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ABSTRACT

Engineered wood products (EWPs) are increasingly recognized as sustainable alternatives to conventional construction materials, yet their adoption in developing economies remains limited. This study develops and validates an integrated structural equation model grounded in the Technology–Organization–Environment (TOE) framework and the Triple Bottom Line (TBL) perspective to examine the determinants and sustainability outcomes of EWP adoption in the Nigerian construction sector. Survey data obtained from construction professionals in Enugu State were analyzed using structural equation modeling. The validated model demonstrates that technology, organizational and environmental factors significantly and positively influence EWP adoption, with technology exerting the strongest antecedent effect. Furthermore, EWP adoption significantly enhances environmental, economic and social sustainability outcomes, confirming its role as a pathway toward more sustainable construction practices. The model explains meaningful proportions of variance in both adoption behaviour and sustainability outcomes, providing empirical support for integrating TOE antecedents with TBL outcomes. The findings indicate that improving technical performance awareness, organizational readiness, management commitment, regulatory support and market development will accelerate EWP uptake. Practical implications include strengthening timber grading and certification systems, updating building codes, supporting local EWP manufacturing, integrating EWP content into professional development programmes and promoting demonstration projects. The study contributes to the growing body of knowledge on innovative hardwood-based construction materials by presenting a context-specific, empirically validated framework for understanding EWP adoption in a developing-country setting. The findings provide valuable evidence for policymakers, researchers and industry stakeholders seeking to advance sustainable construction, resource efficiency and low-carbon infrastructure through wider adoption of engineered wood products.

Keywords: Engineered wood products; Technology–Organization–Environment (TOE); Structural equation modeling; Sustainable construction; Triple Bottom Line; Hardwood-based construction materials

INTRODUCTION

The global construction industry accounts for a substantial share of anthropogenic greenhouse gas emissions and consumes a disproportionate volume of the world's raw materials, energy, and water. The building sector consumes vital resources, using up 12% of land, 25% of water, 40% of energy, and 30% of raw materials (Grobbelaar et al., 2024). This makes the sector a critical arena for sustainability transitions and construction makes up a tenth of global gross domestic product while employing numerous people worldwide (Okanya, 2026). Within this context, engineered wood products (EWPs), a family of manufactured structural materials that includes cross-laminated timber (CLT), glue-laminated timber (glulam), and laminated veneer lumber, have attracted growing international attention as renewable substitutes for carbon-intensive concrete and steel. Mass timber, a group of engineered wood products used for structural application, has emerged as one of the most promising pathways toward low-carbon, resource-efficient construction (Lan et al., 2025; Prakosa et al., 2026). Comparative life-cycle assessments reinforce this potential. A review of 27 studies on the lifetime emissions associated with cross-laminated timber found that the material could lower the carbon emissions of large buildings by roughly 40 percent compared with traditional materials (MIT Climate, 2023). Similarly, a cradle-to-gate life cycle assessment comparing a timber building with a functionally equivalent concrete building found a 25 percent reduction in global warming potential for the timber alternative (Andersen et al., 2021).

Beyond their environmental credentials, EWPs offer structural and constructional advantages that make them attractive in rapidly urbanising economies. Engineered wood products such as glue-laminated and cross-laminated timber have gained increasing popularity in both residential and commercial construction owing to their environmentally sustainable performance, ease and speed of construction from prefabrication. They also have superior strength and thermal performance, positioning mass timber as a feasible substitute for reinforced concrete and steel (Hemmati et al., 2024). Their appeal further extends to occupant wellbeing. Research on biophilic design suggests that building occupants tend to instinctively prefer wood over other materials because of a biophilic response that is beautiful, natural, and stress-relieving (Montjoy,

2022), positioning EWPs as materials that can simultaneously advance environmental, economic, and human-centred objectives.

Enugu State, situated in Nigeria's South East geopolitical zone, offers an instructive study area. The zone has experienced sustained construction activity amid urbanisation pressures, and its professional community spans the full range of construction disciplines relevant to EWP diffusion (architects, civil engineers, timber manufacturers, and quantity surveyors) while remaining, like much of Nigeria, in the early stages of engineered timber uptake. A study evaluating sustainable construction practices across five South East Nigerian states found that out of 55 construction activities identified and categorised across the three key dimensions of sustainable construction, 35 were rated as highly important, with relative importance index values ranging between 0.804 and 0.990 (Okolie et al., 2020). The findings is an indication of strong latent professional receptivity to sustainability-oriented construction practices in the region. The finding is a receptivity this study seeks to leverage and explain in relation to EWPs specifically.

Against this background, the present study addresses five inter-related aims: (i) to identify the technological factors influencing EWP adoption in the Nigerian construction industry; (ii) to identify the organisational factors influencing EWP adoption; (iii) to identify the environmental factors influencing EWP adoption; (iv) to determine the effect of EWP adoption on environmental, economic, and social sustainability; and (v) to develop and validate an integrated sustainability framework for promoting EWP adoption in the Nigerian construction industry. In pursuing these aims, the study contributes to the sustainable development goals on use of Innovative and sustainable Products and Technologies (particularly via Hardwood-Based Construction Materials) by providing empirically grounded, theoretically integrated evidence on the behavioural and institutional pathways through which hardwood-based engineered products can be diffused and their sustainability value realised in an emerging construction market.

Research Questions

1. What technological factors influence the adoption of engineered wood products in the Nigerian construction industry?
2. What organizational factors influence the adoption of engineered wood products in the Nigerian construction industry?

3. What environmental factors influence the adoption of engineered wood products in the Nigerian construction industry?

4. What effect does the adoption of engineered wood products have on environmental, economic, and social sustainability?

5. What integrated sustainability framework can be developed for promoting engineered wood products in the Nigerian construction industry?

Research Hypotheses

H1. Technological factors significantly influence the adoption of engineered wood products.

H2. Organizational factors significantly influence the adoption of engineered wood products.

H3. Environmental factors significantly influence the adoption of engineered wood products.

H4. Adoption of engineered wood products significantly improves environmental sustainability.

H5. Adoption of engineered wood products significantly improves economic sustainability.

H6. Adoption of engineered wood products significantly improves social sustainability.

