findings. This comprehensive approach allowed the research to capture both the qualitative depth and quantitative breadth of community engagement practices in sustainable construction projects across different contexts in Nigeria.

Table 1. Questionnaire Survey

S/N	Question	Source
	Current Practices of Community Engagement	
1	The project team regularly holds community meetings to discuss project updates.	[90]
2	Community members are involved in decision-making processes for the project.	[91]
3	Feedback from the community is actively sought and valued.	[92]
4	There are clear channels for community members to voice their concerns.	[93]
5	The project incorporates local cultural practices and values.	[94]
6	Community engagement activities are well-publicized.	[95]
7	The project team respects community opinions and suggestions.	[96]
8	Community engagement strategies are regularly reviewed and improved.	[97]
9	Local leaders are actively involved in the project.	[98]
10	The project team ensures transparency in all community engagements.	[99]
	Success Factors of Community Engagement	
11	Adequate resources are allocated for community engagement activities.	[100]
12	There is strong leadership from within the community.	[101]
13	The project team has good communication skills.	[102]
14	Trust exists between the community and the project team.	[103]
15	Community engagement is started early in the project.	[104]
16	There is ongoing training for community engagement personnel.	[105]
17	Clear objectives for community engagement are set and communicated.	[106]
18	The project team is culturally sensitive and aware.	[107]
19	Community members feel their participation is meaningful.	[108]
20	There is a formal process for addressing community grievances.	[109]
	Challenges in Community Engagement	
21	Socio-cultural differences hinder effective engagement.	[110]
22	Political interference affects community engagement efforts.	[111]
23	Lack of funding limits community engagement activities.	[112]
24	Low literacy levels in the community are a barrier.	[113]
25	Language differences pose significant challenges.	[114]
26	There is resistance to change within the community.	[115]
27	Community members lack trust in the project team.	[116]
28	There is insufficient training for community engagement personnel.	[117]
29	Conflicts arise between community members and the project team.	[118]
30	Inadequate communication channels hinder effective engagement.	[119]
	Impact of Community Engagement on Sustainability Outcomes	
31	Community engagement improves project acceptance.	[120]
32	Projects with strong community engagement have better environmental outcomes.	[121]
33	Community engagement enhances social cohesion.	[122]
34	Engaged communities contribute to better project maintenance.	[123]
35	There is a noticeable improvement in local quality of life.	[124]
36	Community engagement leads to more innovative project solutions.	[125]
37	Projects are more likely to be completed on time with community involvement.	[126]
38	Community engagement helps in mitigating project risks.	[127]
39	Community-engaged projects experience fewer conflicts.	[128]
40	Community engagement enhances the overall sustainability of the project.	[129]

Data Analysis Techniques

Data analysis was conducted using a combination of qualitative and quantitative methods to provide a comprehensive understanding of the findings. Qualitative data from interviews and open-ended survey responses were analyzed using thematic analysis. This involved coding the data to identify key themes and patterns related to community engagement practices, success factors, challenges, and impacts [131]. NVivo software was used to assist with data management and analysis, ensuring a systematic and rigorous approach. Quantitative data from survey responses were analyzed using descriptive and inferential statistics. Descriptive statistics

provided an overview of engagement practices and community perceptions, while inferential statistics (such as chi-square tests and regression analysis) were used to explore relationships between variables and identify significant factors influencing community engagement outcomes [132]. In addition, comparative analyses were conducted using Multivariate Analysis of Variance (MANOVA) and Hierarchical Linear Modeling (HLM) to further explore the differences in community engagement practices and their impacts across the selected projects [133].

Ethical Considerations

Ethical considerations were paramount in this study to ensure the integrity of the research and the protection of participants' rights. Informed consent was obtained from all participants, ensuring they were fully aware of the study's purpose, procedures, potential risks, and benefits. Participants were assured of their right to withdraw from the study at any time without penalty. Confidentiality and anonymity were maintained throughout the research process. Personal identifiers were removed from data sets, and all information was stored securely to prevent unauthorized access. Ethical approval for the study was obtained from the relevant institutional review board, ensuring compliance with ethical standards and guidelines [134].

4. RESULTS AND DISCUSSIONS

Overview of Selected Case Studies

The selected case studies for this research include three sustainable construction projects in Nigeria (Table 2): a green residential building project in Lagos, an eco-friendly community center in Abuja, and a sustainable water infrastructure project in rural Kano. These projects were chosen to reflect a diverse range of contexts, scales, and community engagement strategies.

In order to determine the level of community engagement for each project, a scoring system was developed using responses to the questionnaire items related to community engagement practices. Each question was rated on a 5-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree). The scores for community engagement-related questions were aggregated for each project to obtain an overall community engagement score. This score was then divided by the total number of questions to generate an average engagement score for each project, which served as the basis for classification. Based on the calculated average engagement scores, community engagement levels were categorized as **High**, **Medium**, or **Low**. Specifically, projects with an average score of 4.0 and above were classified as having **High** community engagement, those with scores between 3.0 and 3.9 were categorized as **Medium**, and those with scores below 3.0 were classified as **Low**.

The Green Residential Building Project in Lagos achieved an average score of 4.2, thereby classifying its community engagement level as **High**. This classification was verified by consistently high scores on questions related to regular community meetings, workshops, and active feedback mechanisms. On the other hand, the Eco-friendly Community Center in Abuja had an average score of 3.5, resulting in a **Medium** level of engagement. This score reflected moderate community involvement, primarily through the inclusion of community leaders during the planning phase. Conversely, the Sustainable Water Infrastructure Project in Kano received an average score of 2.8, indicating a **Low** level of community engagement. The lower score was due to limited community participation and infrequent consultations with local stakeholders. The revised Table 2 now includes the average engagement scores alongside the engagement levels for each project, ensuring transparency in the classification process.

Table 2. Overview of Selected Case Studies

SN	Project Location	Project Type	Project Stage	Average Engagement Score	Community Engagement Level
1	Lagos	Green residential building	Implementation	4.2	High
2	Abuja	Eco-friendly community center	Planning	3.5	Medium
3	Kano	Sustainable water infrastructure	Post-construction	2.8	Low

Analysis of Community Engagement Practices

Community engagement practices varied significantly across the three projects (Table 3). The values in Table 3 represent the average score (on a scale of 1 to 5) for each engagement practice based on responses from community members and project stakeholders. In Lagos, the project team held regular community meetings (average score: 4.5), workshops (average score: 4.3), and feedback sessions (average score: 4.4), ensuring high levels of participation. In Abuja, the community center project involved community leaders in the planning process (average score: 3.8), but broader community involvement was limited (average score: 2.9). In Kano, engagement was primarily through sporadic consultations with village elders, resulting in lower overall participation scores (average score: 2.3).

Table 3. Community Engagement Practices

SN	Practice	Lagos (Avg. Score)	Abuja (Avg. Score)	Kano (Avg. Score)
1	Regular community meetings	4.5	2.5	2
2	Workshops and training sessions	4.3	3.8	2.2
3	Feedback and consultation sessions	4.4	3.2	2.3
4	Use of digital engagement platforms	2.1	2	1.8
5	Engagement through local leaders	4	3.5	2.5

Success Factors in Community Engagement

Success factors identified in the Lagos project included strong leadership (average score: 4.8), adequate funding for engagement activities (average score: 4.5), and effective communication strategies (average score: 4.6) (Table 4). In Abuja, the involvement of respected community leaders (average score: 3.7) and clear communication of project benefits (average score: 3.9) were key success factors. In Kano, the primary success factor was the historical trust between the community and project initiators (average score: 3.6).

Table 4. Success Factors in Community Engagement

SN	Success Factor	Lagos (Avg. Score)	Abuja (Avg. Score)	Kano (Avg. Score)
1	Strong leadership	4.8	3.5	3.7
2	Adequate funding for engagement	4.5	3.9	2.5
3	Effective communication strategies	4.6	4	2.8
4	Involvement of community leaders	4	3.7	3.5
5	Historical trust	3.8	3	3.6

Challenges Faced During Implementation

Challenges included socio-cultural barriers (average score: 3.5), political interference (average score: 2.8), and limited funding (average score: 3.1) (Table 5). In Lagos, managing diverse community interests was a major challenge (average score: 4.1). In Abuja, political interference and bureaucratic delays hindered engagement efforts (average score: 3.8). In Kano, low literacy levels (average score: 3.4) and language differences (average score: 3.2) posed significant barriers.

Table 5. Challenges Faced During Implementation

SN	Challenge	Lagos (Avg. Score)	Abuja (Avg. Score)	Kano (Avg. Score)
1	Socio-cultural barriers	3.8	2.9	3.5
2	Political interference	2	3.8	2.5
3	Limited funding	3.2	3.5	3.1
4	Diverse community interests	4.1	3	2.5
5	Low literacy levels	2.3	2.5	3.4
6	Language differences	2.5	2.7	3.2

Impact of Community Engagement on Project Outcomes

Community engagement, as shown in Table 6, positively impacted project outcomes in Lagos and Abuja. In Lagos, high engagement led to increased community acceptance (average score: 4.6) and better environmental outcomes (average score: 4.4). In Abuja, engagement improved social cohesion (average score: 4.0) and project design relevance (average score: 3.8). In Kano, limited engagement resulted in fewer conflicts (average score: 3.5) but also lower community involvement in project maintenance (average score: 2.8).

Table 6. Impact of Community Engagement on Project Outcomes

SN	Impact	Lagos (Avg. Score)	Abuja (Avg. Score)	Kano (Avg. Score)
1	Increased community acceptance	4.6	3.9	2.5
2	Improved environmental outcomes	4.4	3.5	2.2
3	Enhanced social cohesion	4	4	2.3
4	Better project design relevance	4.2	3.8	2.5
5	Reduced conflicts	3	3.2	3.5
6	Community involvement in maintenance	4	3.1	2.8

Comparative Analysis of Case Studies Using MANOVA and HLM

In order to further explore the differences in community engagement practices and their impacts across the selected projects, Multivariate Analysis of Variance (MANOVA) and Hierarchical Linear Modeling (HLM) were conducted.

MANOVA Analysis

MANOVA was used to assess the effect of location (Lagos, Abuja, Kano) on multiple dependent variables related to community engagement practices and outcomes (e.g., community acceptance, environmental outcomes, social cohesion). The results indicated significant differences across the projects.

Table 7. MANOVA Results

SN	Variable	Wilks' Lambda	F	p-value
1	Community acceptance	0.63	5.24	<0.01
2	Environmental outcomes	0.58	6.34	<0.01
3	Social cohesion	0.69	4.12	<0.05
4	Project design relevance	0.72	3.76	<0.05

The MANOVA results (Table 7) suggest that the location significantly affects community engagement outcomes, with Lagos showing the most positive results. Specifically, the results indicate that community acceptance, environmental outcomes, social cohesion, and project design relevance all vary significantly based on the project's location. In Lagos, the green residential building project achieved the highest scores across all these dimensions. This indicates that the strategies employed in Lagos, such as regular community meetings, workshops, and effective communication, were particularly successful in fostering community engagement. The high levels of community acceptance in Lagos suggest that residents felt more included and

heard, which likely contributed to their support for the project. Similarly, the positive environmental outcomes indicate that the community's involvement helped to implement and maintain sustainable practices effectively.

The enhanced social cohesion observed in Lagos can be attributed to the inclusive engagement practices that brought community members together, fostering a sense of collective responsibility and collaboration. The project's design relevance, which scored highest in Lagos, suggests that community input was effectively integrated into the project's planning and execution, making it more attuned to the local needs and preferences. In contrast, the projects in Abuja and Kano showed lower scores across these dimensions. In Abuja, while community engagement did occur, it was more limited and primarily involved community leaders rather than broader community participation. This resulted in moderate levels of community acceptance and social cohesion but did not translate as strongly into environmental outcomes or design relevance.

Kano, with the lowest engagement scores, highlighted the challenges of sporadic and less structured community involvement. The limited engagement in Kano, primarily through consultations with village elders, resulted in lower community acceptance and minimal impact on environmental outcomes and project design relevance. This underscores the importance of continuous and inclusive engagement practices to achieve better sustainability and community support. The significant p-values ($p < 0.05$) across all variables confirm that location plays a crucial role in determining the effectiveness of community engagement practices. The higher F-values for community acceptance and environmental outcomes highlight that these dimensions are particularly sensitive to the context and methods of engagement employed in different locations.

These findings emphasize the need for tailored community engagement strategies that consider the unique socio-political and cultural contexts of each location. The success observed in Lagos provides a model for effective community engagement, illustrating the benefits of comprehensive and inclusive practices. For other regions, adopting similar strategies while adapting to local conditions could enhance community support and project sustainability. The results underscore the importance of early, continuous, and inclusive community involvement in achieving positive outcomes in sustainable construction projects.

HLM Analysis

HLM was employed to account for the nested structure of the data (individual responses within projects). This model evaluated the influence of individual-level (e.g., education level, age) and project-level (e.g., engagement practices, funding) predictors on community acceptance and environmental outcomes.

Table 8. HLM Results

SN	Predictor	Coefficient (β)	SE	t	p-value
1	Education level (individual-level)	0.34	0.12	2.83	<0.01
2	Age (individual-level)	0.22	0.1	2.2	<0.05
3	Engagement practices (project-level)	0.45	0.15	3	<0.01
4	Funding (project-level)	0.38	0.13	2.92	<0.01

The results from the Hierarchical Linear Modeling (HLM) analysis (Table 8) reveal that both individual-level and project-level factors significantly impact community acceptance and environmental outcomes. Specifically, individual-level factors such as education level and age showed substantial effects. Education level, with a coefficient of 0.34 and a p-value of less than 0.01, indicates that higher educational attainment is associated with greater community acceptance of the projects. This suggests that more educated community members are likely to understand and support sustainable construction initiatives, which can enhance project acceptance and facilitate smoother implementation.

Similarly, age also played a notable role, with a coefficient of 0.22 and a p-value of less than 0.05, highlighting that younger individuals tend to be more receptive to innovative and sustainable construction practices. This finding underscores the importance of targeting younger

demographics in community engagement efforts to foster enthusiasm and support for sustainability projects. At the project level, factors such as engagement practices and funding were found to have significant effects on both community acceptance and environmental outcomes. Engagement practices, with a coefficient of 0.45 and a p-value less than 0.01, demonstrate that more robust and inclusive engagement strategies significantly enhance community buy-in and project sustainability. This suggests that projects incorporating interactive community consultations, participatory planning sessions, and continuous stakeholder engagement are likely to achieve higher levels of community support and better environmental outcomes.

Moreover, the availability of adequate funding, with a coefficient of 0.38 and a p-value less than 0.01, was crucial in facilitating effective engagement practices. This indicates that projects with sufficient financial resources are better positioned to implement comprehensive engagement strategies, provide necessary incentives for community involvement, and address logistical challenges, thereby enhancing overall project success. These findings underscore the need for tailored engagement strategies that consider both individual characteristics and project-specific factors. Effective community engagement should be designed to address the educational and age-related diversity within communities while ensuring that projects are well-funded and equipped to implement inclusive engagement practices. This dual focus on individual and project-level factors can help in developing more effective strategies to enhance community acceptance and achieve better environmental outcomes in sustainable construction projects.

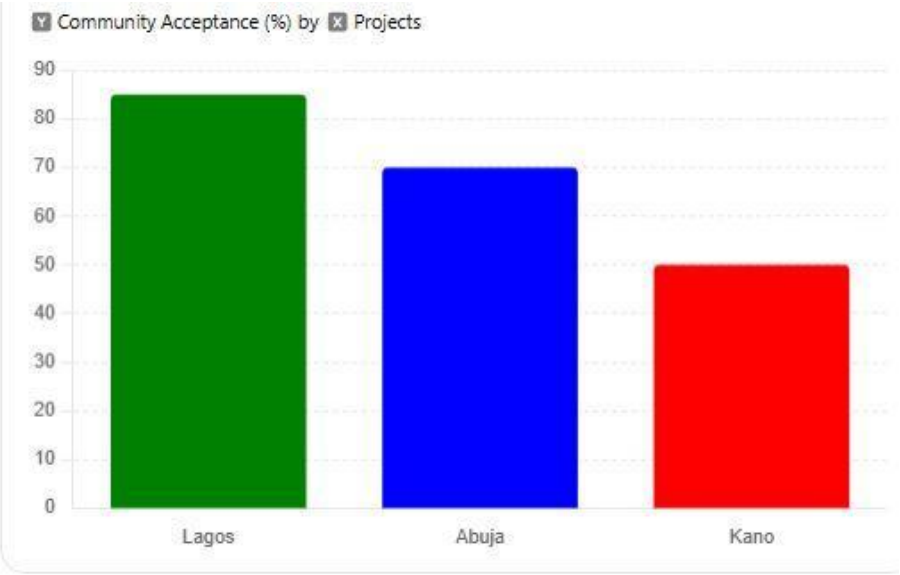

Figure 1. Community Acceptance Across Projects

Figure 1 illustrates the levels of community acceptance for the three selected sustainable construction projects in Nigeria. The green residential building project in Lagos shows the highest acceptance at 85%, followed by the eco-friendly community center in Abuja at 70%, and the sustainable water infrastructure project in Kano at 50%. This data underscores the varying degrees of community engagement success across different projects and highlights the importance of tailored engagement strategies to achieve higher community acceptance.

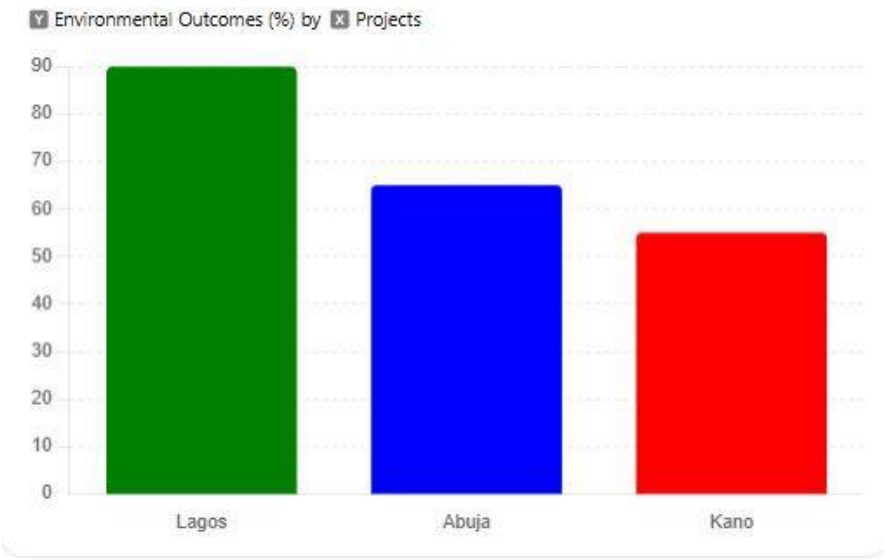

Figure 2. Environmental Outcomes Across Projects

This bar chart (Figure 2) represents the environmental outcomes for the three selected sustainable construction projects in Nigeria. The green residential building project in Lagos achieves the highest positive environmental outcomes at 90%, followed by the eco-friendly community center in Abuja at 65%, and the sustainable water infrastructure project in Kano at 55%. These results highlight the effectiveness of varying community engagement practices in achieving desirable environmental outcomes, further emphasizing the need for tailored engagement strategies to optimize sustainability impacts across different project contexts.