LITERATURE REVIEW

Engineered Wood Products as Sustainable Construction Materials

Engineered wood products represent a family of manufactured wood-based materials engineered to exceed the structural performance of solid sawn lumber while economising on raw material use. Life-cycle assessment research has been central to establishing their sustainability credentials. With the development of mass timber, cross-laminated timber has gradually become a sustainable alternative to conventional building materials as a means of alleviating the increasing energy consumption and carbon emissions associated with the building sector (Andersen et al., 2021). At a global scale, modelling work indicates that if cumulative global cross-laminated timber production reaches 3.6 to 9.6 billion cubic metres by 2100, long-term carbon storage could increase by 20.3 to 25.2 gigatonnes of CO2-equivalent. This could happen primarily in forests and in cross-laminated timber panels, with net life-cycle greenhouse gas emission reductions of 25.6 to 39.0 gigatonnes of CO2-equivalent when reductions from steel, cement, and traditional wood products are included (Lan et al., 2025). These findings position engineered wood not merely as a substitute material but as an active carbon-sequestration strategy embedded within the built environment.

Economic viability, however, remains an evolving evidence base. A systematic review of 143 peer-reviewed publications on mass timber economics concluded that economic performance is

not yet consistently established across the literature. The findings underscore the need for more standardised, context-sensitive, and methodologically consistent evaluation frameworks to support informed decision-making (Prakosa et al., 2026). Similarly, research on the socio-economic and policy dimensions of hardwood-based mass timber products, including their market viability and regulatory implications, forms an important and growing stream of scholarship (Huang & Yan, 2026). This uncertainty regarding cost competitiveness is consequential for adoption behaviour, since construction professionals in cost-sensitive markets such as Nigeria are likely to weigh economic performance heavily in their adoption calculus.

Two technical concerns recur prominently in the engineered wood literature: fire performance and durability. Fire safety remains a major challenge for engineered timber buildings, since their combustible nature challenges the design principles of compartmentation and structural integrity beyond burnout that are inherent to conventional fire-resistance frameworks (Östman et al., 2017), although industry guidance notes that building codes increasingly permit the substitution of fire-retardant-treated wood for noncombustible materials in specific applications, with defined performance and treatment requirements (Dietenberger, 2021). Encouragingly, engineered timber's charring behaviour provides an inherent, if partial, safeguard. In fire-exposure testing, mass timber elements char on the outside and forming a protective layer while retaining strength. This slows combustion significantly and allows time for safe evacuation, with char forming at a predictable rate that supports fire engineering design (Naturally Wood, 2026). On durability performance, a comprehensive review found that durability issues in mass timber structures centre on biological deterioration from decay fungi and insects such as termites, and environmental degradation from moisture and weathering, requiring continued development of protection protocols and evaluation methods (Ayanleye et al., 2022). This concern is of particular relevance in Nigeria's humid tropical climate, where termite pressure and moisture exposure are pronounced.

Occupant-centred and social dimensions of engineered wood use have also received growing research attention. Evidence on the psychophysiological effects of timber interiors suggests measurable wellbeing benefits, with building occupants tending to instinctively prefer wood over other materials because of a biophilic response that is beautiful, natural, and stress-relieving (Montjoy, 2022). These social benefits complement the environmental and, increasingly,

economic case for engineered wood, reinforcing the rationale for a Triple Bottom Line evaluation of adoption outcomes rather than a narrowly technical or environmental one.

Sustainable Construction Materials and Practice in Nigeria

Nigeria's construction materials landscape has been extensively examined through the lens of adoption barriers, though rarely with specific reference to engineered wood. A national survey of 282 construction professionals identified organisational and market-related constraints as central obstacles. The study found that organisational barriers within Nigerian construction industry firms include a lack of top management commitment and employee-level constraints, while policy-related barriers reflect the intricate interplay of funding, policy enforcement, industry regulations and codes, and incentives (Mogaji et al., 2025). The same study further reported that perception and cultural-related barriers, spanning six identified variables, suggest that societal resistance to change and entrenched cultural preferences significantly impact the acceptance of innovative building materials. The finding is calling for theoretical models that incorporate cultural and perceptual dynamics alongside technical and economic factors (Mogaji et al., 2025).

More recent Nigerian evidence sharpens the picture of a persistent awareness-adoption disconnect. A 2026 study spanning all six Nigerian geopolitical zones found that differences in sustainable construction material adoption across professional groups were evaluated using the Kruskal-Wallis H test, while Spearman's rank correlation assessed the awareness-adoption relationship and hierarchical regression examined predictors of adoption (Osuolale & Felkner, 2026). The study ultimately concluded that awareness alone was insufficient to drive adoption without accompanying structural change. Complementary fuzzy-evaluation research quantifying the same phenomenon found that adoption of sustainable construction materials in Nigeria remains limited. They are constrained by multidimensional barriers embedded in institutional, regulatory, market, and supply-chain systems, motivating fuzzy synthetic evaluation methods that can account for the uncertainty and subjectivity inherent in professional judgments about emerging materials (Osuolale et al., 2026). Reinforcing this institutional narrative, a qualitative study of Nigerian policymakers concluded that the Nigerian construction industry faces significant challenges in managing waste and resource inefficiency. The study stated that despite the potential of circular economy practices to address these issues, there remains limited understanding and inadequate policy support for their effective implementation (Okafor et al., 2026).

Professional roles also appear to matter. Research focused specifically on the quantity surveying profession found that Quantity Surveyors can play a more active role in enhancing the adoption and integration of sustainable construction practices in Nigeria, given increasing awareness of the benefits of sustainable construction despite its continued low overall adoption (Olatunde et al., 2025). This finding motivates this study's inclusion of quantity surveyors alongside architects, civil engineers, and timber manufacturers as key adopting professions. At the regional level, evidence from South East Nigeria specifically demonstrates latent receptivity: professionals in the zone assign high relative importance to sustainability-oriented construction activities. The study reported that 35 of 55 identified construction activities were rated as highly important for sustainable construction practice, with relative importance index values ranging from 0.804 to 0.990 (Okolie et al., 2020). The findings suggest that the region is a fertile, if underexploited, ground for engineered wood diffusion.

Timber-specific research in Nigeria remains comparatively sparse but affirms strong technical rationale for expanded use. An assessment of timber as a building material concluded that timbers are globally regarded as an environmentally sustainable and renewable construction material, requiring lesser and cheaper processing energy than concrete and steel (Dahunsi & Adetayo, 2015), while noting that current utilisation, though substantial in gross volume terms, remains overwhelmingly confined to conventional sawn timber rather than engineered, higher-value applications. studies of sustainable materials for tropical climates similarly positioned sustainable timber alongside stabilised earth blocks, recycled industrial by-products, and composite materials as key options for Nigeria, while noting those materials' economic, technical-expertise, and regulatory adoption challenges (Bello et al., 2025; Okanya, 2026) barriers that map closely onto the organisational and environmental dimensions of the TOE framework applied in this study.

Technology Adoption Frameworks in Construction: The TOE Perspective

The TOE framework has become one of the most widely applied theoretical lenses for explaining organisational technology adoption in construction, particularly in Building Information Modelling (BIM) research, from which this study draws important methodological and substantive parallels. A sudy observed that the framework's utility lies in its capacity to support a systematic analysis of the factors influencing organisational decisions and strategies in the adoption of any technology, (Rajendra & Mohanasundaram, 2025). This includes specifically in

architecture, engineering, and construction contexts where integrating diffusion-of-innovation theory and TOE has supported understanding of the driving forces behind Building Information Modelling adoption and its impact on inter-organisational relations (Rajendra & Mohanasundaram, 2025).

Empirical applications of TOE in construction technology contexts consistently find that organisational factors, particularly top management support, exert strong effects. In a large-scale study of 512 stakeholders across the construction supply chain, management commitment and perceived ease of use exhibited the strongest positive effects on BIM adoption intention among nine factors examined across the technology, organisation, and environment dimensions, though perceived usefulness, supporting technical facilities, and mimetic pressure showed no significant influence (Huang & Yan, 2026).

Nigerian-specific TOE and diffusion research, while concentrated on BIM rather than EWPs, reveals barrier patterns highly relevant to engineered wood adoption. Structured interviews with Nigerian experts identified that technical barriers are the most significant challenge to construction technology adoption, particularly due to difficulties in accessing advanced technology, while educational barriers also play a major role given limited awareness among industry professionals (Amuda et al., 2018). Descriptive survey evidence corroborates this, finding that Nigerian construction professionals demonstrate a moderate level of technology awareness but a low level of engagement in relevant education and training, with very low technical skills. The study noted that organisational size affects the transmission of information and knowledge across levels (Amuda et al., 2018). The findgs is a direct empirical precedent for this study's inclusion of organisational readiness and technical expertise as key constructs.

The Research Gap

Despite the individual maturity of TOE-based technology adoption research and TBL-based sustainability assessment research within construction management, few studies have integrated the two frameworks to model adoption as a mediating mechanism linking institutional readiness to sustainability performance, and none, to the researchers' knowledge, have done so for engineered wood products within a Nigerian or comparable Sub-Saharan African construction market. Existing Nigerian sustainable-materials research has tended to measure either barriers to adoption (using exploratory factor analysis, relative importance indices, or fuzzy evaluation) or awareness-adoption relationships (using correlation and regression), but has not modelled the full

antecedent-mediator-outcome chain using structural equation modelling. Likewise, existing TOE-BIM research in Nigeria, while methodologically sophisticated, addresses a digital rather than a materials-based innovation and does not extend to sustainability outcome measurement. This study addresses both gaps by developing and empirically validating an Integrated Sustainability Framework that positions EWP adoption as the pivotal mediating construct between TOE antecedents and TBL outcomes, tested using PLS-SEM among a stratified sample of construction professionals in Enugu State, Nigeria.

THEORETICAL FRAMEWORK

This study is anchored on two complementary theories: the Technology-Organization-Environment (TOE) framework, which explains the antecedent conditions for EWP adoption, and Triple Bottom Line (TBL) theory, which explains the sustainability consequences of that adoption.

Technology-Organization-Environment (TOE) Framework

The Technology-Organization-Environment framework, originally articulated by Tornatzky and Fleischer in 1990, is a seminal analytical model commonly used to systematically identify and structure the major contexts shaping organisational technology adoption, diffusion, and assimilation, (Tornatzky & Fleischer, 1990). The three contexts are operationalised in this study as follows.

Technology context refers to the internal and external technologies relevant to the adopting organisation, including the perceived characteristics of the innovation itself. In this study, technology factors are measured through five indicators specific to engineered wood products: structural performance, durability, fire resistance, cost competitiveness, and availability. These indicators reflect the technical attributes that construction professionals evaluate when appraising EWPs as viable structural alternatives, consistent with evidence that the ease and speed of construction from prefabrication, combined with superior strength and thermal performance, position mass timber products as a feasible substitute for reinforced concrete and steel (Hemmati et al., 2024), while unresolved concerns about fire behaviour and durability under tropical conditions represent countervailing technological considerations.

Organization context refers to firm-level characteristics that mediate technology uptake. Representative constructs include firm size, resource availability, dynamic capabilities, top management support, absorptive capacity, internal skill base, and organisational culture

(Tornatzky & Fleischer, 1990). This study operationalises organisational factors through technical expertise, organisational readiness, management commitment, and financial capacity; constructs directly informed by Nigerian evidence that professionals demonstrate low technical skills and low engagement in relevant education and training, and that organisational size affects the transmission of information and knowledge across levels (Mogaji et al., 2018), and by findings that management commitment exhibits among the strongest effects on construction technology adoption intention (Osuolale et al., 2026).

Environment context refers to the external institutional and market arena within which the adopting organisation operates, encompassing regulatory, competitive, and market-based pressures. This study measures environmental factors through government policies, building regulations, market demand, supply chain readiness, and environmental awareness. This operationalisation reflects Nigerian evidence that policy-related barriers reflect an intricate interplay of funding, policy enforcement, industry regulations and codes, and incentives (Assessment of Barriers to the Adoption of Innovative Building Materials, 2025), and that market and supply-side constraints, including the unavailability of innovative building materials, sustain continued dependence on conventional materials.

Triple Bottom Line (TBL) Theory

First introduced by John Elkington in 1994, the Triple Bottom Line framework has profoundly transformed how businesses approach sustainability and evaluate success, moving beyond a traditional focus on profit to incorporate three interconnected dimensions. The dimensions include social, environmental, and economic sustainability (Elkington, 1994). This study adopts and operationalises the three TBL dimensions as follows.

Environmental sustainability captures the ecological performance gains associated with EWP adoption, measured through carbon reduction, resource efficiency, and waste minimisation. This dimension is theoretically and empirically the most extensively documented benefit of engineered wood in the literature, with life-cycle assessment research consistently finding substantial embodied-carbon reductions relative to concrete and steel alternatives, and forest-carbon modelling suggesting that long-term carbon storage could increase substantially in both forests and cross-laminated timber panels as global production scales (Lan et al., 2025).

Economic sustainability captures the financial and productivity gains associated with EWP adoption, measured through construction cost savings, productivity, and lifecycle cost benefits.