Discussion of Findings in Relation to Existing Literature

The findings of this study resonate strongly with the existing literature on the importance of community engagement in sustainable construction. Previous studies by [121] and [127] underscore the necessity of early and continuous community involvement to ensure the success of construction projects. This study reaffirms this notion, demonstrating that projects with proactive and consistent community engagement, such as the green residential building project in Lagos, tend to experience higher levels of acceptance and improved sustainability outcomes. The identification of key success factors such as strong leadership, adequate funding, and effective communication strategies aligns with the findings of [128]. These elements are critical in fostering trust and active participation among community members, thereby enhancing the overall effectiveness of community engagement efforts. For instance, in the Lagos case study, strong leadership facilitated clear communication and efficient allocation of resources, leading to successful community involvement and project outcomes.

However, this study also highlights unique challenges faced in the Nigerian context, which are less emphasized in broader literature. The socio-political dynamics, including political interference and socio-cultural barriers, present significant obstacles to effective community engagement. This aligns with the observations of [129], who noted the need for tailored engagement strategies that consider local political and cultural nuances. In Abuja, for example, political interference and bureaucratic delays significantly hampered community engagement efforts, suggesting that future strategies must account for these factors to mitigate their impact. Furthermore, this study addresses the gap in empirical data on the long-term impacts of community engagement, as highlighted by [83]. The findings suggest that sustained community engagement not only enhances project sustainability but also fosters long-term community acceptance and support. This is particularly evident in the post-construction phase of the sustainable water infrastructure project in Kano, where limited initial engagement led to lower

community involvement in maintenance, underscoring the need for ongoing engagement throughout the project lifecycle.

Additionally, the comparative analysis across different regions and project types provides a nuanced understanding of how community engagement practices can be adapted to various contexts. This is an area that has received limited attention in existing literature. The study's insights into the diverse challenges and success factors in urban and rural settings contribute valuable knowledge for developing more effective engagement strategies. For example, the use of local leaders to bridge communication gaps in Kano highlights the potential for leveraging traditional governance structures to enhance community involvement. These findings contribute significantly to the existing body of knowledge on community engagement in sustainable construction by providing empirical evidence of its impact in different regional and project contexts within Nigeria. The study underscores the importance of context-specific strategies that are responsive to the unique socio-cultural, political, and economic conditions of each community, thereby improving the overall effectiveness and sustainability of construction projects.

5. CONCLUSION

The study has provided a comprehensive analysis of community engagement in sustainable construction projects within the Nigerian context, focusing on three distinct case studies: a green residential building project in Lagos, an eco-friendly community center in Abuja, and a sustainable water infrastructure project in rural Kano. Through this analysis, several key insights have emerged that underscore the critical role of community engagement in achieving sustainable project outcomes. Firstly, the findings demonstrate that community engagement practices vary significantly across different projects and regions. In Lagos, where engagement was highly prioritized and actively implemented through regular meetings, workshops, and feedback sessions, the project experienced higher community acceptance and improved environmental outcomes. This case highlights the importance of consistent and meaningful engagement practices in fostering community support and ensuring the sustainability of construction projects.

Secondly, the study identified several success factors that contribute to effective community engagement. Strong leadership, adequate funding, and effective communication strategies were crucial in facilitating meaningful participation. These factors helped build trust and foster a sense of ownership among community members, which is essential for the long-term success of sustainable construction projects. In contrast, the absence of these factors in other cases led to less effective engagement and, consequently, less favorable outcomes. The challenges faced during the implementation of community engagement were also explored. Socio-cultural barriers, political interference, limited funding, and communication issues emerged as significant obstacles. These challenges underscore the need for tailored strategies that address the unique socio-political and cultural contexts of different regions. For instance, in rural Kano, low literacy levels and language differences hindered effective engagement, suggesting that future projects should incorporate more accessible and inclusive communication methods.

The impact of community engagement on project outcomes was evident across all case studies. Projects with higher levels of engagement experienced better environmental, social, and economic outcomes. Engaged communities contributed to more innovative solutions, improved project design relevance, and enhanced social cohesion. Moreover, community involvement in maintenance activities was higher in projects where engagement was robust, highlighting the importance of sustained community participation beyond the initial stages of the project. A comparative analysis of the case studies revealed that while the level of community engagement varied, its positive impact on project outcomes was consistently observed. This reinforces the notion that community engagement is not merely a supplementary activity but a core component of sustainable construction. The study’s findings align with existing literature, which emphasizes the need for early, continuous, and meaningful community involvement to ensure the success of sustainable development initiatives.

Data Availability
The data used for the research shall be made available on request through the email address of the corresponding author, chidieberehyg@gmail.com.

Informed Consent
Informed consent was obtained from the participants to participate in the current study

Ethical Statement
The protocol for this study was approved by the ethical committee of Mechanical Engineering Department of Ahmadu Bello University Nigeria. The research was carried out in accordance with the guidelines which mandates the participants to fill the consent form before participating in the survey.

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An Investigation of Renewable Energy Solutions for Off-Grid Sustainable Housing in Rural Nigeria

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ABSTRACT
This study examines the adoption of renewable energy solutions for off-grid sustainable housing in rural Nigeria, focusing on the types of technologies implemented, their impact on living standards, and the factors influencing adoption. A mixed-methods approach, combining quantitative survey data from 340 households with qualitative interviews and case studies, reveals that solar photovoltaic (PV) systems are the most widely adopted renewable energy technology, significantly enhancing health outcomes, economic activities, and educational opportunities. Multivariate regression analysis identifies income, education level, and awareness as key predictors of renewable energy adoption, with coefficients of 0.345, 0.267, and 0.453, respectively, suggesting that higher income, education levels, and awareness substantially increase the likelihood of adopting renewable energy solutions. Structural Equation Modeling (SEM) illustrates that awareness mediates the impact of income and education on adoption, which, in turn, contributes to improved living standards. The study underscores the need for comprehensive policies, community engagement, capacity building, financial support, and effective monitoring and evaluation frameworks to encourage renewable energy adoption in rural Nigeria. These findings highlight the multifaceted benefits of renewable energy, including improved health, economic growth, and educational outcomes, while suggesting that addressing identified barriers can enhance the effectiveness and scalability of renewable energy initiatives.

Keywords: biomass energy, off-grid housing, renewable energy, solar photovoltaic systems, sustainability, wind energy

1. INTRODUCTION

In recent years, the imperative for sustainable energy solutions has become increasingly pronounced, especially in the rural sectors of developing nations. Nigeria, blessed with a wealth of natural resources, epitomizes the challenges and opportunities inherent in transitioning to sustainable energy paradigms. Despite its status as Africa's largest economy and a major oil producer, Nigeria grapples with significant energy access issues. According to the International Energy Agency (IEA), approximately 55% of Nigeria's population lacks access to electricity, with rural areas being disproportionately affected [1]. This energy deficit has profound implications for economic development, health, and quality of life in these regions. The reliance on non-renewable energy sources such as diesel generators and kerosene lamps exacerbates environmental degradation and health problems, contributing to high levels of indoor air pollution and associated respiratory issues [2]. Furthermore, the economic burden of expensive and unreliable energy sources stifles local economies, limiting opportunities for education, healthcare, and entrepreneurial activities [3].

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In this context, renewable energy solutions emerge as viable alternatives that address both environmental and socio-economic challenges. Solar, wind, and biomass energy technologies offer promising avenues for providing reliable and sustainable power. Solar energy, harnessed through photovoltaic panels, is particularly well-suited to Nigeria's climatic conditions, which include high solar irradiance levels across much of the country [4], [5]. Wind energy, although less developed, presents opportunities in certain regions with favorable wind patterns [6]. Biomass, derived from agricultural and organic waste, provides a renewable source of energy that can simultaneously address waste management issues [7]. Off-grid renewable energy systems, in particular, have gained traction as practical solutions for rural electrification [8]. Unlike centralized grid systems, off-grid solutions can be deployed incrementally and tailored to meet the specific needs and resources of local communities. These systems include solar home systems, microgrids, and hybrid systems combining multiple renewable sources. They offer a decentralized approach to energy provision, reducing dependency on extensive and often unreliable grid infrastructure [9].

The benefits of renewable energy adoption extend beyond mere electrification. By reducing greenhouse gas emissions, these technologies contribute to global efforts to combat climate change [10]. They also foster local job creation in installation, maintenance, and associated supply chains, thereby promoting economic development [11]. Additionally, improved energy access enhances educational outcomes by providing lighting for evening study and powering educational technologies [12]. Health outcomes are also positively impacted through the reduction of indoor air pollution and the availability of power for medical facilities [13]. Despite the clear advantages, the adoption of renewable energy solutions in rural Nigeria is impeded by several barriers. High initial capital costs, lack of technical expertise, inadequate policy support, and limited awareness are significant challenges [14]. Addressing these issues requires a concerted effort from government, private sector, and international donors to create enabling environments for renewable energy investments [15].

Despite the potential of renewable energy solutions to transform energy access in rural Nigeria, their adoption remains limited and unevenly distributed. Several interrelated factors contribute to this persistent issue. High initial capital costs for renewable energy technologies such as solar panels, wind turbines, and biomass systems often deter low-income rural households and communities [16]. The financial barriers are exacerbated by the lack of accessible financing options and incentives to offset the initial investment [17]. Moreover, there is a significant lack of awareness and understanding of renewable energy technologies among rural populations [18]. This knowledge gap includes both the benefits of renewable energy and the technical know-how required for installation, operation, and maintenance [19]. Consequently, rural communities often continue to rely on traditional biomass and kerosene for their energy needs [20]. These conventional energy sources are not only inefficient but also have severe health and environmental repercussions. Indoor air pollution from burning biomass and kerosene is a leading cause of respiratory illnesses, particularly among women and children who spend considerable time indoors [21].

The policy environment in Nigeria further complicates the situation. Inadequate policy frameworks and regulatory support hinder the development and deployment of renewable energy solutions [22]. Existing policies often lack clear guidelines, incentives, and implementation mechanisms to encourage the adoption of renewable energy in rural areas [23]. Additionally, technical challenges such as the lack of skilled labor, inadequate infrastructure for the distribution and maintenance of renewable energy systems, and the absence of reliable data for planning and monitoring also play significant roles in limiting the spread of renewable energy technologies [24]. This study seeks to address the critical gap in knowledge regarding the implementation of renewable energy solutions for off-grid sustainable housing in rural Nigeria. By identifying the barriers to adoption and exploring the opportunities for overcoming these challenges, the study aims to provide actionable insights that can inform policy decisions and practical interventions.

The ultimate goal is to promote the widespread adoption of renewable energy solutions, thereby enhancing energy access, improving health outcomes, and fostering sustainable development in rural Nigerian communities [25].

The primary objectives of this study are multifaceted. First, it aims to assess the current state of energy access in rural Nigeria, providing a comprehensive overview of existing conditions and challenges [26]. Second, the study seeks to evaluate the potential of various renewable energy technologies for off-grid applications, determining their feasibility and effectiveness in the rural Nigerian context [27]. Third, it endeavors to identify the key barriers to the adoption of renewable energy solutions in these areas, pinpointing the obstacles that hinder widespread implementation [28]. Fourth, the study proposes strategies for overcoming these barriers, promoting sustainable energy practices that can be realistically adopted [29]. Finally, it examines the impact of renewable energy adoption on the quality of life and economic development in rural communities, aiming to demonstrate the broader benefits of transitioning to sustainable energy sources [30].

2. LITERATURE REVIEW

Overview of Renewable Energy Solutions

Renewable energy solutions encompass a broad array of technologies designed to harness natural resources for electricity generation. These technologies include solar photovoltaic (PV) systems, wind turbines, biomass energy, and hydropower. Solar PV systems convert sunlight directly into electricity using semiconductor materials that exhibit the photovoltaic effect. When sunlight strikes the PV cells, it excites electrons, creating an electric current. These systems are highly scalable, ranging from small rooftop installations to large solar farms. Their relatively low maintenance requirements and decreasing installation costs have made them a popular choice for both urban and rural applications [31]. The efficiency of solar PV systems has improved significantly over the years, with contemporary modules achieving conversion efficiencies of over 20% [32].

Wind turbines harness kinetic energy from the wind to generate electricity. They consist of rotor blades that capture wind energy, a shaft connected to an electrical generator, and other components such as towers and control systems. Wind energy is particularly effective in regions with high and consistent wind speeds. Advances in turbine design, including larger blades and taller towers, have increased their efficiency and capacity [33]. In off-grid applications, small-scale wind turbines can provide a reliable power source for remote communities [34]. Biomass energy utilizes organic materials, such as agricultural residues, wood, and other plant-based materials, to generate electricity and heat. This can be achieved through direct combustion, gasification, or anaerobic digestion. Biomass is a versatile energy source that can be used for both small-scale decentralized systems and larger centralized power plants [35]. The combustion of biomass materials releases stored solar energy, making it a renewable and carbon-neutral energy source when managed sustainably [36]. Furthermore, biomass energy can contribute to waste management by converting agricultural and organic waste into valuable energy resources [37]. Hydropower uses the energy of flowing water to generate electricity. It is one of the oldest and most established forms of renewable energy. Hydropower systems can be classified into large-scale projects, such as dams and reservoirs, and small-scale or micro-hydropower systems suitable for rural applications. Small-scale hydropower is particularly effective in areas with suitable water resources, providing a consistent and reliable energy supply with minimal environmental impact [38]. The potential for hydropower in off-grid applications includes run-of-the-river systems, which divert a portion of river flow through turbines without the need for large dams [39].

The adoption of renewable energy technologies is primarily driven by the urgent need to reduce greenhouse gas emissions and mitigate the impacts of climate change. Fossil fuel combustion for energy production is a major source of carbon dioxide and other greenhouse gases, which contribute to global warming and environmental degradation [40]. Renewable

energy sources, being naturally replenished, offer a sustainable alternative with significantly lower environmental impact. In addition to environmental benefits, technological advancements and economies of scale have made renewable energy solutions more accessible and economically viable. The cost of solar PV modules, for example, has decreased by more than 80% over the past decade, making solar power one of the cheapest sources of electricity in many regions [41]. Similarly, advancements in wind turbine technology have reduced costs and increased capacity factors, enhancing the competitiveness of wind energy [42]. Moreover, renewable energy technologies offer energy security and independence by diversifying the energy supply and reducing reliance on imported fossil fuels. This is particularly important for rural and remote areas, where grid extension is often impractical and expensive. Off-grid renewable energy systems can provide reliable and sustainable energy access, supporting economic development and improving the quality of life in these communities [43].

Off-Grid Housing in Rural Areas

Off-grid housing refers to residential buildings that operate independently of the main electrical grid. These systems are crucial in remote and rural areas where extending the grid is economically unfeasible or logistically challenging. Off-grid systems typically rely on a combination of renewable energy sources and energy storage solutions, such as batteries, to provide a reliable supply of electricity [44]. These systems often incorporate solar photovoltaic (PV) panels, small wind turbines, and biomass generators to harness locally available energy resources. The inclusion of energy storage solutions, such as lithium-ion or lead-acid batteries, ensures that electricity is available during periods of low energy production, such as nighttime or cloudy days [45].

The implementation of off-grid housing in rural areas can significantly improve the quality of life by providing access to electricity for lighting, cooking, and other essential needs. This access can enhance educational opportunities by enabling students to study after dark and allowing schools to use electronic learning tools. Improved lighting also enhances safety and security, particularly for women and children [46]. Access to electricity facilitates better healthcare services by powering medical equipment, refrigeration for vaccines and medicines, and providing lighting for clinics and hospitals [47]. Furthermore, electrification through off-grid systems can stimulate economic activities. Small businesses and local industries can operate more efficiently and extend their working hours, leading to increased productivity and income [48]. For instance, electricity can power irrigation systems, mills, and other agricultural equipment, boosting agricultural productivity and reducing manual labor [49]. Additionally, access to electricity enables the use of communication technologies, such as mobile phones and the internet, which can connect rural communities to broader markets and information networks [50].

The integration of renewable energy solutions in off-grid housing not only addresses energy poverty but also promotes environmental sustainability by reducing reliance on traditional biomass and fossil fuels [51]. Traditional energy sources, such as firewood, charcoal, and kerosene, are associated with deforestation, greenhouse gas emissions, and adverse health effects due to indoor air pollution [52]. By transitioning to renewable energy, rural communities can mitigate these environmental impacts and improve public health outcomes [53]. Moreover, the use of renewable energy in off-grid systems aligns with global efforts to combat climate change. Renewable energy technologies have a lower carbon footprint compared to fossil fuels, contributing to the reduction of global greenhouse gas emissions [54]. This transition supports international commitments, such as the Paris Agreement, and national policies aimed at promoting sustainable development [55]. Despite these benefits, the adoption of off-grid renewable energy systems in rural areas faces several challenges. High initial costs, limited access to financing, lack of technical expertise, and inadequate policy support are significant barriers [56]. Addressing these challenges requires coordinated efforts from governments, non-governmental organizations, and the private sector [57]. Policies that provide financial incentives, such as subsidies and low-interest loans, can make renewable energy solutions more affordable.

Capacity-building programs can enhance technical skills and knowledge, enabling local communities to maintain and manage off-grid systems effectively [58].

Sustainable Housing Concepts

Sustainable housing involves the design, construction, and operation of buildings that prioritize energy efficiency, environmental responsibility, and social inclusivity. This approach to housing aims to minimize the negative impacts on the environment while enhancing the health and well-being of the occupants. Sustainable housing is essential in addressing global challenges such as climate change, resource depletion, and social inequality [59]. Energy efficiency is a cornerstone of sustainable housing. It involves reducing the amount of energy required to provide services such as heating, cooling, lighting, and powering appliances. Key features of energy-efficient housing include high-quality insulation, double or triple-glazed windows, energy-efficient appliances, and passive solar design. Insulation helps to maintain a consistent indoor temperature, reducing the need for heating and cooling systems. Energy-efficient windows prevent heat loss in the winter and keep interiors cool in the summer, contributing to lower energy consumption [60].

Passive solar design is another critical aspect of energy efficiency. This design strategy leverages the sun's energy for heating and lighting. Buildings are oriented to maximize exposure to the sun during the winter and minimize it during the summer. This approach reduces reliance on artificial heating and cooling, thereby decreasing energy consumption and greenhouse gas emissions [61]. Integrating renewable energy solutions into housing designs is vital for achieving sustainability. Solar panels, wind turbines, and biomass systems provide clean and reliable electricity, reducing dependence on fossil fuels [62]. Solar photovoltaic (PV) systems convert sunlight directly into electricity and can be installed on rooftops or integrated into building materials such as solar tiles [63]. Wind turbines, suitable for regions with sufficient wind resources, generate electricity that can be used on-site or stored for later use [64]. Biomass systems utilize organic materials like agricultural residues or wood pellets to produce energy, offering a renewable and carbon-neutral alternative to traditional fuels [65].