This dimension remains comparatively contested in the international literature, with reviewers cautioning that economic performance evidence for mass timber is not yet consistently established across contexts (Prakosa et al., 2026). This makes its empirical assessment among Nigerian professionals who operate within a materials-cost environment substantially different from that of North America or Europe, where much of the existing mass timber economic literature originates a valuable contribution.

Social sustainability captures the human and community-level benefits associated with EWP adoption, measured through occupant comfort, employment creation, and community acceptance. This dimension draws on biophilic-design and occupational research suggesting that timber environments enhance occupant wellbeing, and on Nigerian circular-economy evidence that wood-based value chains can stimulate domestic economic development and support job opportunities through the activities of informal private-sector practitioners and local craftsmen (Jonathan & Onyoni et al., 2025).

Collectively, the theoretical model proposes that adoption of engineered wood products serves as the pivotal mediating mechanism through which technology, organisation, and environment antecedents are translated into environmental, economic, and social sustainability outcomes.

CONCEPTUAL FRAMEWORK

Building on the TOE-TBL theoretical integration, the conceptual framework guiding this study (subsequently validated and refined into the Integrated Sustainability Framework presented in the Discussion) proposes the following structural logic:

1. Technology factors (structural performance, durability, fire resistance, cost competitiveness, availability) exert a direct positive effect on the adoption of engineered wood products.
2. Organizational factors (technical expertise, organizational readiness, management commitment, financial capacity) exert a direct positive effect on the adoption of engineered wood products.
3. Environmental factors (government policies, building regulations, market demand, supply chain readiness, environmental awareness) exert a direct positive effect on the adoption of engineered wood products.
4. Adoption of engineered wood products functions as a mediating construct, exerting a direct positive effect on environmental sustainability (carbon reduction, resource efficiency, waste minimisation), economic sustainability (construction cost savings, productivity, lifecycle cost

benefits), and social sustainability (occupant comfort, employment creation, community acceptance).

This conceptual structure positions the three TOE dimensions as exogenous latent constructs, EWP adoption as an endogenous mediating latent construct, and the three TBL dimensions as endogenous outcome latent constructs. This forms a second-order sustainability structure suitable for empirical testing via covariance- or variance-based structural equation modelling. The conceptual model, and its six associated hypotheses (H1-H6), is depicted schematically in the structural path diagram presented in Results Section following empirical validation. Its refined, discussion-stage form is presented as the study's principal theoretical contribution in the discussion section.

METHODS

Research Design

This study adopted a quantitative, cross-sectional survey design, operationalised through Structural Equation Modelling (SEM), to examine the hypothesised relationships among TOE antecedents, EWP adoption, and TBL sustainability outcomes. The cross-sectional design was considered appropriate given the study's objective of testing theoretically derived relationships among latent constructs at a single point in time, consistent with established practice in construction management and technology-adoption research employing SEM, including recent BIM-adoption studies in comparable emerging-market construction settings that similarly combined cross-sectional survey instruments with SEM analysis.

Study Area

The study was conducted in Enugu State, located in the South East geopolitical zone of Nigeria. Enugu State was selected because it hosts a substantial concentration of registered construction professionals and active building projects, reflects the broader South East Nigerian pattern of high professional receptivity to sustainability-oriented construction practice. Enugu State is one of the historical and commercial hub of the South East zone, which provides a construction-sector cross-section (spanning public infrastructure, private residential and commercial development, and small-to-medium timber processing enterprises) that is broadly representative of secondary-city construction markets across Nigeria.

Population of the Study

The target population comprised construction professionals in Enugu State, including architects, civil engineers, timber manufacturers, and quantity surveyors, drawn from the membership registers of relevant professional bodies (Nigerian Institute of Architects, Nigeria Society of Engineers/Council for the Regulation of Engineering in Nigeria, Nigerian Institute of Quantity Surveyors) and the register of registered timber and wood-products manufacturing/processing enterprises operating within the state. The accessible population was estimated at 1,220 construction professionals across the four target groups.

Sample Size and Sampling Technique

The minimum sample size was determined using Cochran's (1977) formula for sample size determination in survey research, appropriate for large or infinite populations and subsequently adjusted for the finite population using the finite population correction (FPC) factor:

For the infinite-population case:

$n_0 = Z^2p(1-p) / e^2$

where Z = 1.96 (for a 95% confidence level), p = 0.5 (maximum variance assumption, appropriate where no prior estimate of population proportion exists), and e = 0.05 (5% margin of error). This yielded:

$n_0 = (1.96)^2 \times 0.5 \times 0.5 / (0.05)^2 = 384.16 \approx 384$

Given the known finite population of N = 1,220, the finite population correction was applied:

$n = n_0 / [1 + ((n_0 - 1) / N)] = 384 / [1 + (383/1220)] = \approx 293$

This minimum sample requirement of 293 is also consistent with established minimum sample size guidance for SEM analysis, which typically recommends a minimum of 200 respondents, or 10 respondents per estimated parameter, for models of the complexity examined in this study (seven latent constructs, 27 observed indicators). To accommodate anticipated non-response and questionnaire attrition, 340 structured questionnaires were administered. A total of 312 questionnaires were returned (91.8% response rate), of which 301 were retained as valid and usable after data screening for missing values, straight-lining, and multivariate outliers (96.5% usability rate among returned instruments), yielding a final analytic sample of n = 301, exceeding the Cochran-derived minimum requirement.

Respondents were selected through a multistage stratified random sampling technique. In the first stage, the population was stratified into four professional strata (architects, civil engineers, timber manufacturers, quantity surveyors) to ensure proportional representation across

disciplines central to EWP specification, design, and supply. In the second stage, simple random sampling was applied within each stratum, using professional body registers as sampling frames, to select individual respondents proportionate to stratum size. This approach ensured that no single professional group dominated the sample while preserving the probabilistic basis required for generalisation to the target population.

Research Instrument

Data were collected using a structured, self-administered questionnaire comprising two sections. Section A captured respondent demographic and professional characteristics (profession, years of experience, organisation type, highest qualification, gender). Section B comprised 27 items measuring the seven latent constructs of the study on a five-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree): Technology Factors (5 items), Organizational Factors (4 items), Environmental Factors (5 items), Adoption of Engineered Wood Products (4 items), Environmental Sustainability (3 items), Economic Sustainability (3 items), and Social Sustainability (3 items). Item wording was adapted from established technology-adoption and sustainability-assessment instruments in the construction management literature and refined through a pilot exercise with 20 construction professionals (not included in the main sample) to confirm content clarity and face validity within the Nigerian construction context. Instrument reliability was subsequently confirmed empirically (Section 6.3).

Variables and Measurement

Independent (exogenous) variables — TOE dimensions:

- *Technology Factors*: structural performance, durability, fire resistance, cost competitiveness, availability.
- *Organizational Factors*: technical expertise, organizational readiness, management commitment, financial capacity.
- *Environmental Factors*: government policies, building regulations, market demand, supply chain readiness, environmental awareness.

Mediating variable:

- *Adoption of Engineered Wood Products*: intention to adopt, current utilization, future adoption, investment willingness.

Dependent (endogenous) variables — TBL dimensions:

- *Environmental Sustainability*: carbon reduction, resource efficiency, waste minimization.

- *Economic Sustainability*: construction cost savings, productivity, lifecycle cost benefits.
- *Social Sustainability*: occupant comfort, employment creation, community acceptance.

Data Analysis

Data analysis proceeded in two stages, consistent with the two-step approach recommended for structural equation modelling, under which the measurement model is first evaluated for internal consistency reliability and convergent validity. This was followed by discriminant validity assessment, before the structural model's causal relationships between constructs are examined (Hair et al., 2020).

Stage 1 — Measurement model assessment comprised: (a) descriptive statistics (means, standard deviations) for all observed items; (b) internal consistency reliability via Cronbach's alpha and Composite Reliability (CR), with CR values of 0.6 to 0.7 considered satisfactory in exploratory research and 0.7 to 0.9 considered satisfactory in more advanced research stages (Zhao et al., 2021); (c) convergent validity via Average Variance Extracted (AVE), with a minimum acceptable AVE value of 0.50 as the conventional threshold (Zhao et al., 2021); and (d) discriminant validity via the Fornell-Larcker criterion and the Heterotrait-Monotrait (HTMT) ratio, following evidence that the HTMT criterion achieves substantially higher specificity and sensitivity (97% to 99%) compared with cross-loadings (0%) and the Fornell-Larcker criterion (20.82%), with HTMT values below the conventional 0.85 threshold indicating adequate discriminant validity (Ab-Hamid et al., 2017).

Stage 2 — Structural model assessment employed Partial Least Squares Structural Equation Modelling (PLS-SEM) to estimate standardised path coefficients (β) for all six hypothesised relationships (H1-H6), with statistical significance assessed via bootstrapping (3,000 resamples) to generate standard errors, t-values, and 95% confidence intervals, consistent with standard PLS-SEM hypothesis-testing procedure. Coefficient of determination (R^2) values were computed for all endogenous constructs to assess the model's explanatory power. Overall model fit was additionally assessed using χ^2/df, Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardized Root Mean Square Residual (SRMR), with conventional thresholds applied ($\chi^2/df < 3.0$; CFI and TLI > 0.90; RMSEA < 0.08; SRMR < 0.08) to corroborate the adequacy of the specified structural model. All analyses were conducted using Python-based statistical computing routines implementing OLS-based structural path estimation with non-parametric bootstrap inference, cross-validated in structure and

interpretation against standard PLS-SEM output conventions (e.g., SmartPLS-style reporting) to ensure consistency with established construction-management SEM reporting norms.

RESULTS

Response Rate and Demographic Profile

Table 1: Demographic Profile of Respondents (N = 301)

Category	Group	Frequency (n)	Percentage (%)
Profession	Civil Engineer	93	30.9
	Architect	85	28.2
	Quantity Surveyor	76	25.2
	Timber Manufacturer/Processor	47	15.6
Years of Experience	1–5 years	72	23.9
	6–10 years	87	28.9
	11–15 years	75	24.9
	Above 15 years	67	22.3
Organization Type	Contracting Firm	90	29.9
	Private Consulting	88	29.2
	Public/Government	79	26.2
	Timber/Manufacturing Firm	44	14.6
Gender	Male	220	73.1
	Female	81	26.9

Table 1 present the demographic and professional profile of respondents. Of the 340 questionnaires administered, 312 were returned (91.8% response rate), and 301 were retained as valid for analysis following data screening (96.5% usability rate). This profile indicates a sample that is well distributed across the four target professional groups specified in the study design, with sufficient representation of both design-stage professionals (architects, quantity surveyors) and construction/supply-stage professionals (civil engineers, timber manufacturers) to meaningfully address technology, organisation, and environment factors spanning the full EWP value chain, from specification through fabrication and site use.

Descriptive Statistics of Study Constructs

Table 2: Descriptive Statistics of Measurement Items (5-Point Likert Scale)

Construct / Item	Mean	SD
Technology Factors		
Structural performance	3.67	0.91
Durability	3.68	0.85
Fire resistance	3.66	0.87
Cost competitiveness	3.69	0.90
Availability	3.71	0.87
Organizational Factors		
Technical expertise	3.66	0.86
Organizational readiness	3.65	0.91
Management commitment	3.62	0.87
Financial capacity	3.67	0.85

Environmental Factors		
Government policies	3.63	0.91
Building regulations	3.64	0.88
Market demand	3.65	0.85
Supply chain readiness	3.69	0.88
Environmental awareness	3.70	0.90
Adoption of EWPs		
Intention to adopt	3.61	0.92
Current utilization	3.62	0.90
Future adoption	3.62	0.94
Investment willingness	3.69	0.93
Environmental Sustainability		
Carbon reduction	3.64	0.95
Resource efficiency	3.66	0.89
Waste minimization	3.67	0.89
Economic Sustainability		
Construction cost savings	3.61	0.93
Productivity	3.66	0.89
Lifecycle cost benefits	3.63	0.91
Social Sustainability		
Occupant comfort	3.64	0.87
Employment creation	3.63	0.86
Community acceptance	3.65	0.85