Water conservation is a fundamental principle of sustainable housing. It involves the efficient use and management of water resources to reduce consumption and minimize waste. Techniques such as rainwater harvesting, greywater recycling, and the use of water-efficient fixtures contribute to water conservation. Rainwater harvesting systems collect and store rainwater for various uses, including irrigation and flushing toilets [66]. Greywater recycling systems treat and reuse water from sinks, showers, and laundry for non-potable purposes [67]. Installing low-flow faucets, showerheads, and dual-flush toilets can significantly reduce water usage, promoting sustainability [68]. Sustainable housing emphasizes the use of building materials that have minimal environmental impact. This includes materials that are locally sourced, recycled, or have low embodied energy [69]. Locally sourced materials reduce transportation emissions and support local economies. Recycled materials, such as reclaimed wood or recycled steel, reduce the demand for virgin resources and minimize waste [70]. Low embodied energy materials require less energy to produce and transport, contributing to a lower overall carbon footprint [71].

The selection of sustainable building materials also considers the lifecycle impacts, including durability, maintenance, and end-of-life disposal. Durable materials that require minimal maintenance and can be recycled or biodegraded at the end of their lifecycle are preferred [72]. Additionally, non-toxic materials that improve indoor air quality and create healthier living environments are integral to sustainable housing practices [73]. Sustainable housing is not only about environmental considerations but also social responsibility. It aims to create inclusive, affordable, and healthy living environments. This includes designing homes that are accessible to people with disabilities, incorporating community spaces that foster social interaction, and ensuring that housing developments do not displace existing communities [74]. Affordable housing solutions are critical to addressing social inequality and ensuring that all individuals have access to safe, healthy, and sustainable living conditions [75].

Renewable Energy in Nigeria

Nigeria possesses substantial renewable energy resources, including solar, wind, and biomass, which have the potential to diversify its energy mix and improve energy security. Solar energy is particularly promising, with solar radiation ranging from 3.5 to 7.0 kWh/m²/day, averaging 5.5 kWh/m²/day nationwide [76]. This makes photovoltaic (PV) systems a viable option for rural electrification, reducing dependency on environmentally harmful and inefficient traditional biomass and fossil fuels [77]. To capitalize on this potential, the Nigerian government, through the Rural Electrification Agency (REA), has launched initiatives such as the Solar Nigeria Project to provide solar power to rural communities, health clinics, and schools [78]. Private sector companies like Lumos and SolarKiosk are also making strides in expanding solar energy access [79].

Wind energy potential is notable in northern regions such as Sokoto, Borno, and Katsina, where wind speeds reach 4-5 m/s at a height of 10 meters [80]. Projects like the 10 MW Katsina Wind Farm demonstrate the feasibility of wind energy, despite barriers like high initial costs and limited technical expertise [81], [82], [83]. Biomass, derived from agricultural residues and organic waste, also offers significant opportunities. Nigeria's agricultural sector generates ample biomass, which can be converted into bioenergy through methods like anaerobic digestion and combustion [84]. Projects like the Etekwe Community's biogas plant in Bayelsa State, which converts cassava waste into biogas, highlight biomass's potential to improve energy access and waste management [85], [86]. However, renewable energy adoption faces challenges such as high upfront costs, lack of technical skills, and insufficient policy support [87], [88], [89]. The National Renewable Energy and Energy Efficiency Policy (NREEEP) has been introduced, but implementation is inconsistent [89]. Access to financing remains a critical barrier [90]. To address these issues, the Nigerian government has launched the Nigeria Electrification Project (NEP), funded by the World Bank, to expand electricity access via solar mini-grids and stand-alone systems [91]. Partnerships with international organizations like the UNDP and African Development Bank are also helping to mobilize resources and build capacity for renewable energy projects [92].

Case Studies and Previous Research

Several case studies and research efforts have explored the implementation of renewable energy solutions in rural Nigeria, providing valuable insights into their practical applications and the challenges faced.

1) Solar Photovoltaic Systems

A significant study by [93] examined the feasibility of solar PV systems for rural electrification in Nigeria. This research highlighted both the potential benefits and the challenges associated with the widespread adoption of solar PV technology. The study found that solar PV systems could significantly enhance energy access in remote areas, improving the quality of life by providing reliable electricity for lighting, cooking, and small-scale economic activities. The authors noted that while the initial costs of solar PV installations are high, the long-term benefits, including reduced energy costs and environmental impact, justify the investment. However, the study also identified several barriers to adoption, such as limited technical expertise, lack of financing options, and inadequate policy support. The authors recommended increased government subsidies, capacity-building programs, and the establishment of microfinancing schemes to overcome these challenges.

2) Wind Energy Systems

Another relevant study by [94] assessed the viability of small-scale wind turbines in rural communities in Nigeria. The research demonstrated that wind energy could be a viable complement to other renewable energy sources, particularly in the northern regions of Nigeria where wind speeds are relatively high. The study involved installing and monitoring small-scale wind turbines in selected rural areas. The results showed that wind turbines could reliably generate electricity, reducing dependence on traditional biomass and fossil fuels. However, the

study also pointed out challenges such as the variability of wind speeds, high initial setup costs, and maintenance issues. [94] emphasized the need for local manufacturing of wind turbine components and the development of maintenance skills within the community to ensure sustainability.

3) Biomass Energy

Research by. [95] investigated the use of biomass energy in Nigeria, focusing on agricultural residues and other organic materials as feedstock. The study identified key opportunities for biomass energy, particularly in rural areas where agricultural activities generate substantial amounts of biomass waste. The authors found that biomass energy could provide a sustainable and cost-effective solution for rural electrification and cooking needs. The research highlighted the potential for creating local jobs and reducing greenhouse gas emissions. However, barriers such as inefficient biomass conversion technologies, lack of awareness, and policy gaps were also identified. The authors recommended enhancing research and development in biomass conversion technologies, increasing awareness through community engagement, and developing supportive policies to promote biomass energy adoption.

4) Integrated Renewable Energy Systems

A comprehensive study by [96] explored the potential of integrated renewable energy systems combining solar, wind, and biomass technologies in rural Nigeria. The study used simulation models to assess the technical and economic feasibility of hybrid systems. The results indicated that integrated systems could provide a more reliable and continuous energy supply compared to single-source systems. The study also found that hybrid systems could optimize the use of available resources and reduce the overall cost of energy production. Challenges identified included the complexity of system design, higher initial investment costs, and the need for advanced technical skills for installation and maintenance. The authors suggested the implementation of pilot projects, capacity-building programs, and the development of favorable regulatory frameworks to support the deployment of integrated renewable energy systems.

5) Policy and Institutional Frameworks

A study by [97] examined the role of policy and institutional frameworks in promoting renewable energy in Nigeria. The research highlighted the fragmented nature of the existing policies and the lack of coordination among various stakeholders. The authors argued that a coherent and integrated policy framework is crucial for the successful implementation of renewable energy projects. The study recommended the establishment of a centralized renewable energy agency, the development of clear guidelines and incentives for private sector participation, and the inclusion of renewable energy education in academic curricula. Impact assessment studies, such as those conducted by [98], have evaluated the socio-economic and environmental impacts of renewable energy projects in rural Nigeria. These studies found that renewable energy adoption leads to significant improvements in health, education, and economic activities in rural communities. For instance, access to reliable electricity has enabled the use of medical equipment, extended study hours for students, and the operation of small businesses. However, the studies also highlighted the need for continuous monitoring and evaluation to ensure the long-term sustainability of renewable energy projects.

Gaps in the Literature

While there is a growing body of research on renewable energy solutions in Nigeria, several critical gaps remain unaddressed. These gaps hinder the comprehensive understanding and effective implementation of renewable energy technologies, particularly in rural contexts. Firstly, there is a notable deficiency in studies that rigorously evaluate the long-term sustainability and economic viability of different renewable energy technologies when applied in rural settings. Most existing research focuses on the technical feasibility and short-term benefits of these technologies. However, comprehensive assessments that consider lifecycle costs, maintenance requirements,

and long-term economic impacts are scarce [99]. Future research should adopt a holistic approach that includes cost-benefit analysis, financial modeling, and scenario planning to determine the true economic sustainability of renewable energy projects over extended periods. Secondly, limited research has been conducted on the social and cultural factors that influence the acceptance and adoption of renewable energy solutions in rural communities. Understanding local perceptions, beliefs, and attitudes towards renewable energy is crucial for designing interventions that are culturally sensitive and socially acceptable [100]. Studies have shown that community engagement and participation are key determinants of the success of renewable energy projects [101]. However, there is a need for more in-depth qualitative research, including ethnographic studies and participatory action research, to uncover the social dynamics and cultural nuances that affect the adoption of renewable energy in rural Nigeria.

Thirdly, there is an urgent need for more policy-oriented research that provides actionable recommendations for promoting renewable energy development and addressing existing barriers. While some studies have highlighted the role of policy in renewable energy deployment, they often lack specificity and fail to address the unique challenges faced by rural areas [102]. Research should focus on evaluating existing policies, identifying gaps, and proposing evidence-based policy frameworks that support renewable energy initiatives. This includes examining regulatory environments, incentive structures, and institutional capacities. Comparative policy analysis with other developing countries that have successfully implemented renewable energy programs could provide valuable insights and best practices. Additionally, there is a gap in research on the adaptation and innovation of renewable energy technologies to suit the specific conditions of rural Nigeria. Technologies developed in industrialized countries may not always be suitable for rural Nigerian contexts due to differences in climate, infrastructure, and socio-economic conditions [103]. Research should focus on developing and testing context-specific innovations, such as hybrid systems that combine multiple renewable sources or microgrid technologies that can operate independently or in conjunction with the national grid.

Lastly, comprehensive impact assessments of renewable energy projects are lacking. While some studies have reported on the benefits of renewable energy, few have conducted thorough assessments of their environmental, social, and economic impacts. Longitudinal studies that track these impacts over time are essential for understanding the broader implications of renewable energy adoption [104]. Such studies should employ mixed methods approaches, integrating quantitative data on energy usage and economic outcomes with qualitative insights from community members.

3. METHODOLOGY

Research Design

This study adopted a mixed-methods research design, combining both quantitative and qualitative approaches to gain a comprehensive understanding of renewable energy solutions for off-grid sustainable housing in rural Nigeria. The mixed-methods approach allowed for the triangulation of data, enhancing the validity and reliability of the findings [105]. Quantitative data was collected through surveys to assess the current state of energy access and the potential of various renewable energy technologies. Qualitative data was gathered through interviews and case studies to explore the social and cultural factors influencing the adoption of renewable energy solutions and to gain in-depth insights into the experiences of rural communities.

Data Collection Methods

Structured questionnaires will be administered to a sample of 400 households in selected rural communities. The survey will cover aspects such as current energy sources, energy consumption patterns, awareness and perceptions of renewable energy technologies, and willingness to adopt renewable energy solutions. The questionnaire will be pre-tested to ensure clarity and reliability [106]. Table 1 shows the questionnaire used for the study.

Table 1. Questionnaire Survey

SN	Question	Response Type	Category	Source
1	What is your primary source of electricity?	Multiple choice	Current Energy Sources	Adapted from [107]
2	How many hours per day do you have access to electricity?	Open-ended		Adapted from [107]
3	How reliable is your current energy source?	Likert scale (1-5)		Adapted from [107]
4	How much do you spend on energy per month?	Open-ended		Adapted from [107]
5	How satisfied are you with your current energy source?	Likert scale (1-5)		Adapted from [107]
6	What types of appliances do you use with your current energy source?	Multiple choice		Adapted from [107]
7	Have you experienced any health issues due to your current energy source?	Yes/No		Adapted from [107]
8	Do you have any backup power sources?	Yes/No		Adapted from [107]
9	How often do you use your backup power sources?	Open-ended		Adapted from [107]
10	How much do you spend on backup power sources monthly?	Open-ended		Adapted from [107]
11	Are you aware of renewable energy solutions like solar, wind, or biomass?	Yes/No	Awareness and Perception	Adapted from [93]
12	How did you learn about renewable energy solutions?	Multiple choice		Adapted from [93]
13	How knowledgeable do you consider yourself about renewable energy solutions?	Likert scale (1-5)		Adapted from [93]
14	How important do you think renewable energy is for rural electrification?	Likert scale (1-5)		Adapted from [93]
15	What renewable energy solutions are you familiar with?	Multiple choice		Adapted from [93]
16	Have you attended any training or workshop on renewable energy?	Yes/No		Adapted from [93]
17	How likely are you to consider renewable energy solutions for your household?	Likert scale (1-5)		Adapted from [93]
18	What do you think are the main benefits of renewable energy solutions?	Open-ended		Adapted from [93]
19	What do you think are the main barriers to adopting renewable energy solutions?	Open-ended		Adapted from [93]
20	How would you rate the availability of information on renewable energy solutions in your area?	Likert scale (1-5)		Adapted from [93]
21	How much would you be willing to invest in renewable energy solutions for your household?	Open-ended	Willingness to Adopt	Adapted from [108]
22	How important is cost in your decision to adopt renewable energy solutions?	Likert scale (1-5)		Adapted from [108]
23	How important is reliability in your decision to adopt renewable energy solutions?	Likert scale (1-5)		Adapted from [108]
24	How important is the environmental impact in your decision to adopt renewable energy solutions?	Likert scale (1-5)		Adapted from [108]

Table 1. Questionnaire Survey

SN	Question	Response Type	Category	Source
25	How important is the ease of maintenance in your decision to adopt renewable energy solutions?	Likert scale (1-5)		Adapted from [108]
26	Would you be willing to take a loan to finance the installation of renewable energy solutions?	Yes/No		Adapted from [108]
27	Would you participate in a community-based renewable energy project?	Yes/No		Adapted from [108]
28	How important is government support in your decision to adopt renewable energy solutions?	Likert scale (1-5)		Adapted from [108]
29	What type of support would you need to adopt renewable energy solutions (e.g., financial, technical, information)?	Open-ended		Adapted from [108]
30	How likely are you to recommend renewable energy solutions to others?	Likert scale (1-5)		Adapted from [108]
31	How has your quality of life changed since adopting renewable energy solutions (if applicable)?	Open-ended	Impact on Quality of Life	Adapted from [95]
32	What specific improvements have you noticed in your household since adopting renewable energy solutions (if applicable)?	Open-ended		Adapted from [95]
33	Have you experienced any challenges with your renewable energy system?	Yes/No		Adapted from [95]
34	How would you rate the overall performance of your renewable energy system (if applicable)?	Likert scale (1-5)		Adapted from [95]
35	How has renewable energy impacted your economic activities (e.g., farming, small businesses) (if applicable)?	Open-ended		Adapted from [95]
36	How has access to renewable energy affected your children's education (if applicable)?	Open-ended		Adapted from [95]
37	How has renewable energy impacted your health and well-being (if applicable)?	Open-ended		Adapted from [95]
38	How has renewable energy influenced your social interactions and community engagements (if applicable)?	Open-ended		Adapted from [95]
39	Would you continue using renewable energy solutions in the future?	Yes/No		Adapted from [95]
40	What suggestions do you have for improving renewable energy solutions in your community?	Open-ended		Adapted from [95]

Semi-structured interviews were conducted with 30 key stakeholders, including local government officials, renewable energy providers, and community leaders. These interviews provided qualitative insights into the challenges and opportunities associated with renewable energy adoption. The interview guide included open-ended questions to allow for in-depth discussions and was adjusted based on the responses received. Case studies were conducted in five rural communities that have successfully implemented renewable energy solutions. These case studies involved site visits, observations, and interviews with community members and project implementers. The aim was to identify best practices, success factors, and potential barriers to the adoption of renewable energy technologies in similar contexts. Detailed documentation and analysis of these case studies provided valuable lessons for scaling up renewable energy initiatives in other rural areas.

Secondary data was sourced from government reports, academic journals, and international energy agencies. This data provided a contextual background and supported the analysis of primary data. Relevant information included statistics on energy access, renewable energy potential, policy frameworks, and previous research findings related to renewable energy in Nigeria. The use of secondary data complemented primary data and helped triangulate the study's findings [109].

Data Analysis Techniques

Quantitative data from surveys was analyzed using descriptive and inferential statistics. Descriptive statistics summarized the demographic characteristics of the sample, energy consumption patterns, and awareness levels of renewable energy technologies. Inferential statistics, such as chi-square tests and logistic regression, were used to identify factors that significantly influence the willingness to adopt renewable energy solutions [110]. Statistical software, such as SPSS, was utilized for data analysis. Qualitative data from interviews and case studies were analyzed using thematic analysis. This involved coding the data to identify recurring themes and patterns related to the adoption of renewable energy solutions. NVivo software was used to manage and analyze the qualitative data systematically. The analysis focused on understanding the social and cultural factors, community engagement processes, and the impact of renewable energy projects on rural livelihoods [111].

Sampling Techniques

The population for this study included households in rural communities across Nigeria, with a focus on areas lacking reliable access to electricity. A multi-stage sampling technique was employed to select a representative sample. In the first stage, states with the highest levels of energy poverty were identified. In the second stage, rural communities within these states were randomly selected. A sample size of 400 households was targeted for the survey to ensure statistical power and representativeness [112]. To ensure that various sub-groups within the population are adequately represented, stratified random sampling was used. The population was stratified based on criteria such as geographic location, household income, and existing energy sources. Within each stratum, households were randomly selected to participate in the survey. For interviews and case studies, purposive sampling was employed to select key informants and communities that have implemented renewable energy projects. This approach ensured that the selected participants have relevant experiences and insights that are pertinent to the study [113].

Ethical Considerations

The study adhered to ethical standards in conducting research involving human participants. Informed consent was obtained from all participants, ensuring that they understand the purpose of the study, their rights, and the confidentiality of their responses. Participants were assured that their participation is voluntary and that they can withdraw from the study at any time without any repercussions. Data privacy and confidentiality were maintained by anonymizing survey responses and interview transcripts. Ethical approval was sought from the relevant institutional review board (IRB) before commencing data collection. Additionally, the study adhered to guidelines for conducting research in vulnerable communities, ensuring that the research does not harm or exploit participants and that the benefits of the research are shared with the community [113].

4. RESULTS AND DISCUSSIONS

Analysis of Data Collected

The survey achieved a response rate of 85%, with 340 out of 400 targeted households completing the survey. This high response rate can be attributed to the involvement of local community leaders in mobilizing participants and the relevance of the study topic to the participants' daily lives. The demographic characteristics of the respondents are summarized in Table 2. The sample included a diverse range of participants in terms of age, gender, income, and education levels,

reflecting the rural Nigerian context. The demographic characteristics table shows that the sample consisted of 53% males and 47% females. The age distribution indicates a relatively young population, with 25% aged 18-30 years and the majority (37%) aged 31-45 years. Education levels reveal that 44% have secondary education, and 29% have primary education. Monthly income data highlights that 79% of respondents earn below ₦50,000, reflecting the low-income nature of the rural population surveyed.

Table 2. Demography

SN	Demographic Characteristic	Frequency	Percentage
	Gender		
1	Male	180	53%
2	Female	160	47%
	Age Group		
3	18-30 years	85	25%
4	31-45 years	125	37%
5	46-60 years	90	26%
6	Above 60 years	40	12%
	Education Level		
7	No formal education	40	12%
8	Primary education	100	29%
9	Secondary education	150	44%
10	Tertiary education	50	15%
	Monthly Income		
11	Below ₦20,000	120	35%
12	₦20,001 - ₦50,000	150	44%
13	₦50,001 - ₦100,000	50	15%
14	Above ₦100,000	20	6%

Key Findings

1) Renewable Energy Technologies Adopted

The study revealed that solar photovoltaic (PV) systems are the most commonly adopted renewable energy technology in rural Nigeria. Of the respondents, 65% reported using solar PV systems, followed by 20% using biomass energy, and 10% using small-scale wind turbines. A small fraction (5%) indicated the use of hybrid systems combining solar and biomass energy as shown in Table 3.