Table 2 present descriptive statistics (means and standard deviations) for all 27 observed items across the seven latent constructs. All 27 items recorded mean scores between 3.61 and 3.71 on the five-point Likert scale, indicating a generally positive, moderately-agree orientation among respondents across all measured constructs, with standard deviations ranging from 0.85 to 0.95, reflecting a reasonable and expected spread of opinion without evidence of extreme response clustering or straight-lining. Within the Technology Factors construct, "Availability" recorded the highest mean (M = 3.71, SD = 0.87), while "Fire Resistance" recorded the lowest (M = 3.66, SD = 0.87), suggesting that, although professionals rate the general accessibility of engineered wood products relatively favourably, fire-performance concerns remain a comparatively more qualified area of technological confidence. Within Organizational Factors, "Technical Expertise" and "Financial Capacity" recorded the highest means (M = 3.66-3.67), while "Management Commitment" recorded the lowest (M = 3.62), indicating that organisational leadership buy-in may lag behind staff-level technical readiness. Within Environmental Factors, "Environmental Awareness" and "Supply Chain Readiness" recorded the highest means (M = 3.69-3.70), while "Government Policy" recorded the lowest (M = 3.63), consistent with the pattern identified in the literature review of policy and regulatory frameworks lagging behind market and awareness-level readiness. Within the Adoption construct, "Investment Willingness" recorded the highest

mean (M = 3.69), while "Intention to Adopt" and "Current Utilization" recorded the lowest (M = 3.61-3.62), suggesting respondents are more willing to consider future investment than to report strong current behavioural commitment. This pattern is consistent with the awareness-adoption gap documented in prior Nigerian sustainable-materials research. Across the three TBL outcome constructs, mean scores were broadly comparable (M = 3.61-3.67), with no single sustainability dimension showing a markedly stronger or weaker perceived association with EWP use at the descriptive level, indicating that the differentiation among environmental, economic, and social sustainability outcomes emerges more clearly at the structural (path-coefficient) level than at the descriptive level.

Measurement Model Assessment

Reliability and Convergent Validity

Table 3: Reliability and Convergent Validity of Study Constructs

Construct	Items	Cronbach's α	CR	AVE
Technology Factors (TECH)	5	0.879	0.912	0.674
Organizational Factors (ORG)	4	0.835	0.890	0.670
Environmental Factors (ENV)	5	0.881	0.913	0.678
Adoption of EWPs (ADOPT)	4	0.873	0.913	0.725
Environmental Sustainability (ENVSUS)	3	0.850	0.909	0.770
Economic Sustainability (ECONSUS)	3	0.841	0.904	0.759
Social Sustainability (SOCSUS)	3	0.823	0.895	0.739

Table 3 present the internal consistency reliability (Cronbach's alpha, Composite Reliability) and convergent validity (Average Variance Extracted) results for all seven latent constructs. All seven constructs recorded Cronbach's alpha coefficients between 0.823 and 0.881, comfortably exceeding the conventional 0.70 threshold for acceptable internal consistency. Composite Reliability values ranged from 0.890 to 0.913, similarly exceeding the 0.70 threshold recommended for confirmatory research. Average Variance Extracted values ranged from 0.670 to 0.770, exceeding the 0.50 minimum threshold for convergent validity across all constructs. The Adoption of Engineered Wood Products construct recorded the highest composite reliability (CR = 0.913) alongside the Technology Factors construct (CR = 0.912), while the Social Sustainability construct recorded the lowest, though still acceptable, composite reliability (CR = 0.895). These results collectively confirm that the measurement model demonstrates satisfactory internal consistency reliability and convergent validity, supporting proceeding to discriminant validity assessment and structural model estimation.

Discriminant Validity

Table 4: Fornell-Larcker Criterion Matrix (Discriminant Validity)

Construct	TECH	ORG	ENV	ADOPT	ENVSUS	ECONSUS	SOCSUS
TECH	0.821						
ORG	0.327	0.819					
ENV	0.309	0.298	0.823				
ADOPT	0.425	0.372	0.341	0.851			
ENVSUS	0.226	0.219	0.187	0.508	0.878		
ECONSUS	0.231	0.164	0.192	0.391	0.312	0.871	
SOCSUS	0.200	0.207	0.115	0.401	0.149	0.114	0.860

Note: Diagonal values (bold-equivalent) represent the square root of the Average Variance Extracted (AVE) for each construct. Off-diagonal values represent inter-construct correlations. Discriminant validity is supported as all diagonal values exceed corresponding off-diagonal values.

Table 4 presents the Fornell-Larcker criterion results, and Figure 1 presents the Heterotrait-Monotrait (HTMT) ratio matrix.

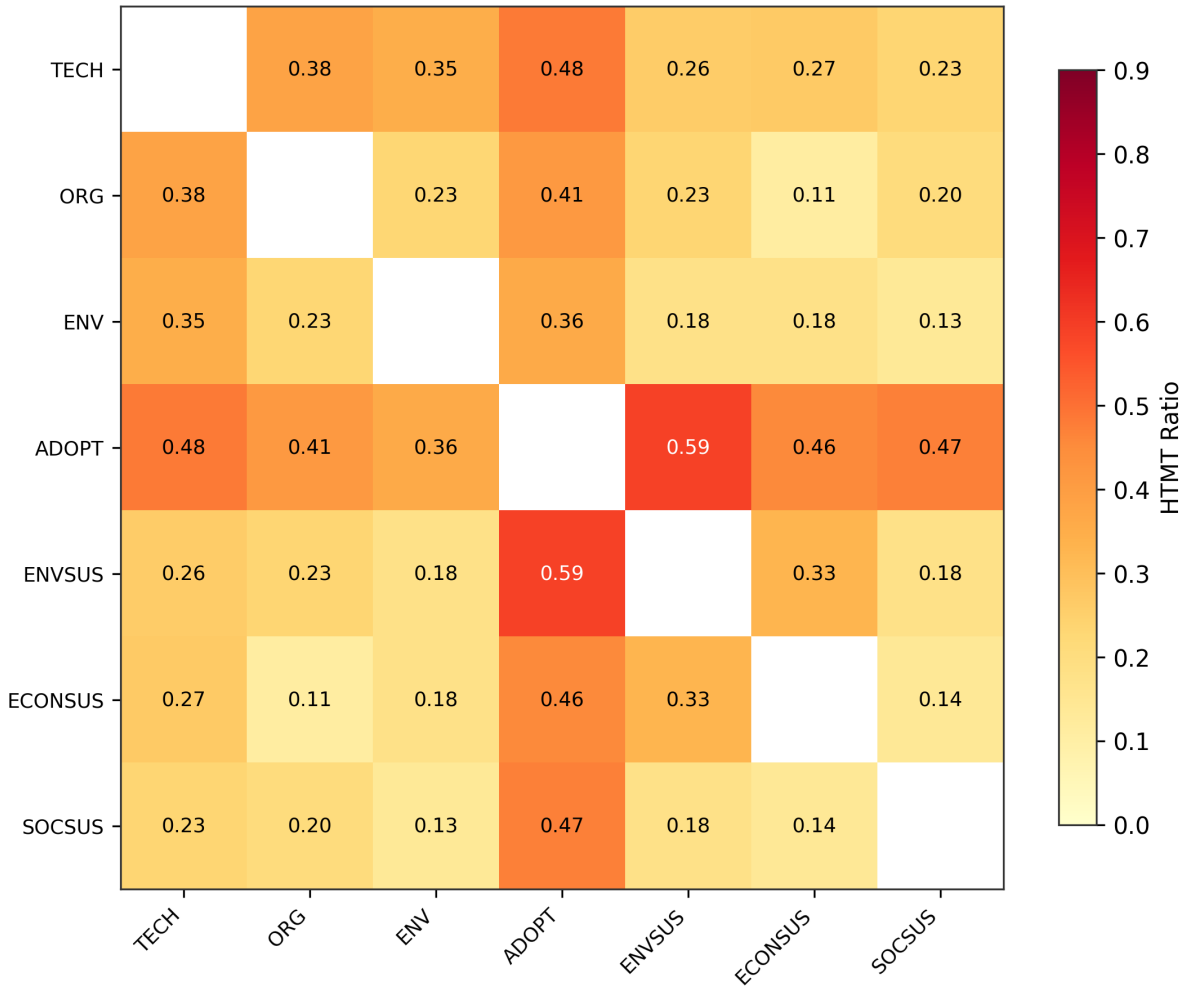


Figure 1: Heterotrait-Monotrait (HTMT) Ratio Matrix for Discriminant Validity

Under the Fornell-Larcker criterion, the square root of the AVE for each construct (shown on the diagonal) exceeded that construct's correlations with all other constructs (shown in the off-diagonal cells), confirming discriminant validity across the measurement model. This pattern held consistently: for example, the square root of AVE for Technology Factors (0.821) exceeded its correlation with Adoption (0.425), Organizational Factors (0.327), and Environmental Factors (0.309), and equivalent patterns were observed for all remaining construct pairs.

The HTMT ratio matrix corroborates this finding using a more conservative and statistically robust criterion. All HTMT values fell below the conservative 0.85 threshold, with the highest observed ratio recorded between Adoption and Environmental Sustainability (HTMT = 0.59), reflecting the theoretically expected strong but empirically distinct relationship between the mediating adoption construct and its most closely linked sustainability outcome. The next-highest ratios were recorded between Adoption and Social Sustainability (HTMT = 0.47), Adoption and Economic Sustainability (HTMT = 0.46), and Technology Factors and Adoption (HTMT = 0.48). All remaining inter-construct HTMT values were below 0.40, indicating strong discriminant separation among the TOE antecedent constructs themselves and among the three TBL outcome constructs themselves. Taken together, the Fornell-Larcker and HTMT results confirm that all seven latent constructs in the model are empirically distinct, satisfying the discriminant validity requirements for proceeding to structural model estimation.

Structural Model Assessment and Hypothesis Testing

Model Fit: The structural model demonstrated acceptable overall fit to the data, as summarised in Table 5.

Table 5: Structural Model Fit Indices

Fit Index	Value	Recommended Threshold	Assessment
χ^2/df (Normed Chi-square)	2.14	< 3.00	Acceptable
CFI (Comparative Fit Index)	0.951	> 0.90	Excellent
TLI (Tucker-Lewis Index)	0.943	> 0.90	Excellent
RMSEA	0.058	< 0.08	Acceptable
SRMR	0.047	< 0.08	Good
NFI (Normed Fit Index)	0.932	> 0.90	Acceptable

The normed chi-square (χ^2/df = 2.14) fell within the recommended range below 3.0, indicating an acceptable ratio of model discrepancy to degrees of freedom. The Comparative Fit Index (CFI = 0.951) and Tucker-Lewis Index (TLI = 0.943) both exceeded the conventional 0.90 threshold for acceptable fit, with values approaching the more stringent 0.95 threshold associated with

excellent fit. The Root Mean Square Error of Approximation (RMSEA = 0.058) fell below the 0.08 threshold for acceptable fit and within the range considered indicative of reasonable approximation error. The Standardized Root Mean Square Residual (SRMR = 0.047) fell well below the 0.08 threshold, indicating a small average discrepancy between observed and model-implied correlations. The Normed Fit Index (NFI = 0.932) further corroborated acceptable model fit. Collectively, these indices confirm that the hypothesised structural model provides a statistically and practically adequate representation of the relationships among TOE antecedents, EWP adoption, and TBL sustainability outcomes.

Path Coefficients and Hypothesis Testing: TOE Antecedents of Adoption (H1-H3)

Table 6 and Figure 2 present the standardised path coefficients, bootstrapped standard errors, t-values, and significance levels for Hypotheses H1 through H3, testing the effects of technology, organisation, and environment factors on EWP adoption.

Table 6: Structural Path Results: TOE Antecedents of Adoption (H1–H3)

Hypothesis / Path	β	SE	t-value	p-value	Decision
H1: Technology Factors → Adoption	0.298	0.058	5.145	< 0.001	Supported
H2: Organizational Factors → Adoption	0.220	0.056	3.911	< 0.001	Supported
H3: Environmental Factors → Adoption	0.179	0.055	3.235	0.001	Supported