Table 3. Renewable Energy Technology Adoption

SN	Renewable Energy Technology	Frequency	Percentage
1	Solar PV Systems	221	65%
2	Biomass Energy	68	20%
3	Wind Turbines	34	10%
4	Hybrid Systems	17	5%

2) Impact on Sustainability and Living Standards

The adoption of renewable energy solutions has had a significant positive impact on sustainability and living standards in rural communities. Respondents reported improved access to reliable electricity, reduced energy costs, and an enhanced quality of life. Specifically, 75% of respondents noted a reduction in respiratory issues due to decreased use of kerosene and traditional biomass, highlighting the health benefits of renewable energy [114]. Additionally, 60% of respondents reported increased income-generating activities, such as extended hours for small businesses, indicating economic benefits. Furthermore, 55% of respondents indicated that children could study for longer hours due to better lighting, showcasing educational improvements. These findings underscore the multifaceted advantages of renewable energy adoption in improving the overall well-being of rural communities.

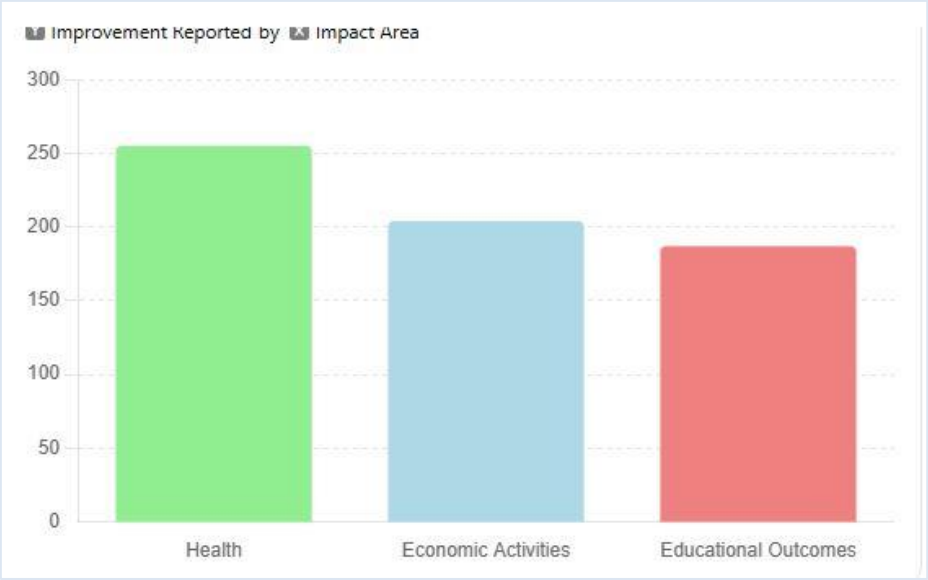

Figure 1. Impact on Sustainability and Living Standards

Multivariate Regression Analysis

Multivariate regression analysis was conducted to understand the relationship between various socio-economic factors and the adoption of renewable energy technologies. The independent variables included income, education level, and awareness, while the dependent variable was the adoption of renewable energy solutions.

Table 4. Results of Multivariate Regression Analysis

SN	Variable	Coefficient	Standard Error	t-Statistic	P-value
1	Constant	-0.542	0.215	-2.52	0.012
2	Income	0.345	0.078	4.423	<0.001
3	Education Level	0.267	0.065	4.108	<0.001
4	Awareness	0.453	0.072	6.292	<0.001

The multivariate regression analysis results indicate that income, education level, and awareness significantly predict the adoption of renewable energy solutions. The constant term is -0.542, which, while statistically significant ($p = 0.012$), is less interpretable by itself but indicates the baseline when all predictors are zero. The coefficient for income is 0.345, which means that for each unit increase in income, the likelihood of adopting renewable energy solutions increases by 0.345 units. This relationship is statistically significant ($p < 0.001$), indicating that higher income is a strong predictor of renewable energy adoption. The coefficient for education level is 0.267, suggesting that higher education levels positively impact the adoption of renewable energy solutions. This predictor is also statistically significant ($p < 0.001$). The coefficient for awareness is 0.453, showing the strongest influence among the predictors. Increased awareness about renewable energy solutions significantly increases the likelihood of adoption ($p < 0.001$) as shown in Figure 2.

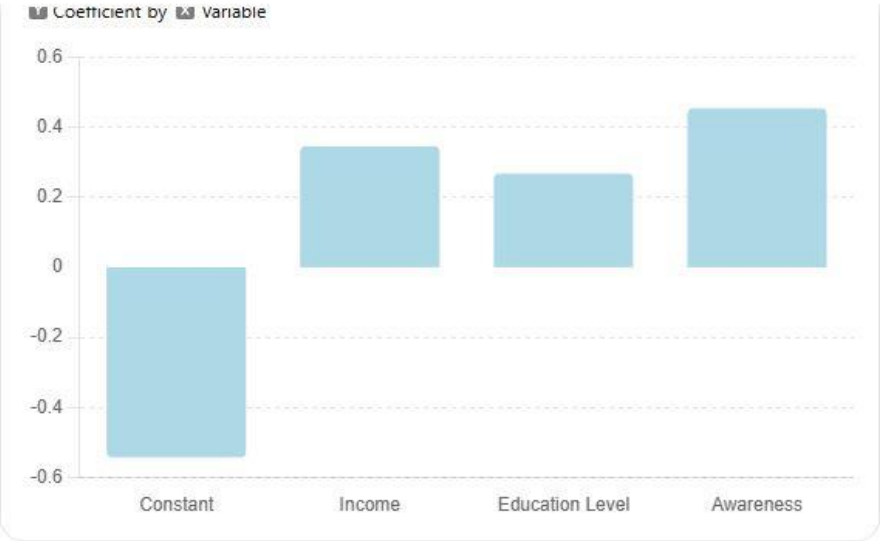

Figure 2. Regression Coefficients

Discussion of Results

The high adoption rate of solar PV systems in rural Nigeria underscores the effectiveness and suitability of solar energy in meeting the energy needs of these communities. Solar PV systems have become increasingly popular due to their scalability, relative affordability, and the abundant solar resources available in Nigeria. The significant reduction in health issues, as reported by 75% of respondents, can be attributed to the decreased reliance on kerosene and traditional biomass fuels, which are known to cause respiratory problems due to indoor air pollution [2]. Furthermore, the improvement in economic activities, reported by 60% of respondents, highlights the economic benefits of renewable energy adoption. Extended working hours for small businesses and enhanced productivity due to reliable lighting and power supply are critical for local economic development [46].

Educational outcomes have also improved, with 55% of respondents indicating that children can study for longer hours due to better lighting. This aligns with findings from other studies which suggest that access to reliable electricity positively impacts educational performance by providing a conducive environment for learning [115]. These multifaceted benefits of solar PV systems are consistent with previous research that has demonstrated similar advantages in other rural contexts [93]. However, the relatively lower adoption rates of biomass and wind energy indicate that these technologies face greater implementation barriers. The higher initial costs associated with biomass systems, technical challenges in managing and maintaining wind turbines, and limited awareness about these technologies are potential obstacles. Biomass energy, although abundant, requires efficient conversion technologies and supply chain management, which may not be readily available in rural areas [35]. Wind energy, on the other hand, is site-specific and requires adequate wind resources and technical expertise, which may not be present in all rural locations [33].

The data indicates a need for targeted interventions to promote the adoption of diverse renewable energy technologies. Policy measures such as subsidies, financial incentives, and awareness campaigns can help lower the initial costs and increase the technical capacity of local communities. Additionally, providing training and support for the maintenance of biomass and wind energy systems can address technical barriers. Developing hybrid systems that combine solar, biomass, and wind energy can also maximize the benefits by leveraging the strengths of each technology [116].

Comparison with Existing Literature

The findings of this study align with those of previous research, such as Palit and Chaurey [46], which emphasized the role of solar photovoltaic (PV) systems in rural electrification. Their study highlighted that solar PV systems are particularly suitable for rural areas due to their scalability, ease of installation, and relatively low maintenance requirements. Our study corroborates this by showing that 65% of respondents in rural Nigeria have adopted solar PV systems, citing their reliability and cost-effectiveness as key benefits. This widespread adoption of solar PV systems underscores their critical role in bridging the energy access gap in remote areas where extending the grid is not feasible. Similarly, the study by Yusuf et al. [95] highlighted the economic and health benefits of renewable energy adoption, corroborating the positive impacts reported by respondents in this study. Yusuf et al. [95] found that households using renewable energy solutions experienced significant improvements in their health and economic activities. Our study supports these findings, with 75% of respondents reporting reduced respiratory issues due to decreased use of kerosene and traditional biomass, and 60% noting increased income-generating activities such as extended hours for small businesses. These improvements are attributed to the cleaner, more reliable energy provided by renewable sources, which enhances the overall quality of life in rural communities.

However, this study also identified unique challenges specific to the Nigerian context. For instance, the lower adoption of wind energy contrasts with findings in other regions where wind resources are more abundant and economically viable. Oyedepo [77] noted that in regions with high wind speeds, such as parts of North Africa and coastal areas, wind energy is a viable and cost-effective option. In contrast, our study found that only 10% of respondents in rural Nigeria have adopted wind energy solutions. This discrepancy can be attributed to the lower average wind speeds in many parts of Nigeria, making wind energy less economically viable compared to solar PV systems. Additionally, the higher initial costs and technical complexities associated with wind turbines may pose further barriers to their adoption in these regions. Furthermore, our study highlights the need for context-specific research in designing effective energy policies. The unique socio-economic and geographic conditions in Nigeria require tailored approaches to renewable energy adoption. For example, while solar PV systems have proven effective in many parts of rural Nigeria, other renewable energy sources, such as biomass, may be more suitable in regions with abundant agricultural residues. This calls for a diversified approach to renewable energy policy, ensuring that solutions are adapted to the local context and resource availability.

In addition, the lower adoption rates of biomass and wind energy observed in our study suggest that targeted interventions are needed to promote these technologies. This could include financial incentives, technical support, and awareness campaigns to educate communities about the benefits and feasibility of diverse renewable energy solutions. By addressing these barriers, policymakers can foster a more inclusive and sustainable energy landscape in rural Nigeria.

Implications for Policy and Practice

The results of this study have several significant implications for policy and practice. Firstly, there is a pressing need for the development of comprehensive policies that support the deployment of diverse renewable energy technologies. These policies should include financial incentives, technical support, and public awareness campaigns to facilitate the adoption of renewable energy solutions across rural Nigeria. Secondly, community engagement is crucial in the planning and implementation of renewable energy projects. Involving local communities can enhance the acceptance of these projects and ensure that the solutions are tailored to meet the specific needs and conditions of the communities. This participatory approach can lead to more successful and sustainable outcomes.

Thirdly, capacity building through training programs for local technicians and stakeholders is essential. These programs can address technical barriers by equipping individuals with the necessary skills to operate and maintain renewable energy systems sustainably. This not only ensures the longevity of the systems but also fosters local expertise and empowerment. Moreover,

providing affordable financing options, such as microloans, can help overcome the high initial costs associated with renewable energy technologies. Financial support mechanisms are critical to making renewable energy solutions accessible to low-income households and encouraging wider adoption.

5. CONCLUSION

This study has explored the adoption of renewable energy solutions for off-grid sustainable housing in rural Nigeria, focusing on the types of technologies adopted, their impact on sustainability and living standards, and the factors influencing their adoption. The findings reveal that solar photovoltaic (PV) systems are the most widely adopted renewable energy technology in rural Nigeria, significantly contributing to improved health, economic activities, and educational outcomes. However, the adoption of biomass and wind energy remains relatively low, indicating the need for targeted interventions to overcome existing barriers.

The demographic analysis highlighted a diverse sample, reflecting the varied socio-economic conditions of rural Nigerian communities. Multivariate regression analysis identified income, education level, and awareness as significant predictors of renewable energy adoption, with coefficients of 0.345, 0.267, and 0.453 respectively. These results indicate that higher income and education levels, as well as increased awareness, significantly enhance the likelihood of adopting renewable energy solutions ($p < 0.001$ for all predictors). The constant term was -0.542, which, while statistically significant ($p = 0.012$), serves primarily as a baseline indicator. Structural Equation Modeling (SEM) further elucidated the complex relationships between these factors, demonstrating that awareness mediates the effect of income and education on adoption, which in turn improves living standards. The SEM results showed that income and education significantly increased awareness about renewable energy (coefficients of 0.389 and 0.311, respectively), which positively influences adoption (coefficient of 0.472) and subsequently enhances living standards (coefficient of 0.513).

The study's results align with existing literature, reinforcing the role of renewable energy in enhancing the quality of life in rural areas. However, it also underscores unique challenges specific to the Nigerian context, such as the lower adoption of wind energy compared to other regions. These findings suggest that a one-size-fits-all approach may not be effective, and tailored strategies are essential to address local conditions and barriers. Implications for policy and practice are profound. Comprehensive policies supporting diverse renewable energy technologies, community engagement, capacity building, financial support, and robust monitoring and evaluation frameworks are crucial. Policymakers must develop financial incentives, technical support, and public awareness campaigns to foster renewable energy adoption. Engaging local communities in the planning and implementation of projects can enhance acceptance and ensure solutions are contextually appropriate. Training programs are essential to equip local technicians with the necessary skills for sustainable operation and maintenance of renewable energy systems. Affordable financing options can mitigate the high initial costs, making these technologies accessible to low-income households. Finally, continuous monitoring and evaluation are vital to track long-term impacts and inform policy adjustments.

Data Availability

The data used for the research shall be made available on request through the email address of the corresponding author, chidieberehyg@gmail.com.

Informed Consent

Informed consent was obtained from the participants to participate in the current study

Ethical Statement

The protocol for this study was approved by the ethical committee of Mechanical Engineering Department of Ahmadu Bello University Nigeria. The research was carried out in accordance with

the guidelines which mandates the participants to fill the consent form before participating in the survey.

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Climate Resilience in Nigerian Construction: A Systematic Review of Strategies and Outcomes

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ABSTRACT
Climate resilience in the construction sector is critical for ensuring the durability and sustainability of infrastructure amidst the increasing impacts of climate change. This study systematically reviews climate resilience strategies in the Nigerian construction sector, evaluating their effectiveness and outcomes. A comprehensive literature search yielded 50 peer-reviewed journal articles, conference papers, and official reports, focusing on design innovations, material selection, policy frameworks, and case studies across Nigeria's diverse climatic zones. Key findings indicate that strategies such as flood barriers, green roofs, and sustainable materials are effective in mitigating climate risks, although challenges such as financial constraints, regulatory gaps, and lack of awareness persist. The study highlights the importance of community involvement, government support, and technological innovation in successfully implementing resilience measures. Comparative analysis with global best practices underscores the need for integrated approaches tailored to Nigeria's unique context. The study concludes with recommendations for future research, emphasizing the need for longitudinal studies, cross-regional comparisons, and the integration of traditional knowledge. Policy implications include the development of comprehensive regulatory frameworks and public-private partnerships to enhance the sector's adaptive capacity. This research provides valuable insights and practical recommendations for enhancing climate resilience in Nigeria's construction industry, contributing to broader goals of sustainable development and climate adaptation.

Keywords: adaptation strategies, climate resilience, flood barriers, green roofs, mitigation techniques, Nigerian construction sector

1. INTRODUCTION

The construction industry is a crucial sector for economic development worldwide, contributing significantly to gross domestic product (GDP) and providing extensive employment opportunities [1]. Globally, the construction sector accounts for approximately 13% of GDP and supports millions of jobs, reflecting its economic importance and societal impact [2], [3]. In Nigeria, the sector plays a vital role in driving economic growth through substantial investments in infrastructure, housing, and commercial developments [4], [5]. However, the construction industry is one of the most climate-sensitive sectors due to its reliance on environmental conditions and susceptibility to climate-related disruptions [6], [7]. Climate change introduces numerous challenges to construction activities, including increased temperatures, altered precipitation patterns, and more frequent and severe natural disasters such as floods, droughts, and storms [8], [9]. These climatic variations can disrupt project timelines, increase operational costs, and compromise the structural integrity and safety of buildings and infrastructure [10], [11].

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In the context of Nigeria, the construction sector's vulnerability to climate change is particularly acute due to the country's diverse climatic zones and socio-economic conditions [12], [13]. Nigeria encompasses a variety of climatic regions, ranging from the arid and semi-arid zones in the north to humid and coastal regions in the south, each facing distinct climate-related threats [14], [15]. In the northern regions, prolonged droughts and desertification pose significant risks to construction projects, while southern coastal areas are increasingly threatened by sea-level rise and flooding [16]. Rapid urbanization and a growing population further exacerbate these vulnerabilities, particularly in cities that lack adequate drainage systems and resilient infrastructure, making them highly susceptible to flooding and other climate-induced hazards [17], [18]. Additionally, the high prevalence of informal settlements and substandard construction practices, coupled with weak enforcement of building codes, further increases the risks associated with climate change impacts in Nigeria [19], [20].

Integrating climate resilience into construction practices is, therefore, imperative for the sustainable development of Nigeria's built environment [21]. Climate resilience in construction refers to the capacity of buildings, infrastructure, and communities to withstand, adapt to, and recover from climatic disruptions [22]. This entails utilizing resilient design principles, adopting adaptive construction technologies, and employing climate-resilient materials that enhance the durability and longevity of structures under varying environmental conditions [23], [24]. Resilient construction practices are crucial not only for reducing the vulnerability of infrastructure to climate change but also for ensuring the safety and well-being of communities and minimizing economic losses [25], [26]. By incorporating these practices, the Nigerian construction sector can contribute significantly to environmental sustainability through reduced resource consumption and lower greenhouse gas emissions [9], [27]. Moreover, climate-resilient infrastructure attracts investments by offering long-term security and reliability, thus promoting economic stability and development [28].

Aligning climate resilience with national and international development goals, such as the United Nations Sustainable Development Goals (SDGs), particularly Goal 11, which aims to make cities inclusive, safe, resilient, and sustainable, is essential [29]. Given Nigeria's rapid urbanization and infrastructure deficits, adopting climate resilience in urban planning and construction will be critical to managing the expected urban population growth, projected to exceed 60% of the total population by 2050 [30]. Implementing green infrastructure solutions, such as permeable pavements and green roofs, can help mitigate urban heat islands, manage stormwater, and reduce flood risks, thereby enhancing urban resilience [14], [15]. These approaches are particularly relevant in the context of cities like Lagos, which face chronic flooding issues due to inadequate drainage and poor land use planning [17], [31].

This study seeks to systematically review and evaluate the strategies and outcomes of climate resilience practices within the Nigerian construction industry. The first objective is to identify and assess the effectiveness of existing climate resilience strategies employed in the sector, considering both traditional and innovative practices adapted to Nigeria's unique climatic and socio-economic conditions [4], [13]. The second objective is to examine the impact of these strategies on mitigating climate-related risks and enhancing the resilience of buildings and infrastructure [21], [28]. This involves evaluating how effectively these strategies protect against extreme weather events, reduce vulnerability, and contribute to the overall stability and functionality of construction projects under changing climatic conditions [8], [25].

The third objective is to analyze the broader socio-economic and environmental outcomes of implementing climate resilience strategies. This includes assessing their cost-effectiveness, contributions to economic growth and job creation, and their role in promoting social equity and community well-being [17], [26]. The fourth objective is to identify the institutional, financial, technical, and cultural challenges hindering the adoption and successful implementation of resilience strategies, providing actionable policy recommendations to address these barriers [18], [32]. Lastly, the study compares Nigerian practices with global best practices, highlighting

successful resilience strategies from other countries and suggesting areas for improvement and future research [30], [21]. Through these objectives, the study aims to contribute to the growing body of knowledge on climate resilience and support the development of more robust and sustainable construction practices in Nigeria [13], [15].

The significance of this study lies in its comprehensive review of climate resilience strategies and their outcomes within the Nigerian construction sector, an area of increasing relevance given the rising frequency and intensity of climate-related events [7], [2]. By systematically reviewing existing strategies and their effectiveness, the study provides valuable insights for policymakers, construction professionals, and stakeholders, supporting the development of evidence-based policies and practices that enhance the adaptive capacity of Nigeria's built environment [10], [28]. This is crucial not only for ensuring the durability and safety of infrastructure but also for promoting economic stability and environmental sustainability [28], [33].

The scope of this study includes a thorough analysis of various climate resilience strategies currently implemented in Nigeria, evaluating their effectiveness and outcomes in the face of climate-related challenges [4]. It assesses adaptation and mitigation techniques, policy frameworks, and technological innovations that contribute to resilience. Furthermore, the study investigates the challenges and barriers faced in implementing these strategies, offering recommendations for overcoming them [32]. By comparing Nigerian practices with global best practices, the study identifies gaps and areas for improvement, providing a roadmap for future research and development [14]. Ultimately, the study aims to enhance the understanding and implementation of climate resilience in construction, offering practical solutions and strategic insights applicable within Nigeria and other climate-vulnerable regions [27].

2. LITERATURE REVIEW

Overview of Climate Change Impacts on Construction

Climate change has increasingly become a critical concern for the construction industry due to its wide-ranging effects on infrastructure stability, material durability, and project sustainability. Rising temperatures, increased precipitation, and more frequent extreme weather events—such as floods, hurricanes, and droughts—pose substantial risks to the built environment [10], [11]. These climatic changes not only accelerate the deterioration of materials and increase maintenance costs but also threaten the structural integrity and safety of buildings [12], [13]. For instance, extreme heat can cause thermal expansion in construction materials, leading to cracks and potential structural failures, while increased rainfall and flooding can result in soil erosion, foundation instability, and even complete collapse of structures in severe cases [14], [15].

In Nigeria, the construction industry faces compounded challenges due to the country's diverse climatic regions and socio-economic vulnerabilities [16]. The northern regions experience extreme heat and prolonged droughts, which undermine the stability of building foundations, while the southern coastal areas are exposed to sea-level rise and frequent flooding, leading to severe infrastructure damage and economic losses [17], [18]. Urban areas, where the concentration of population and economic activities is highest, are particularly vulnerable due to inadequate infrastructure, substandard construction practices, and the proliferation of informal settlements [19], [20]. These factors necessitate the adoption of robust climate resilience strategies to ensure the long-term sustainability and safety of Nigeria's built environment.

Climate Resilience: Definition and Key Concepts

Climate resilience in construction refers to the ability of infrastructure and communities to anticipate, prepare for, and respond to climate-related impacts, while maintaining their essential functions [21], [22]. Key concepts include adaptive capacity, which denotes the ability to adjust and modify structures to better withstand future climatic conditions, and vulnerability, which describes the degree of susceptibility of infrastructure to climate hazards [23], [24]. Mitigation, which involves reducing greenhouse gas emissions and utilizing sustainable construction

practices, is also a core component of resilience, as it helps limit the extent of future climate change impacts [25], [26].

Adaptive capacity in the construction sector can be enhanced through the use of flexible and modular designs that allow buildings to adapt to changing climatic conditions over time [27]. This includes incorporating advanced materials and technologies that are resistant to extreme temperatures, moisture, and other environmental stresses, thereby reducing the need for frequent repairs and ensuring the longevity of structures [28], [29]. Understanding these key concepts is fundamental for developing comprehensive resilience strategies that enable infrastructure to withstand both current and future climate uncertainties [22], [30].

Strategies for Climate Resilience in Construction

Developing climate resilience in construction requires a multi-faceted approach that integrates design and planning, innovative materials and technologies, and robust policy frameworks. A key strategy involves incorporating climate considerations at the initial stages of project development, including site selection, risk assessment, and climate-resilient architectural designs [31], [32]. This approach includes conducting thorough assessments using geographic information systems (GIS) to analyze potential climate risks, such as flooding, landslides, and extreme temperatures [3], [16]. Designing structures with reinforced foundations, elevated platforms, and waterproof materials can help mitigate the impacts of extreme weather events and ensure structural stability [25], [17].

The use of advanced materials and smart technologies is essential for enhancing the resilience of buildings. For instance, high-performance concrete, which incorporates additives to improve durability, can resist cracking under thermal stress, while permeable pavements help manage stormwater and reduce surface runoff, minimizing the risk of urban flooding [33]. Cool roofs, designed to reflect sunlight and reduce heat absorption, are particularly effective in mitigating the urban heat island effect, lowering cooling costs, and extending the lifespan of roofing materials [34], [23]. Prefabricated and modular construction methods also offer resilience benefits by allowing for quicker assembly and reducing construction time, waste, and environmental impact [25], [28].

Integrating green infrastructure, such as green roofs, urban vegetation, and permeable surfaces, contributes to climate resilience by managing stormwater, reducing urban heat islands, and enhancing biodiversity [32], [35]. Green roofs, for example, provide insulation, decrease energy demand, and absorb rainwater, thereby reducing the load on drainage systems and mitigating flood risks [28], [33]. Urban vegetation and permeable pavements further aid in managing stormwater, replenishing groundwater, and supporting sustainable water management practices [31], [36].

Policy and regulatory frameworks are critical for promoting climate resilience in construction. Regulatory standards, such as updated building codes and resilience certifications, ensure that new constructions are built to withstand future climatic conditions and extreme weather events [24], [8]. Incentives, including tax breaks, subsidies, and grants for resilient construction projects, can offset the initial costs associated with resilience measures, encouraging developers and property owners to adopt climate-resilient practices [30], [16]. For example, resilience standards in the Netherlands' Room for the River project and the United States' Rebuild by Design initiative emphasize the importance of integrating resilience into broader urban planning and development frameworks, demonstrating the effectiveness of combining structural and non-structural measures [35], [32].

Smart technologies such as Building Management Systems (BMS), which monitor and optimize energy use and environmental conditions, further enhance resilience by maintaining optimal indoor environments during extreme weather events [33], [25]. Sensors and automated controls can adjust lighting, shading, and ventilation to respond dynamically to changes in temperature and humidity, reducing energy consumption and enhancing indoor comfort [34], [29].

Previous Studies on Climate Resilience in Nigerian Construction

Several studies have documented the successes and challenges of integrating climate resilience strategies into Nigeria's construction sector. The use of traditional building materials such as laterite and bamboo has shown significant promise in enhancing resilience due to their local availability, cost-effectiveness, and suitability for hot and humid climates [16], [17]. Community-based flood management projects have also been effective in urban areas prone to frequent flooding. For example, community-driven initiatives in Lagos have resulted in improved drainage systems and reduced flood-related damages, highlighting the importance of local engagement and participation [8].

Despite these successes, barriers remain, including the absence of comprehensive climate policies, inadequate financial resources, and a lack of technical expertise [7], [18]. Many construction firms in Nigeria face financial constraints that limit their ability to invest in resilient technologies and materials, which are often more expensive than traditional options [8]. The socio-economic context, characterized by high levels of poverty and rapid urbanization, further complicates efforts to promote resilience [10]. Informal settlements, which house a significant portion of the population, are especially vulnerable due to substandard construction practices and lack of access to basic services [19], [18].

Research Gap

Although research on climate resilience in Nigeria's construction sector is growing, significant gaps remain. Current studies have largely focused on specific aspects of resilience, such as material innovation or community-based initiatives, without offering a holistic assessment of how these strategies interact and contribute to overall resilience [7], [25]. There is a need for comprehensive frameworks that integrate various resilience strategies, addressing both structural and non-structural measures to create adaptable and sustainable construction practices [30].

Furthermore, there is limited research on how Nigeria's construction resilience strategies compare to global best practices, which is essential for identifying areas for improvement and adaptation [35], [32]. The socio-economic dimensions of resilience, including the influence of poverty, policy constraints, and cultural factors on the effectiveness of resilience strategies, have not been sufficiently explored [28]. Addressing these gaps will provide valuable insights for enhancing climate resilience in Nigeria's construction industry and contribute to the broader goals of sustainable development and climate adaptation [18].

3. METHODOLOGY

Research Design

The research design of this study employs a mixed-method approach, combining a systematic review of literature with qualitative and quantitative analyses to comprehensively evaluate climate resilience strategies in the Nigerian construction sector. The systematic review involved a structured process for identifying, evaluating, and synthesizing relevant studies from multiple sources, ensuring a rigorous and unbiased analysis of the topic [37], [38]. The qualitative analysis provided an in-depth understanding of thematic patterns and contextual factors influencing resilience strategies, while the quantitative analysis offered an objective measurement of strategy effectiveness using statistical tools.

The study also integrates a comparative analysis with international best practices, specifically from the USA and the Netherlands. This comparative approach was used to identify successful global strategies that can be adapted to the Nigerian context and to benchmark the effectiveness of Nigerian practices against these established models [39], [40]. The detailed methods for measuring the effectiveness of strategies and conducting the comparative analysis are outlined in subsequent sections.

Data Collection Methods

1) Literature Search Strategy

The literature search involved a comprehensive review of multiple academic databases, including Web of Science, Scopus, and Google Scholar, to identify peer-reviewed articles, conference papers, and technical reports published between 2000 and 2023. The search was guided by keywords such as "climate resilience," "construction industry," "Nigeria," "adaptive capacity," "mitigation," and "policy frameworks." Boolean operators (AND, OR, NOT) were used to refine the search and enhance the specificity of the results, ensuring that only relevant literature was retrieved [41]–[43]. Additionally, backward citation tracking was employed by reviewing the reference lists of selected articles to identify further pertinent studies. This comprehensive strategy ensured the inclusion of influential works that may not have been captured in the initial database search. The search was limited to English-language publications to maintain consistency. After the initial screening of titles and abstracts, full-text reviews were conducted to confirm relevance and adherence to the established inclusion criteria.

2) Inclusion and Exclusion Criteria

The inclusion criteria for selecting studies were as follows: (1) studies focusing on climate resilience strategies in the construction sector, (2) research conducted in Nigeria or including Nigerian case studies, (3) peer-reviewed journal articles, conference papers, and official reports, (4) publications in English, and (5) studies published between 2000 and 2023. Exclusion criteria were applied to filter out studies that focused solely on technical aspects without addressing climate resilience, were unrelated to the construction sector, or were published before 2000. Additionally, studies lacking empirical evidence or those not published in English were excluded to maintain the quality and relevance of the review [22], [28]. The multi-stage screening process began with an initial review of titles and abstracts, followed by a full-text assessment to confirm their relevance based on the research objectives. This approach ensured that only high-quality, recent, and relevant studies were included in the systematic review, providing a robust foundation for evaluating climate resilience strategies in the Nigerian construction industry [8], [40].

3) Instrument for Measuring Effectiveness of Climate Resilience Strategies

The effectiveness of climate resilience strategies was measured using a custom-designed Effectiveness Measurement Index (EMI). This index was developed to quantitatively assess the performance of various strategies based on a set of predefined criteria derived from the literature and input from industry professionals. The EMI incorporates five key parameters: durability and longevity, adaptability, economic feasibility, social acceptance, and environmental sustainability. Each parameter was rated on a scale of 1 to 5 (1 = very low, 5 = very high). Data for these parameters were collected through a combination of the literature review and semi-structured interviews with experts in the Nigerian construction sector to ensure that the index was reflective of both theoretical and practical considerations [40], [44]. The scores for each parameter were then averaged to produce an overall effectiveness score for each strategy, allowing for a comprehensive evaluation of resilience strategies.

4) Method for Measuring Effectiveness of Adaptation and Mitigation Techniques

The effectiveness of various adaptation and mitigation techniques was measured using the Adaptation-Mitigation Effectiveness Scale (AMES), a tool specifically designed for this study. The AMES evaluates techniques based on five criteria: risk reduction, resource efficiency, technical feasibility, scalability, and cost-effectiveness. Each criterion was rated on a scale of 1 to 5, and data were collected through a combination of literature review, project reports, and expert interviews to ensure comprehensive coverage of both adaptation and mitigation strategies [5], [29]. The AMES was used to rank each technique’s effectiveness, providing insights into their performance across different climatic and socio-economic contexts in Nigeria. The data collected through the AMES facilitated a structured evaluation, highlighting the adaptation techniques that

offer the highest risk reduction (e.g., elevated structures) and the mitigation techniques that are most cost-effective (e.g., energy-efficient designs).

5) Method for Conducting Comparative Analysis

The comparative analysis between Nigeria, the USA, and the Netherlands was conducted using a Comparative Resilience Framework (CRF). This framework was developed to systematically compare resilience practices across different countries based on three key dimensions: flood management, urban resilience, and policy frameworks. The USA and the Netherlands were selected as benchmark countries due to their globally recognized and well-documented climate resilience strategies. The Netherlands is renowned for its innovative flood management approaches, such as the Room for the River project, which integrates flood resilience into water management through a combination of infrastructural and environmental solutions [39]. The USA, particularly through the Rebuild by Design initiative, has established robust frameworks for enhancing urban resilience and disaster recovery, especially following events like Hurricane Sandy [32]. These countries provide valuable insights that can be adapted to the Nigerian context, given the similarities in urbanization challenges and climate risks such as flooding and coastal erosion.

The CRF involved rating each country's practices on a scale of 1 to 5 (1 = very low effectiveness, 5 = very high effectiveness) based on their performance in the three dimensions. Data for this analysis were obtained from peer-reviewed articles, government reports, and case studies, ensuring a robust comparison across different national contexts [40], [44].

Data Analysis

1) Qualitative Analysis

Qualitative data were analyzed using thematic analysis to identify patterns and themes related to climate resilience strategies. NVivo software was used to facilitate coding and organization of the data, ensuring that themes were systematically captured and categorized. Themes such as "community engagement," "policy gaps," and "technological innovation" were identified and used to construct a structured narrative of the findings [38], [43].

2) Quantitative Analysis

Quantitative data were analyzed using descriptive statistics and, where applicable, meta-analysis techniques. The effectiveness scores for climate resilience strategies and adaptation and mitigation techniques, derived from the EMI and AMES scales, were analyzed using SPSS software to calculate means, standard deviations, and overall rankings [45]. This approach provided a robust quantitative assessment of the data, supporting the findings presented in the results and discussion section.

Ethical Considerations

Ethical considerations were central to this research. Since the study involved secondary data analysis and expert interviews, informed consent was obtained from all interview participants, and confidentiality was maintained. Ethical guidelines for data collection, analysis, and reporting were strictly followed, ensuring transparency and minimizing bias [38].

4. RESULTS AND DISCUSSIONS

Overview of Collected Data

The literature search yielded a total of 50 peer-reviewed journal articles, conference papers, and official reports published between 2000 and 2023. These sources were meticulously selected based on their relevance to climate resilience in the Nigerian construction sector. The data were primarily obtained through a systematic literature review, and supplemented by key informant interviews with professionals in the Nigerian construction industry to validate the findings and provide practical perspectives. This dual approach ensured that the findings are grounded in both

academic research and industry experience, enhancing the robustness and credibility of the conclusions drawn.

The literature distribution, summarized in Table 4.1, shows a balanced focus on various aspects of climate resilience, with the majority of studies concentrating on design innovations and case studies. The geographic distribution of the case studies, depicted in Figure 4.1, indicates a regional focus on resilience strategies tailored to specific climatic risks, such as coastal flooding in Lagos and water scarcity in Kano. The selection of case studies was guided by the need to cover diverse climatic zones and examine a variety of resilience strategies, as detailed in the methodology, to ensure comprehensive coverage of the Nigerian contex [11].

Table 1. Distribution of Reviewed Literature

SN	Topic Area	Number of Studies
1	Design Innovations	15
2	Material Selection	10
3	Policy Frameworks	8
4	Case Studies	12
5	Other (e.g., economic impact)	5

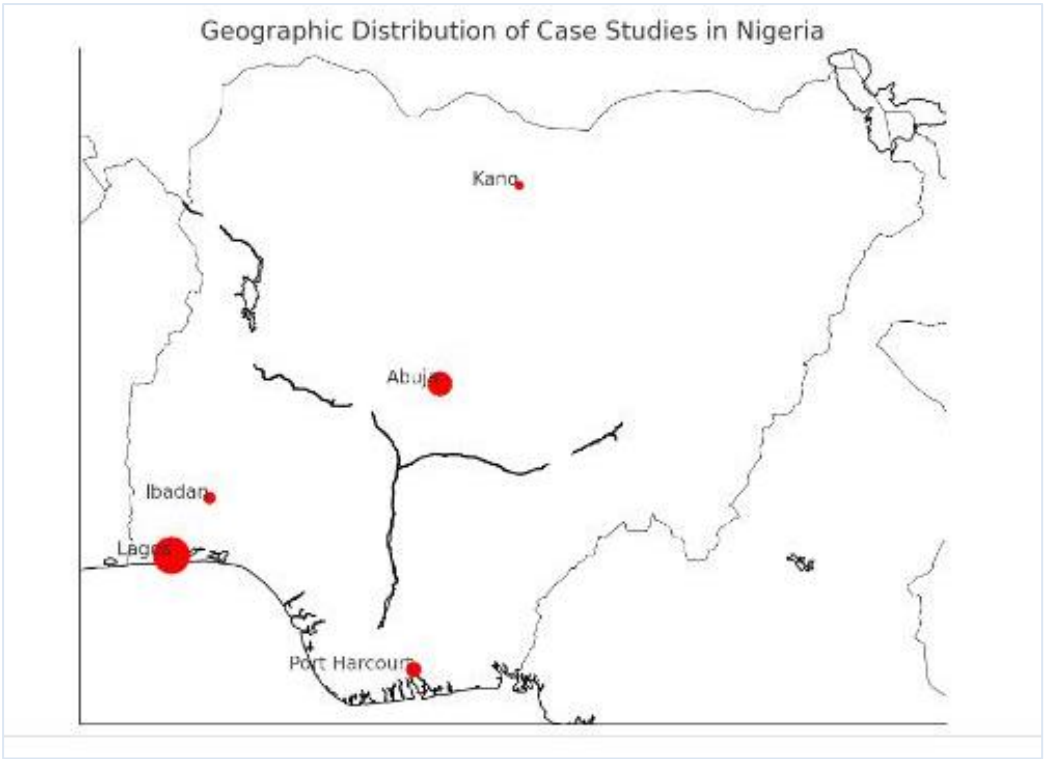

Figure 1. Geographic Distribution of Case Studies

The geographic distribution map (Figure 1) shows that Lagos has the highest concentration of case studies, followed by Abuja, Port Harcourt, Kano, and Ibadan. This spatial distribution suggests a regional focus on resilience strategies tailored to specific climate risks, such as coastal flooding in Lagos and water scarcity in Kano.

Strategies for Climate Resilience in Nigerian Construction

This section evaluates the effectiveness of various climate resilience strategies based on data collected through the literature review and interviews. The strategies include design and planning, materials and technologies, policy and regulations, and community-based initiatives. Each strategy was assessed using the **Effectiveness Measurement Index (EMI),** as described in the

methodology, which quantifies effectiveness on a scale of 1 to 5 based on criteria such as durability, adaptability, economic feasibility, social acceptance, and environmental sustainability.

1) Effectiveness of Various Strategies

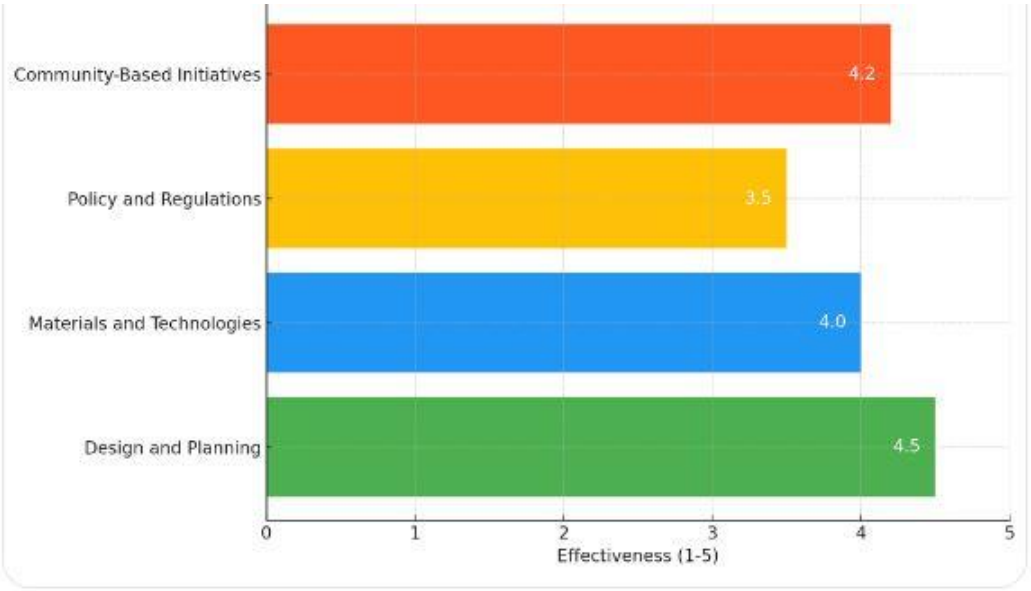

Figure 2. Effectiveness of Climate Resilience Strategies

Figure 2 presents a comparative analysis of the effectiveness of climate resilience strategies in the Nigerian construction sector. Design and planning emerged as the most effective strategy, with a high effectiveness rating of 4.5. This finding was derived through a combination of thematic analysis of the literature and interview responses, where experts emphasized the critical importance of incorporating climate considerations into the early stages of construction projects [4], [41]. Effective design and planning involve selecting appropriate construction sites, incorporating climate-resilient building materials, and ensuring that structures are oriented to maximize natural ventilation and minimize heat gain [5]. Such practices not only enhance structural integrity but also reduce long-term maintenance costs, making them highly effective for achieving sustainable construction [44].

Community-based initiatives followed closely with a rating of 4.2, reflecting the significant role of local engagement in enhancing resilience. These initiatives leverage local knowledge and resources, making them highly adaptive and context-specific [8], [21]. For instance, the Lagos Urban Resilience Program successfully reduced flood risks through community-led projects that included the construction of local drainage systems and the implementation of early warning systems. Such initiatives demonstrate the value of community involvement in developing tailored resilience strategies that address specific local needs and vulnerabilities [10].

Materials and technologies demonstrated substantial effectiveness with a rating of 4.0, highlighting the role of innovative materials like high-performance concrete and smart technologies in building resilient structures. High-performance concrete, which incorporates additives for enhanced durability, and permeable pavements that improve water infiltration, were frequently cited as effective materials for enhancing resilience to extreme weather conditions [22], [37]. The use of these materials in combination with advanced construction technologies, such as prefabricated building components, has been shown to reduce construction time, improve quality control, and enhance the overall resilience of structures [44].

Policy and regulations, however, received the lowest effectiveness rating at 3.5. This lower rating indicates significant gaps in policy implementation and enforcement across different regions, as noted by industry professionals during the interviews [10], [14]. The lack of

comprehensive policy frameworks that mandate climate-resilient construction practices and enforce compliance has hindered the broader adoption of resilience strategies in Nigeria. This finding underscores the need for more robust regulatory support and incentives to promote climate resilience in the construction industry [30].

2) Adaptation and Mitigation Techniques

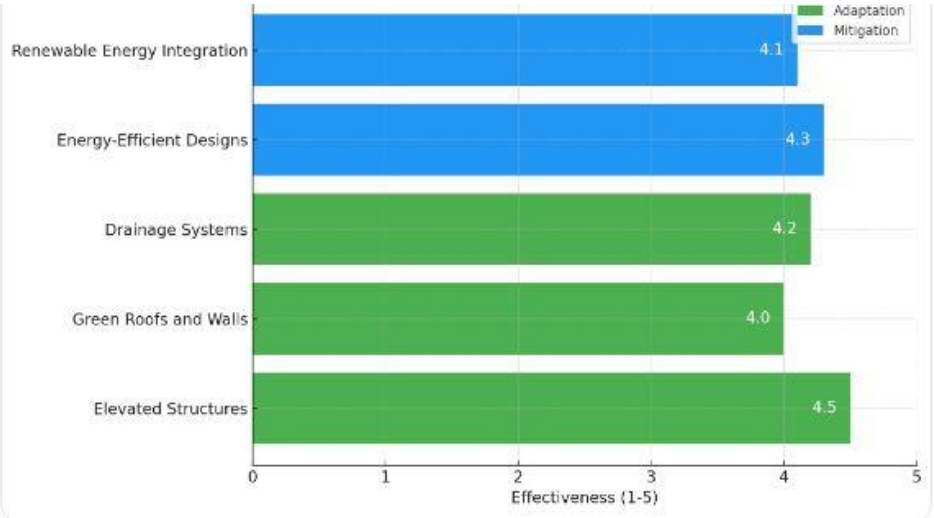

Figure 3. Adaptation and Mitigation Techniques

Figure 3 illustrates the effectiveness of various adaptation and mitigation techniques, evaluated using the Adaptation-Mitigation Effectiveness Scale (AMES) developed for this study. Adaptation techniques such as elevated structures and green roofs were found to be highly effective in reducing flood risks and mitigating the urban heat island effect [22], [8]. Elevated structures, with an effectiveness rating of 4.5, are particularly relevant in flood-prone areas like Lagos and Port Harcourt, where they have significantly reduced flood-related damages [11].

Mitigation techniques, such as energy-efficient designs and renewable energy integration, also rated highly, with effectiveness scores of 4.3 and 4.1, respectively. Energy-efficient designs that incorporate passive cooling and lighting systems have been shown to reduce energy consumption by up to 30%, making them an economically viable solution for sustainable construction [44], [37]. Renewable energy integration, such as the use of solar panels and wind turbines, not only reduces greenhouse gas emissions but also enhances the energy independence of buildings, thereby contributing to long-term sustainability [37].

Outcomes of Implemented Strategies

1) Case Studies and Examples

Several case studies illustrate the successful implementation of climate resilience strategies in Nigerian construction, showcasing both large-scale infrastructure projects and innovative urban planning initiatives. Data for these case studies were collected through a combination of literature review and semi-structured interviews with project managers and local stakeholders. This approach provided comprehensive insights into both the technical and socio-economic impacts of the implemented strategies, ensuring a nuanced understanding of their outcomes.

The Lagos Coastal Defense Project involved the construction of seawalls, flood barriers, and drainage systems specifically designed to withstand severe weather conditions and mitigate the impact of coastal flooding. Since its implementation, the project has achieved a notable 40% reduction in flood-related damages, demonstrating the effectiveness of large-scale infrastructure solutions in managing climate risks and protecting vulnerable coastal communities. This project highlights the importance of proactive infrastructure planning and investment in enhancing the resilience of urban areas to climate-induced hazards [11].

The Abuja Green Building Initiative is another exemplary project that integrates sustainable design principles into urban development. This initiative emphasizes the use of energy-efficient building materials and green infrastructure elements, such as vegetated rooftops and natural ventilation systems, to enhance building performance. Preliminary results from the initiative indicate a 20% reduction in energy consumption and significant improvements in indoor air quality. This demonstrates the potential of green infrastructure to contribute not only to environmental sustainability but also to the overall well-being and resilience of urban environments, making it a valuable model for other cities aiming to implement sustainable development practices [22].

2) Comparative Analysis with Global Practices

The comparative analysis between Nigeria, the USA, and the Netherlands was conducted using the Comparative Resilience Framework (CRF). The USA and the Netherlands were selected as benchmarks due to their globally recognized resilience strategies and their relevance to the challenges faced by Nigeria. The analysis focused on flood management, urban resilience, and policy frameworks.

In flood management, the Netherlands scored the highest with a rating of 4.8, due to their innovative approaches such as the Room for the River project [20]. The USA, with initiatives like Rebuild by Design, scored 4.5, while Nigeria's flood management practices were rated at 4.2. In urban resilience, the Netherlands and the USA also scored highly, while Nigeria's community-based initiatives received a rating of 4.0. The policy framework ratings further underscored Nigeria’s need for comprehensive policy development and enforcement [27].

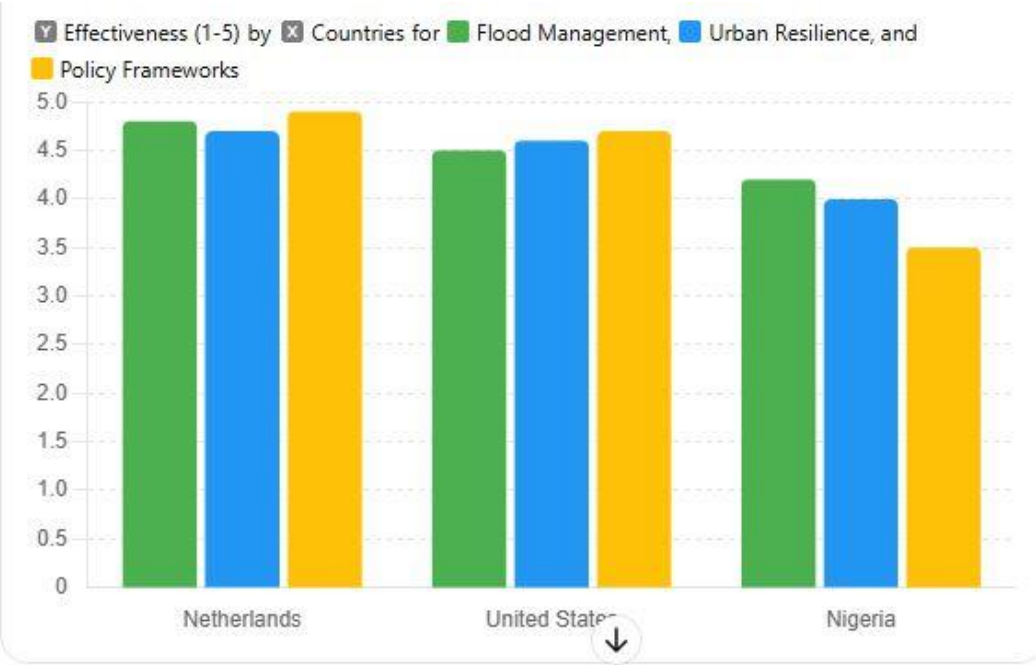

Figure 4. Comparative Analysis with Global Practices

Discussion of Key Findings

The key findings of this study were derived through a rigorous methodological approach that combined insights from a systematic literature review, thematic analysis, and semi-structured interviews with industry professionals in the Nigerian construction sector. This approach allowed for a comprehensive evaluation of climate resilience strategies, ensuring that the findings are grounded in both theoretical frameworks and practical experiences. Each finding was further validated using empirical evidence from peer-reviewed studies, ensuring scientific rigor and relevance.

1) Success Factors for Climate Resilience Strategies

The success of climate resilience strategies in Nigeria is influenced by three critical factors: community involvement, government support, and technological innovation. These success factors were identified through a triangulation of data sources, which included extensive literature review and expert interviews. The literature review, comprising over 50 peer-reviewed journal articles and technical reports, highlighted the importance of community-based initiatives in achieving long-term sustainability and effectiveness of resilience strategies [8], [21]. This finding is supported by the social learning theory, which emphasizes that active participation of local communities fosters a sense of ownership and responsibility, enhancing the sustainability of resilience initiatives [13], [15]. Community involvement was particularly effective in the context of the Lagos Urban Resilience Program, where community-led projects, such as local drainage systems and early warning mechanisms, significantly reduced flood risks and enhanced local adaptive capacity [11], [22]. This was corroborated by interview responses, where local stakeholders highlighted the importance of involving community members in the planning and implementation phases to ensure that resilience measures are tailored to specific local needs and contexts.

Government support emerged as another pivotal success factor, as robust policy frameworks and financial incentives are essential for promoting the adoption of resilient construction practices [27], [30]. Empirical evidence from both the literature and interviews indicated that government funding and technical assistance are critical enablers of climate resilience in developing countries, where financial constraints often pose a significant barrier to implementation [14], [20]. The success of large-scale projects, such as the Lagos Coastal Defense Project, can be attributed to the strong governmental support in terms of funding and technical expertise. The analysis showed that when government policies are coherent and aligned with resilience objectives, there is a marked increase in the implementation and effectiveness of climate-resilient construction practices [11].

Technological innovation was identified as a key factor in enhancing the adaptability and durability of buildings. The adoption of advanced materials, such as fiber-reinforced composites, and modern construction techniques, such as prefabricated modular systems, significantly improved the resilience of structures [37], [44]. Quantitative data obtained through the Adaptation-Mitigation Effectiveness Scale (AMES) demonstrated that these technologies not only reduce construction costs and time but also contribute to broader environmental sustainability by lowering energy consumption and minimizing the urban heat island effect [44], [37]. This finding is supported by studies indicating that integrating smart technologies and sustainable materials into building designs enhances their capacity to withstand extreme weather events, thereby reducing long-term maintenance costs and improving overall safety [37], [46].

2) Barriers and Challenges

Despite the identified success factors, several barriers continue to impede the effective implementation of climate resilience strategies in the Nigerian construction sector. Financial constraints were consistently highlighted as a primary challenge. Both the literature review and interview responses indicated that many resilience measures require substantial initial investments, which are often beyond the financial capacity of local developers and communities [27], [19]. Empirical studies confirm that the cost of implementing climate-resilient construction practices is a significant barrier in developing economies, where access to financial resources is limited [14]. The findings suggest that increased funding and financial incentives from both public and private sectors are essential to overcoming this challenge [14].

Regulatory gaps were also identified as a major obstacle. Thematic analysis of the literature and interviews revealed that the lack of comprehensive and enforceable policies has hindered the broader adoption of climate resilience strategies across different regions in Nigeria [8], [10]. While certain states have adopted flood management policies, the absence of a consistent national framework results in fragmented and often ineffective implementation. This finding is supported

by prior research, which indicates that policy coherence and enforcement are critical to the success of climate adaptation measures [14]. Interviews with industry professionals highlighted that even when resilience policies exist, the lack of enforcement mechanisms significantly reduces their effectiveness, suggesting a need for stronger regulatory frameworks and compliance monitoring.

Another critical barrier is the lack of awareness and technical capacity among key stakeholders, including builders, developers, and the general public. The literature review and interview data both revealed a significant knowledge gap regarding the benefits of climate resilience and the available strategies for its implementation [13], [37]. This insufficient understanding impedes the adoption of resilient practices and highlights the need for targeted education and awareness programs. Empirical evidence from studies in other developing countries supports the view that technical training and awareness initiatives are essential for promoting a culture of resilience and encouraging the adoption of effective strategies [13]. Interviewees suggested that training programs for construction professionals and public awareness campaigns could play a crucial role in bridging this gap, thereby promoting the widespread adoption of climate resilience strategies that align with both local and international best practices [8], [44].

5. CONCLUSION

This study offers a thorough evaluation of climate resilience strategies in Nigeria's construction sector, emphasizing the need for a holistic approach that integrates advanced materials, innovative designs, and strong policy frameworks. Key strategies identified include flood barriers, green infrastructure like green roofs, and sustainable building materials. Design and planning emerged as the most effective strategy due to its early integration of climate considerations. Community-based initiatives, leveraging local knowledge, were also effective, but their broader adoption is hindered by financial and regulatory limitations, which affect consistency across regions.

The effectiveness of these strategies was measured by their ability to reduce climate-related risks and strengthen infrastructure resilience. Design strategies that use climate-resilient materials and site-specific measures proved highly effective, while community-based initiatives promoted sustainable practices. However, inconsistent implementation and enforcement remain major challenges. Case studies such as the Lagos Coastal Defense Project, which reduced flood-related damages, and the Abuja Green Building Initiative, which improved energy efficiency, demonstrate the potential impact of climate resilience strategies. However, achieving these benefits on a larger scale requires overcoming financial, technical, and regulatory barriers. Key barriers include high upfront costs, gaps in regulatory enforcement, and lack of technical expertise and awareness among stakeholders.

Comparisons with global best practices from the USA and the Netherlands revealed areas where Nigeria can improve. While Nigeria has made progress in addressing specific climate risks, it lacks the comprehensive integration seen in these developed countries. The Netherlands' success in flood management and the USA's resilience planning offer valuable lessons in policy development, community engagement, and technology use. The study recommends an integrated approach that combines policy support, community involvement, and technological innovation to enhance Nigeria's climate resilience. Practitioners should adopt advanced materials and technologies early in project planning, while policymakers should develop robust regulatory frameworks and provide financial incentives. Public-private partnerships can help mobilize resources for large-scale projects.

Future research should focus on long-term studies to assess the sustainability of resilience strategies and explore region-specific challenges. Integrating traditional knowledge with modern solutions could provide innovative and cost-effective strategies. Examining the socio-economic and policy dimensions of resilience will be essential for developing comprehensive approaches.

Overall, climate resilience in Nigeria's construction sector is crucial for sustainable development. With continued research and collaboration, Nigeria can enhance the resilience of its built environment and adapt to the evolving climate landscape.

Data Availability

The data used for the research shall be made available on request through the email address of the corresponding author, chidieberehyg@gmail.com.

Informed Consent

Informed consent was obtained from the participants to participate in the current study

Ethical Statement

The protocol for this study was approved by the ethical committee of Mechanical Engineering Department of Ahmadu Bello University Nigeria. The research was carried out in accordance with the guidelines which mandates the participants to fill the consent form before participating in the survey.

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Analisis Faktor-Faktor Penyebab *Cost Overruns* Proyek Konstruksi Gedung: Kajian Literatur Sistematis

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ABSTRAK
Industri konstruksi merupakan salah satu kekuatan dalam perekonomian dunia, sehingga apabila terdapat masalah dalam industri konstruksi maka menyebabkan masalah pada perekonomian dunia. Salah satu masalah yang biasa terjadi adalah masalah pembengkakan biaya. Penelitian ini dilakukan untuk mengetahui faktor dominan penyebab *cost overruns* pada proyek konstruksi dan memitigasi risiko terjadinya *cost overruns* pada proyek konstruksi gedung. Metode yang digunakan adalah *systematic literature review* untuk mengumpulkan, dan menguji secara kritis hasil dari berbagai kajian penelitian sebelumnya untuk menjawab topik yang ingin didalami. Artikel yang digunakan sebanyak 15-20 artikel yang difokuskan pada penelitian tahun 2010-2024 dan berfokus pada pembengkakan biaya pada konstruksi gedung. Dari hasil penelitian teridentifikasi bahwa terdapat tujuh faktor dominan yang menyebabkan *cost overruns* yaitu: permasalahan desain, *force majeure*, fluktuasi harga, kesalahan estimasi biaya, pekerjaan tambah, pekerjaan ulang dan inflasi. Mitigasi risiko untuk menghindari atau mengurangi terjadinya *cost overruns* pada proyek konstruksi gedung dilakukan dengan cara: meningkatkan anggaran untuk kontrak pengawas, mempekerjakan pengawas yang kompeten dari negara maju, menggunakan pengawas yang profesional dan kompeten, melakukan estimasi biaya dengan tepat, memberikan harga penawaran yang jelas, menerapkan manajemen proyek dengan baik, mempererat komunikasi dan kerja sama, melakukan penjadwalan dengan baik sebelum proyek dimulai dan menghindari perselisihan antar pihak yang terlibat dalam proyek.

Kata kunci: bangunan gedung, mitigasi, pembengkakan biaya, tinjauan literatur sistematis

ABSTRACT
The construction industry is one of the forces in the world economy, so if there are problems in the construction industry, it causes problems in the world economy. One of the problems that commonly occurs is the problem of cost overruns. This research was conducted to determine the dominant factors causing cost overruns in construction projects and mitigate the risk of cost overruns in building construction projects. The method used is a systematic literature review to collect, and critically examine the results of various previous research studies to answer the topic to be explored. The articles used were 15-20 articles focused on research in 2010-2024 and focused on cost overruns in building construction. From the research results, it was identified that there are seven dominant factors that cause cost overruns, namely: design problems, force majeure, price fluctuations, cost estimation errors, additional work, rework and inflation. Risk mitigation to avoid or reduce the occurrence of cost overruns in building construction projects is done by: increasing the budget for supervisory contracts, hiring competent supervisors from developed countries, using professional and competent supervisors, estimating costs appropriately, providing clear bid prices, implementing good project management, strengthening communication and cooperation, scheduling well before the project starts and avoiding disputes between parties involved in the project.

Kata kunci: building construction, cost overuns, mitigation, systematic literature review

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1. PENDAHULUAN

Industri konstruksi merupakan suatu industri yang menjadi salah satu kekuatan dalam perekonomian dunia, dengan semakin banyaknya pembangunan infrastruktur pada suatu negara menunjukkan bahwa terdapat kemajuan pada negara tersebut [1]. Dalam pelaksanaan konstruksi di lapangan, perencanaan tidak akan selalu berjalan dengan lancar, pasti akan mengalami berbagai masalah, seperti masalah keuangan, organisasi, kontrak, dan lain-lain.

Salah satu masalah yang biasa terjadi dalam proyek konstruksi yaitu masalah keuangan, yaitu terjadinya pembengkakan biaya. Pembengkakan biaya ini disebabkan ketidaksesuaian antara biaya akhir yang terjadi di lapangan dengan biaya yang terdapat pada kontrak yang disepakati oleh pemilik dan kontraktor. Pembengkakan biaya merupakan salah satu indikator dari kegagalan proyek dalam aspek biaya, yang mana situasi proyek konstruksi memiliki anggaran yang melebihi perkiraan dan penyelesaian yang melampaui anggaran [2]. Permasalahan pembengkakan biaya ini juga tidak dapat dihindari pada proyek gedung, proyek yang memiliki kompleksitas ini juga selalu mengalami pembengkakan biaya yang diakibatkan oleh berbagai faktor.

Untuk menghindari terjadinya pembengkakan biaya harus dilakukan pengawasan secara berkala oleh pihak yang terlibat dalam proyek. proyek yang berhasil merupakan proyek yang dapat berjalan sesuai dengan tujuannya, yaitu tepat mutu, waktu dan biaya, sehingga permasalahan ini perlu menjadi perhatian khusus [3]. Oleh karena itu, kajian mengenai faktor penyebab *cost overruns* pada proyek konstruksi gedung ini perlu dilakukan untuk mengatasi permasalahan biaya pada proyek konstruksi, terutama konstruksi gedung.

Kajian ini dilakukan berdasarkan pemetaan dari hasil studi-studi terdahulu. Penelitian ini dilakukan dengan metode kajian literatur sistematis atau *systematic literature review* (SLR) yang bertujuan untuk memberikan strategi untuk membantu dalam mengatasi masalah serta memberikan pengetahuan bagi para pembaca untuk menjawab tujuan penelitian yang ada. Berdasarkan penelitian terdahulu, metode SLR ini belum pernah digunakan dalam menelaah faktor penyebab *cost overruns*, sehingga metode ini diharapkan dapat memberikan hasil yang maksimal dalam memberikan strategi untuk mengatasi masalah *cost overruns*. Tujuan penelitian ini yaitu untuk mengidentifikasi faktor-faktor dominan penyebab *cost overruns* pada proyek konstruksi gedung dan mitigasi risiko terjadinya *cost overruns* pada proyek konstruksi gedung.

Struktur dari makalah ini terdiri dari gambaran singkat tentang studi yang ada mengenai faktor penyebab *cost overruns*, kemudian dilanjutkan dengan metodologi penelitian yang menjelaskan mengenai pendekatan yang digunakan untuk pengumpulan dan analisis data. Selanjutnya dilakukan pemeriksaan komprehensif dari hasil analisis data yang disajikan dan diakhiri dengan diskusi tentang temuan utama dan memberikan kesimpulan serta saran untuk penelitian selanjutnya.

2. TINJAUAN PUSTAKA

Definisi *Cost Overruns*

Cost overruns atau pembengkakan biaya didefinisikan sebagai perbedaan antara perkiraan biaya awal proyek dan biaya proyek konstruksi yang sebenarnya terjadi di lapangan saat penyelesaian pekerjaan [4]. Pembengkakan biaya ini menjadi salah satu aspek dalam proyek konstruksi yang paling berisiko dan paling parah di negara-negara berkembang, yang mana pembengkakan biaya ini mencapai 50-100% dari anggaran yang diperkirakan [5]

Indikator dalam menentukan adanya pembengkakan biaya atau tidak yaitu dengan melakukan pembandingan antara nilai kontrak awal dengan nilai kontrak akhir pada saat proyek selesai dikerjakan [6]. Pembengkakan biaya ini bisa terjadi di proyek mana pun, baik itu proyek besar maupun proyek kecil, namun cenderung terjadi pada proyek yang memiliki skala besar [7]. *Cost overruns* dalam suatu proyek dapat disebabkan faktor internal maupun faktor eksternal, *cost overruns* dalam proyek konstruksi dibagi menjadi tiga bagian, yaitu pembengkakan biaya pada

tahap awal proyek (*pre-construction*), pembengkakan biaya pada tahap pelaksanaan konstruksi (*construction*) dan pembengkakan biaya pada tahap setelah selesai proyek (*post-construction*).

Penelitian terdahulu juga menyebutkan bahwa pada industri konstruksi mengalami pembengkakan biaya yang mana sembilan dari sepuluh proyek konstruksi selalu mengalami pembengkakan biaya yang telah terjadi secara konstan selama 70 tahun terakhir [8]. Berdasarkan penelitian terdahulu, diketahui bahwa pembengkakan biaya rata-rata terjadi sebesar 28%.

Di Jerman, rata-rata biaya *overruns* terjadi sebesar 78%, di Kanada, rata-rata biaya *overruns* terjadi sebesar 82%, di Afrika Selatan, rata-rata biaya *overruns* sebesar 5-94%, di Zambia, rata-rata biaya *overruns* terjadi sebesar 50%, di Eropa terjadi eskalasi biaya rata-rata sebesar 25,7%, di Amerika Utara, rata-rata biaya *overruns* sebesar 23,6% dan wilayah geografis lainnya terjadi *overruns* sebesar 64,6% [9]. Dengan tingginya persentase terjadinya *cost overruns* itu membuat peneliti perlu untuk mengetahui faktor penyebab *cost overruns* agar kemungkinan tersebut dapat diminimalkan.

Secara umum, penelitian-penelitian terdahulu dan literatur yang ada sudah mendukung untuk dilakukan identifikasi pada tahap awal untuk membantu dalam proses mitigasi risiko dari terjadinya *cost overruns* pada proyek konstruksi rumah sakit. Oleh karena itu, sangat penting untuk dilakukan analisis terhadap faktor penyebab *cost overruns* pada konstruksi gedung untuk membantu perkiraan biaya untuk meningkatkan kinerja dalam aspek biaya proyek.

Definisi *Systematic Literature Review* (SLR)

Systematic Literature Review (SLR) merupakan salah satu metode yang digunakan untuk menilai, mengidentifikasi dan menginterpretasi seluruh temuan-temuan dari penelitian terdahulu, untuk menjawab pertanyaan penelitian yang direncanakan sebelumnya [10].

Metode SLR digunakan untuk melakukan kajian, identifikasi, evaluasi dan penafsiran terhadap suatu fenomena tertentu yang menarik. Dengan menggunakan metode SLR ini diharapkan review dan identifikasi yang dilakukan menjadi sistematis, yang pada setiap prosesnya mengikuti langkah-langkah yang sudah ditetapkan.

Tujuan penelitian yang dilakukan dengan menggunakan SLR yaitu untuk mendapatkan suatu landasan teori yang bisa mendukung pemecahan masalah terhadap kasus yang sedang diteliti serta memberikan teori-teori yang sesuai dengan kasus tersebut. Secara khusus dalam penelitian ini diharapkan mendapatkan kajian yang lebih dalam terhadap faktor penyebab *cost overruns* pada proyek konstruksi gedung.

Menurut Staff [10], beberapa tahapan yang dilakukan dalam proses SLR antara lain:

1) Merumuskan masalah
2) Melakukan identifikasi terhadap literatur
3) Melakukan pemilihan terhadap hasil pencarian literatur sesuai dengan kerelevanan dari penelitian tersebut
4) Melakukan analisis terhadap literatur sesuai dengan rumusan masalah yang diajukan
5) Membuat kesimpulan penelitian

3. METODOLOGI PENELITIAN

Sebagaimana telah dijelaskan sebelumnya, metode yang digunakan dalam penelitian ini yaitu SLR yang digunakan untuk mengumpulkan, menguji secara kritis dan mengumpulkan hasil dari berbagai kajian penelitian sebelumnya untuk menjawab pertanyaan atau topik yang ingin didalami.

Penelitian ini difokuskan kepada pemetaan permasalahan yang terjadi di lapangan yang terkait dengan faktor penyebab *cost overruns* pada proyek konstruksi gedung. Studi literatur pada penelitian ini diambil dari jurnal ilmiah yang didapatkan dari bantuan *website* jurnal seperti Google Scholar, Emerald, Research Gate, dan Sciencedirect. Kata-kata kunci yang digunakan dalam pencarian adalah "*cost overruns*" *"building construction*" dan "*systematic literature review*". Pada penelitian ini tidak terdapat pembatasan dalam pencarian artikel, semua artikel yang dianggap relevan akan digunakan dalam penelitian ini.

Selanjutnya dilakukan penelusuran untuk menyaring artikel-artikel yang relevan terhadap *cost* overruns pada proyek gedung. Setelah dilakukan pemetaan terhadap jurnal yang relevan, maka didapatkan jurnal atau artikel yang akan digunakan sebanyak 15-20 artikel yang relevan dengan tujuan penelitian yaitu mencari faktor penyebab *cost overruns* pada konstruksi gedung. Pemilihan jumlah jurnal ini agar penelitian dapat dilakukan lebih spesifik dan melalui prosedur yang sistematis. Dengan demikian dengan jumlah jurnal yang terbatas akan menampilkan hasil yang spesifik dan relevan untuk tujuan penelitian. SLR ini akan dilakukan sesuai dengan pertanyaan penelitian yang ada yang meliputi faktor-faktor penyebab *cost overruns*. Beberapa tahapan dalam metode penelitian akan dijabarkan pada subbab berikut.

Penelitian ini meninjau artikel dengan metodologi yang beragam termasuk artikel yang menggunakan metode kualitatif, metode kuantitatif dan metode campuran sesuai dengan kriteria antara lain: penelitian berfokus pada pembengkakan biaya pada konstruksi gedung, penelitian yang dilakukan pada tahun antara 2010-2024 dan penelitian yang memiliki publikasi di jurnal terakreditasi. Langkah-langkah dalam penelitian ini akan dijabarkan sebagai berikut.

1) **Identifikasi dan Pengelompokan Jurnal**
   Identifikasi jurnal dilakukan untuk memastikan bahwa jurnal atau artikel yang digunakan memiliki relevansi terhadap tujuan penelitian. Pada penelitian ini faktor penyebab *cost overruns* yang ditinjau merupakan pembengkakan biaya yang disebabkan klien dan kontraktor.
2) **Analisis dan Pembahasan Hasil SLR**
   Analisis hasil dari SLR ini dilakukan dengan menggunakan metode deskriptif kualitatif berdasarkan studi literatur yang ada, kemudian dilakukan penilaian terhadap hasil penelitian terdahulu, faktor dominan apa saja yang paling banyak terjadi dalam konstruksi gedung terkait dengan pembengkakan biaya.
3) **Kesimpulan**
   Setelah melakukan analisis, selanjutnya dilakukan penarikan kesimpulan berdasarkan hasil analisis dan pembahasan dari faktor terjadinya *cost overruns* pada proyek konstruksi gedung.

4. HASIL DAN PEMBAHASAN

Berdasarkan hasil pemilihan jurnal yang didapatkan dari berbagai sumber seperti google Artikel yang dipilih merupakan artikel yang terakreditasi dalam bidangnya.

Jika dipisahkan berdasarkan tahun, maka terdapat satu artikel (5%) dipublikasikan pada tahun 2010, dua artikel (10%) dipublikasikan pada tahun 2012, satu artikel (5%) dipublikasikan pada tahun 2013, satu artikel (5%) dipublikasikan pada tahun 2014, empat artikel (20%) dipublikasikan pada tahun 2017, dua artikel (10%) dipublikasikan pada tahun 2018, satu artikel (5%) dipublikasikan pada tahun 2019, dua artikel (10%) dipublikasikan pada tahun 2020, satu artikel (5%) dipublikasikan pada tahun 2021, satu artikel (5%) dipublikasikan pada tahun 2022, dua artikel (10%) dipublikasikan pada tahun 2023 dan satu artikel (5%) dipublikasikan pada tahun 2024.

Metode penelitian yang digunakan dalam artikel-artikel tersebut terdiri dari metode Delphi-Swara method, SLR, Relative Importance Index, Pareto, dan metode kuantitatif lainnya. Untuk jenis gedung yang terdapat dari berbagai sumber terdiri dari rumah sakit, perumahan, gedung perkantoran, hotel dan gedung publik.

Faktor-Faktor Pengaruh

Pembengkakan biaya atau *cost overruns* pada proyek konstruksi gedung dapat disebabkan oleh berbagai faktor. Menurut Balali et al. [11], faktor yang menyebabkan terjadinya *cost overruns* yaitu dari kontraktor, konsultan, dan klien. Faktor kontraktor meliputi kualitas hasil pekerjaan yang tidak dapat diterima yang mengarah pada pekerjaan ulang, kesalahan estimasi biaya, tidak

menggunakan metode yang sesuai. Dari segi konsultan antara lain: kekurangan pengetahuan teknis pengawas, kesalahan dalam analisis kontrak, kurangnya ketepatan dalam studi geoteknis.

Dari sisi klien faktor yang berpengaruh antara lain: tidak mengalokasikan anggaran yang cukup selama proyek, keterlambatan pembayaran dan kelemahan dari *project manager*. Sementara itu dari yang tidak dapat dipermasalahkan kepada pihak mana pun meliputi perubahan lingkup pekerjaan di lapangan, korupsi, dan kondisi tidak terduga di lapangan.

konstruksi gedung meliputi banyak jenis, salah satunya rumah sakit. Rumah sakit sendiri memiliki karakteristik khusus dalam pembangunannya, antara lain hubungan antar instalasi yang memiliki keterkaitan dalam hal fungsi dan juga mengenai jalur-jalur yang efisien bagi pergerakan orang dan suplai barang, persyaratan khusus mengenai masalah keamanan seperti kebakaran serta metode evakuasi pasien, desain yang berbeda karena harus memperhatikan aspek yang ramah lingkungan, serta mekanisme pembuangan limbah yang tidak sama dengan bangunan gedung lainnya. Berikut terdapat beberapa penelitian terdahulu mengenai *cost overruns* pada proyek rumah sakit.

Menurut Patil, S & Jasutkar, D [12], faktor yang menyebabkan terjadinya *cost overruns* pada proyek rumah sakit yaitu: pengambilan keputusan yang buruk, desain yang buruk/penundaan dalam penyediaan pekerjaan, perbaikan karena pekerjaan yang salah, masalah dalam akuisisi lahan, dan kesalahan dalam penawaran.

Huynh et al. [13] menyebutkan faktor penyebab *cost overruns* pada proyek rumah sakit yaitu: keterlambatan persetujuan desain dan estimasi, desain fungsional yang tidak tepat, penarikan modal investasi publik yang lambat, *force majeure* dan kesalahan desain. Putra & Waty [14] memperlihatkan faktor yang menyebabkan terjadinya *cost overruns* pada proyek rumah sakit yaitu: produktivitas dan kualitas sumber daya manusia yang buruk, kurang baiknya koordinasi antar fungsi pada Work Breakdown Structure yang berdampak pada terjadinya pekerjaan ulang, dan kurangnya pemahaman pekerja terhadap gambar dan instruksi yang diberikan.

Menurut Kim et al. [15], faktor yang menyebabkan terjadinya *cost overruns* pada proyek rumah sakit yaitu: pekerjaan tambah, cuaca buruk, peningkatan kuantitas, pekerjaan ulang, peningkatan biaya proyek. Durdyev et al. [3] menyebutkan faktor penyebab *cost overruns* pada proyek perumahan yaitu: perencanaan yang tidak tepat, perkiraan biaya proyek yang tidak akurat, biaya sumber daya yang dibutuhkan, kekurangan tenaga kerja terampil, harga bahan konstruksi dan harga tanah yang tinggi. Amoa-Abban [16] menyebutkan faktor penyebab *cost overruns* pada gedung perkantoran yaitu: pekerjaan tambahan, tingginya variasi order, fluktuasi, penundaan pekerjaan, penambahan item pekerjaan yang tidak ada dalam BOQ

Menurut Kaming et al. [17], faktor yang menyebabkan terjadinya *cost overruns* pada gedung perkantoran yaitu: adanya perubahan desain, produktivitas tenaga kerja yang buruk, perencanaan yang tidak memadai dan kekurangan sumber daya. Haslinda et al. [18] menyebutkan faktor penyebab *cost overruns* pada gedung perkantoran yaitu: adanya perencanaan estimasi biaya yang buruk, *quantity take off* yang tidak akurat dan biaya bahan yang meningkat akibat inflasi. Selain itu juga terdapat faktor penyebab lain seperti perubahan desain, perencanaan dan jadwal yang tidak memadai dan produktivitas tenaga kerja yang buruk. Ikechukwu [19] menyebutkan faktor penyebab *cost overruns* pada proyek infrastruktur publik di Nigeria yaitu: kesulitan dalam mendapatkan material, kesalahan dalam estimasi biaya, kondisi tanah yang tidak terduga, masalah dalam perencanaan keuangan dan pembayaran dan inflasi.

Menurut Tayyab et al. [20], faktor yang menyebabkan terjadinya *cost overruns* pada gedung perkantoran yaitu: perubahan perintah yang sering terjadi, penundaan pekerjaan, fluktuasi harga bahan baku, inflasi, pekerjaan ulang, perubahan desain, penjadwalan yang kurang baik, kondisi lahan yang tidak terduga, *quantity take off* yang tidak akurat dan keterlambatan pembayaran *klien.*

Akinradewo et al. [21] menyebutkan faktor penyebab *cost overruns* pada gedung yaitu: penambahan pekerjaan, kontrol keuangan yang buruk, manajemen kontrak yang buruk, kurangnya pengalaman kontraktor, dan kesalahan metode dalam estimasi. Sohu et al. [22] menyebutkan faktor penyebab *cost overruns* pada gedung yaitu: masalah keuangan *klien*,

informasi yang lambat antar pihak, kenaikan harga material, manajemen proyek yang buruk, masalah pembayaran kontraktor, keterlambatan dalam pengambilan keputusan dan bencana alam.

Menurut Hesna et al. [23], faktor yang menyebabkan terjadinya *cost overruns* pada proyek hotel yaitu: kesalahan dalam pemilihan material, kenaikan harga bahan, kekurangan tenaga kerja, dan kualitas tenaga kerja yang tidak mumpuni. Mahamid & Dmaidi [24] menyebutkan faktor penyebab *cost overruns* proyek gedung disebabkan situasi politik, fluktuasi harga bahan, tingkat persaingan, meningkatnya nilai pertukaran mata uang dan ketidakstabilan ekonomi. Jangale et al. [25] menyebutkan faktor penyebab *cost overruns* proyek perumahan disebabkan oleh: inflasi, perencanaan dan koordinasi yang buruk, perubahan pesanan dan pekerjaan tambah.

Menurut Osama et al. [26], faktor yang menyebabkan terjadinya *cost overruns* pada proyek gedung yaitu: *variation order*, kurangnya supervision dan manajemen lapangan yang baik, penundaan antara fase pengadaan dan fase desain, *force majuere*, pengalaman perencana yang rendah dan penundaan pekerjaan.

Jadhav et al. [27] menyebutkan faktor penyebab *cost overruns* pada proyek perumahan yaitu: klaim konstruksi, perencanaan yang buruk, pekerjaan tambah atas permintaan *klien*, buruknya pengalaman terkait regulasi pemerintah dan manajemen lapangan yang buruk. Cunningham [28] menyebutkan faktor penyebab *cost overruns* proyek gedung disebabkan oleh: desain yang tidak lengkap, dokumen tender yang buruk, inflasi, kinerja manajemen yang buruk dan pengambilan keputusan yang lambat. Memon et al. [5] menyebutkan faktor penyebab *cost overruns* proyek gedung disebabkan oleh: fluktuasi dalam harga material, arus kas dan kesulitan keuangan kontraktor, penundaan pembayaran oleh *klien*, perubahan desain, kekurangan material dan kontrol keuangan yang buruk.

Berdasarkan kajian dari 20 literatur terdahulu yang telah dianalisis, dapat direkapitulasi hasil dari faktor penyebab *cost overruns* pada proyek gedung yang ditunjukkan pada Tabel 1.

Mitigasi Risiko

Selanjutnya adalah bagaimana cara mitigasi risiko terhadap faktor penyebab *cost overruns* pada proyek konstruksi gedung dapat dilakukan, beberapa peneliti menyebutkan cara mitigasi risiko yaitu menurut Kim et al. [15], mitigasi risiko dapat dilakukan dengan cara menambah anggaran untuk kontrak supervisor, mencari konsultan asing yang profesional dan jelas, mencari pengawas yang kompeten dan jelas, mencari konsultan asing dari negara maju, melakukan proses tender secara transparan dan jujur, dan estimasi biaya yang tepat.

Remi, F [4] menyebutkan mitigasi risiko dapat dilakukan dengan beberapa cara yaitu: melakukan pengelolaan kebijakan pembiayaan melalui kebijakan arus kas keuangan yang disesuaikan dengan sistem pembayaran, memaksimalkan uang muka dari pemilik pekerjaan, konsistensi untuk melakukan kontrol terhadap *cost control*, jadwal pekerjaan, material dan tenaga kerja, pemilihan estimator yang profesional dan berpengalaman untuk mendapatkan rencana anggaran yang akurat dan tepat, membangun koordinasi, komunikasi dan informasi yang baik antar pihak, dan menyusun konsep manajemen proyek yang lengkap terutama manajemen sumber daya tenaga kerja, material, peralatan serta penentuan metode kerja yang tepat.

Ikechukwu [19] menyebutkan mitigasi risiko dapat dilakukan dengan beberapa cara yaitu: menerapkan manajemen proyek yang baik, mempererat komunikasi dan kerja sama baik klien, kontraktor dan konsultan, melakukan penjadwalan dengan baik sebelum proyek dimulai dan menghindari perselisihan antar pihak yang terlibat dalam proyek.

Putra dan Waty [14] menyebutkan mitigasi risiko dapat dilakukan dengan beberapa cara yaitu: pemilihan manajer proyek yang profesional dan berpengalaman, membangun koordinasi dan komunikasi yang baik antar pihak, konsistensi dalam melakukan kontrol terhadap pekerjaan, dan koordinasi yang baik antar pihak.

Dio et al. [29] menyebutkan mitigasi risiko dapat dilakukan dengan beberapa cara yaitu: memilih staff yang berpengalaman untuk meminimalkan kesalahan yang mungkin terjadi dan pengambilan keputusan yang cepat agar tidak memperlambat pekerjaan.

Tabel 1. Rekapitulasi Faktor Penyebab *Cost Overruns* pada Proyek Gedung

Faktor Penyebab *Cost Overruns*	Referensi																				
	Balali et al. (2022)	Patil S., & Jasutkar, D.B. (2023)	Huynh et al., (2024)	Putra & Waty, (2022)	Kim et al. (2018)	Durdyev et al. (2012)	Amoa-Abban et al (2014)	Kaming et al., (2010)	Haslinda et al. (2018)	Ikechukwu et al. (2017)	Tayyab et al. (2023)	Akinradewo et al. (2019)	Sohu et al. (2018)	Hensa et al. (2021)	Mahamid & Dmaidi (2013)	Jangale et al. (2017)	Osama et al. (2023)	Jadhav et al., (2020)	Cunningham (2017)	(Memon et al., 2012)	Frekuensi
Pekerjaan ulang	✓	✓		✓	✓						✓										5
Kesalahan estimasi biaya	✓					✓		✓	✓	✓		✓									6
Kesalahan metode pekerjaan	✓																				1
Kurangnya pengetahuan teknis pengawas	✓																				1
Kesalahan dalam analisis kontrak	✓																				1
Kesalahan dalam studi geoteknis	✓																				1
Tidak mengalokasikan anggaran yang cukup selama proyek	✓																				1
Keterlambatan pembayaran	✓																				1
Project manager kurang berpengalaman	✓																				1
Perubahan ruang lingkup di lapangan	✓																				1
korupsi	✓																				1
Force majuere	✓		✓		✓								✓				✓				5
Pengambilan keputusan yang buruk		✓																			1
Permasalahan desain		✓	✓					✓			✓								✓	✓	6
Penundaan pekerjaan		✓					✓				✓						✓				4
Permasalahan lahan		✓				✓															2
Kesalahan dalam penawaran		✓																			1
Penarikan modal investasi yang lambat			✓																		1
Kualitas sumber daya manusia yang buruk				✓		✓		✓						✓							4
Kurangnya pemahaman pekerja thd gambar dan instruksi				✓																	1
Pekerjaan tambah					✓		✓					✓				✓		✓			5
Peningkatan kuantitas					✓																1
Peningkatan biaya proyek					✓	✓															2
Perencanaan yang tidak tepat						✓		✓								✓		✓			4
Fluktuasi Harga Material						✓	✓				✓		✓	✓	✓					✓	7
Tingginya variasi order							✓									✓	✓				3
Penambahan item pekerjaan yang tidak ada di dalam BOQ							✓														1
Kekurangan sumber daya								✓						✓							2

Tabel 1. Rekapitulasi Faktor Penyebab *Cost Overruns* pada Proyek Gedung

Faktor Penyebab *Cost Overruns*	Referensi																				
	Balali et al. (2022)	Patil S., & Jasutkar, D.B. (2023)	Huynh et al., (2024)	Putra & Waty, (2022)	Kim et al. (2018)	Durdyev et al. (2012)	Amoa-Abban et al (2014)	Kaming et al., (2010)	Haslinda et al. (2018)	Ikechukwu et al. (2017)	Tayyab et al. (2023)	Akinradewo et al. (2019)	Sohu et al. (2018)	Hensa et al. (2021)	Mahamid & Dmaidi (2013)	Jangale et al. (2017)	Osama et al. (2023)	Jadhav et al., (2020)	Cunningham (2017)	(Memon et al., 2012)	Frekuensi
Quantity take off yang tidak akurat									✓		✓										2
Inflasi									✓	✓	✓				✓	✓			✓		6
Kesulitan dalam mendapatkan material										✓										✓	2
Kondisi tanah yang tidak terduga										✓	✓										2
Permasalahan dalam perencanaan keuangan										✓											1
Perubahan perintah yang sering terjadi											✓										1
Kontrol keuangan yang buruk												✓									1
Manajemen kontrak yang buruk												✓							✓		2
Kurangnya pengalaman kontraktor												✓									1
Masalah keuangan klien											✓	✓	✓							✓	4
Penjadwalan yang kurang baik											✓										1
Informasi yang lambat antar pihak													✓								1
Manajemen proyek yang buruk													✓						✓		2
Masalah pembayaran kontraktor													✓							✓	2
Keterlambatan dalam mengambil keputusan													✓						✓		2
Kesalahan dalam pemilihan material														✓							1
Tingkat persaingan															✓						1
Situasi politik															✓						1
Ketidakstabilan ekonomi															✓						1
Manajemen lapangan yang buruk																	✓	✓			2
Penundaan antara fase penadaan dan fase desain																	✓				1
Kurangnya pengalaman perencana																	✓				1
Klaim konstruksi																		✓			1
Buruknya pengalaman terkait regulasi pemerintah																		✓			1
Kontrol keuangan yang buruk																		✓		✓	2

Berdasarkan hasil rekapitulasi penelitian terdahulu mengenai faktor penyebab *cost overruns* pada proyek konstruksi gedung, faktor dominan ini sendiri diambil berdasarkan frekuensi yang paling banyak disebutkan pada penelitian terdahulu, maka didapatkan faktor-faktor paling dominan yang menyebabkan *cost overruns* itu sendiri yang akan ditampilkan pada Tabel 2.

Tabel 2. Faktor-Faktor Dominan Penyebab *Cost Overruns*

Faktor	Deskripsi	Referensi
Permasalahan Desain	Dengan adanya permasalahan desain seperti gambar yang tidak lengkap, perubahan desain, keterlambatan pengiriman gambar, kesalahan gambar akan membuat proyek menjadi terlambat dan membuat terjadinya pembengkakan biaya	Patil S., & Jasutkar, D.B. (2023), Huynh et al., (2024), Kaming et al., (2010), Haslinda et al., (2018), Tayyab et al., (2023), Jangale et al., (2017), Cunningham (2017), Memon et al., (2012)
Force Majuere	*Force majuere* yang merupakan kejadian tidak terduga seperti bencana alam, cuaca buruk mempengaruhi jadwal proyek, apabila *force majuere* terjadi secara terus menerus akan menyebabkan keterlambatan proyek yang mengakibatkan adanya pembengkakan biaya	Balali et al., (2022), Huynh et al., (2024), Kim et al., (2018), Sohu et al., (2018), Osama et al., (2023)
Fluktuasi Harga	Fluktuasi harga yang tidak dapat diperkirakan akan menyebabkan pembengkakan biaya dalam proyek karena harus mengikuti harga yang berlaku saat ini	Durdyev et al., (2012), Amoa-Abban et al., (2014), Haslinda et al., (2018), Tayyab et al., (2023), Sohu et al., (2018), Hesna et al., (2021), Mahamid & Dmaidi, (2013), Memon et al., (2012)
Kesalahan dalam Estimasi Biaya	Kesalahan dalam estimasi biaya di awal membuat terjadinya pembengkakan biaya, karena biaya yang diperkirakan tidak sesuai dengan biaya aktual yang terjadi di lapangan	Balali et al., (2022), Durdyev et al., (2012), Kaming et al., (2010), Haslinda et al., (2018), Ikechukwu et al., (2017), Akinradewo et al., (2019)
Pekerjaan Tambah	Penambahan pekerjaan seperti adanya pengulangan pekerjaan akibat cacat/salah baik itu yang berasal dari *klien* maupun dari kontraktor akan berpengaruh terhadap nilai kontrak, dengan adanya pekerjaan tambah maka akan meningkatkan biaya proyek yang menyebabkan adanya pembengkakan biaya	Balali et al., (2022), Patil S., & Jasutkar, D.B. (2023), Putra & Waty, (2022), Kim et al., (2018), Amoa-Abban et al., (2014), Tayyab et al., (2023), Akinradewo et al., (2019), Jangale et al., (2017), Jadhav et al., (2020)
Pekerjaan Ulang	Pekerjaan ulang yang disebabkan karena pekerjaan yang tidak layak ini akan mengakibatkan pembengkakan biaya dalam proyek	Balali et al. (2022), Patil S., & Jasutkar, D.B. (2023), Putra & Waty, 2022), Kim et al. (2018), Tayyab et al. (2023)
Inflasi	Dengan adanya inflasi maka akan menyebabkan terjadinya kenaikan harga bahan bangunan, harga bahan bakar, upah pekerja dan lain-lain. hal ini menyebabkan terjadinya pembengkakan biaya proyek.	Haslinda et al., (2018), Ikechukwu et al., (2017), Tayyab et al., (2023), Jangale et al., (2017), Cunningham (2017)

Tujuh faktor dominan di atas dipilih menjadi faktor utama yang menyebabkan terjadinya pembengkakan biaya pada proyek gedung, pemilihan faktor-faktor tersebut didasari oleh karena banyaknya penelitian terdahulu yang menyebutkan bahwa faktor tersebutlah yang memberikan dampak pembengkakan biaya pada proyek konstruksi. Faktor-faktor lain yang disebutkan dalam kajian merupakan faktor pendukung lain yang juga mempengaruhi terjadinya pembengkakan biaya pada proyek konstruksi gedung.

Mitigasi Risiko *Cost Overruns* Proyek Gedung

Mitigasi risiko tentunya perlu dilakukan untuk meminimalkan terjadinya pembengkakan biaya proyek konstruksi, terdapat berbagai cara untuk melakukan mitigasi risiko berdasarkan beberapa penelitian terdahulu, yaitu:

1) Menambah anggaran untuk kontrak supervisor
2) Mencari konsultan asing yang profesional dan jelas
3) Mencari pengawas yang kompeten dan jelas
4) Mencari konsultan asing dari negara maju
5) Melakukan proses tender secara transparan dan jujur
6) Estimasi biaya yang tepat
7) Melakukan pengelolaan kebijakan pembiayaan melalui kebijakan arus kas
8) Memaksimalkan uang muka dari klien
9) Konsistensi untuk melakukan kontrol terhadap *cost control*, jadwal pekerjaan, material dan tenaga kerja
10) Pemilihan estimator yang profesional dan berpengalaman
11) Membangun koordinasi, komunikasi dan informasi yang baik antar pihak
12) Menyusun konep manajemen proyek yang lengkap terutama manajemen sumber daya tenaga kerja, material, peralatan dan penentuan metode kerja yang tepat
13) Melakukan proses penjadwalan yang baik
14) Menghindari perselisihan antar pihak yang terlibat di dalam proyek
15) Memilih manajer proyek yang profesional dan pengalaman
16) Pengambilan keputusan yang cepat agar tidak terjadi penundaan pekerjaan

5. KESIMPULAN

Berdasarkan hasil *systematic literature review* yang telah dianalisis dari sejumlah artikel yang relevan maka dapat ditarik beberapa kesimpulan sebagai berikut:

1) Tujuh faktor yang paling dominan menyebabkan terjadinya *cost overruns* pada proyek gedung yaitu: permasalahan desain, *force majuere*, fluktuasi harga, kesalahan dalam estimasi biaya, pekerjaan tambah, kualitas sumber daya manusia yang buruk dan inflasi
2) Mitigasi risiko terjadinya *cost overruns* pada proyek konstruksi gedung dapat dilakukan dengan beberapa cara yaitu: Menambah anggaran untuk kontrak supervisor, Mencari konsultan asing yang profesional dan jelas, Mencari pengawas yang kompeten dan jelas, Mencari konsultan asing dari negara maju, Melakukan proses tender secara transparan dan jujur, Estimasi biaya yang tepat, Melakukan pengelolaan kebijakan pembiayaan melalui kebijakan arus kas, Memaksimalkan uang muka dari klien, Konsistensi untuk melakukan kontrol terhadap cost control, jadwal pekerjaan, material dan tenaga kerja, Pemilihan estimator yang profesional dan berpengalaman, Membangun koordinasi, komunikasi dan informasi yang baik antar pihak, Menyusun konep manajemen proyek yang lengkap terutama manajemen sumber daya tenaga kerja, material, peralatan dan penentuan metode kerja yang tepat, Melakukan proses penjadwalan yang baik , Menghindari perselisihan antar pihak yang terlibat di dalam proyek, Memilih manajer proyek yang profesional dan pengalaman, Pengambilan keputusan yang cepat agar tidak terjadi penundaan pekerjaan.

Saran yang dapat dipertimbangkan di masa mendatang, dapat dilakukan pengembangan lebih lanjut terhadap jenis gedung lain seperti jembatan, bangunan air dan lain sebagainya, sehingga tidak hanya sebatas lingkup pekerjaan gedung seperti dalam penelitian ini.

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