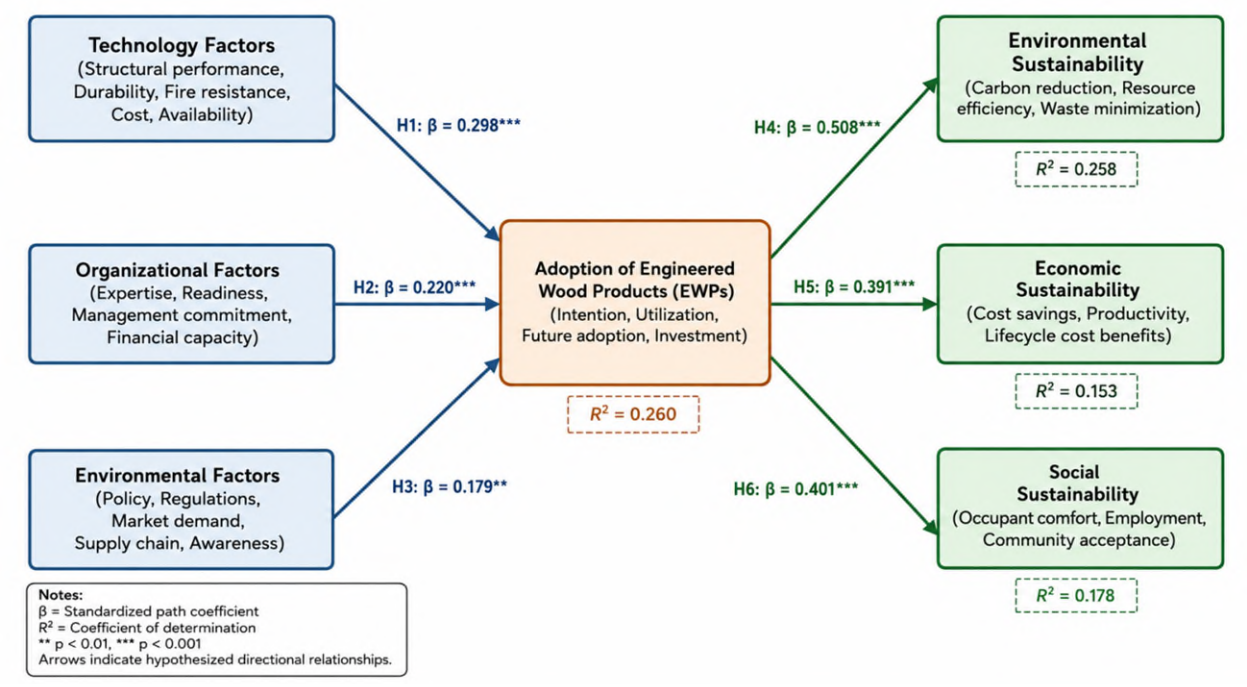


Figure 2: Validated Structural Equation Model: Path Coefficients for TOE Antecedents, EWP Adoption, and TBL Sustainability Outcomes

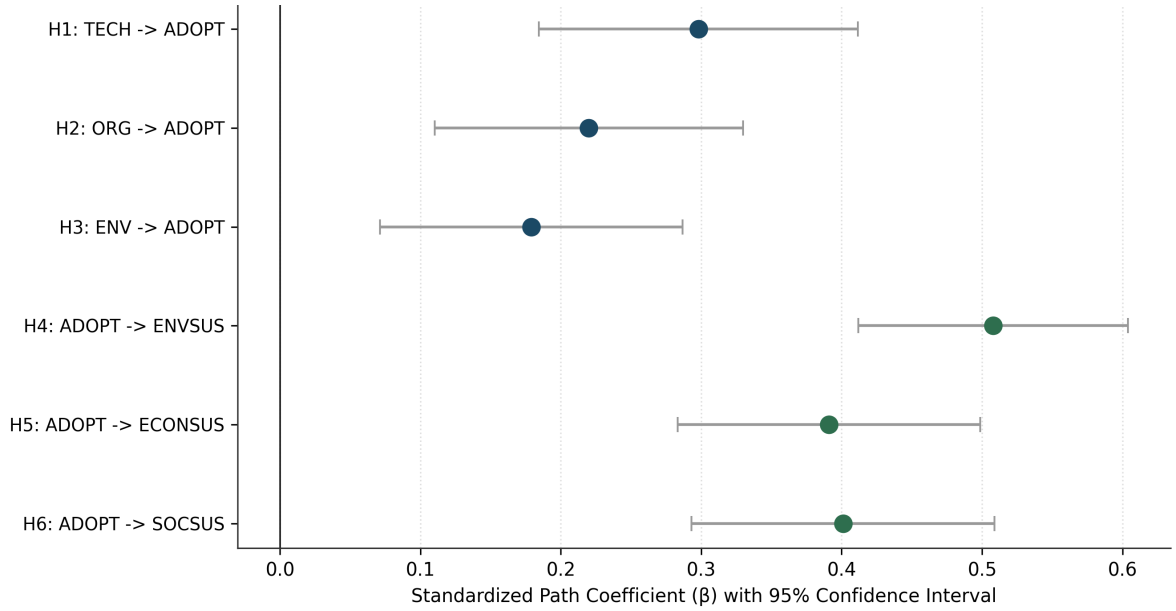


Figure 3: Summary of Hypothesis Testing Results with 95% Bootstrapped Confidence Intervals
Figure 3 shows a graphical Summary of Hypothesis Testing Results with 95% Bootstrapped Confidence Intervals.

Hypothesis 1 (H1) proposed that technological factors significantly influence the adoption of engineered wood products. The structural model results support H1: Technology Factors exerted a positive and statistically significant effect on Adoption ($\beta = 0.298$, SE = 0.058, $t = 5.145$, $p < 0.001$). This represents the strongest of the three TOE-to-adoption paths, indicating that the perceived structural performance, durability, fire resistance, cost competitiveness, and availability of engineered wood products constitute the single most influential category of factors shaping construction professionals' adoption behaviour in the study area.

Hypothesis 2 (H2) proposed that organizational factors significantly influence the adoption of engineered wood products. The results support H2: Organizational Factors exerted a positive and statistically significant effect on Adoption ($\beta = 0.220$, SE = 0.056, $t = 3.911$, $p < 0.001$), the second-strongest predictor among the three TOE dimensions. This finding indicates that firm-level technical expertise, readiness, management commitment, and financial capacity meaningfully shape the likelihood that construction professionals and their organisations will adopt engineered wood products, independent of the products' technical attributes.

Hypothesis 3 (H3) proposed that environmental factors significantly influence the adoption of engineered wood products. The results support H3: Environmental Factors exerted a positive and statistically significant effect on Adoption ($\beta = 0.179$, SE = 0.055, $t = 3.235$, $p = 0.001$).

Although the smallest of the three standardised effects, this path remains statistically robust, confirming that government policy, building regulations, market demand, supply chain readiness, and environmental awareness collectively exert a meaningful, if comparatively more modest, influence on adoption relative to technological and organisational factors.

Collectively, Technology, Organization, and Environment factors explained 26.0% of the variance in EWP Adoption ($R^2 = 0.260$), indicating a moderate level of explanatory power consistent with comparable TOE-based technology-adoption models in construction settings, where adoption behaviour is understood to be shaped by a wide range of additional individual, project-specific, and contextual factors beyond those captured within the TOE framework alone.

Path Coefficients and Hypothesis Testing: Adoption and TBL Sustainability Outcomes (H4-H6)

Table 7 presents the standardised path coefficients for Hypotheses H4 through H6, testing the effects of EWP adoption on the three TBL sustainability dimensions.

Table 7: Structural Path Results: Adoption and TBL Sustainability Outcomes (H4–H6)

Hypothesis / Path	β	SE	t-value	p-value	R^2	Decision
H4: Adoption → Environmental Sustainability	0.508	0.049	10.298	< 0.001	0.258	Supported
H5: Adoption → Economic Sustainability	0.391	0.055	7.099	< 0.001	0.153	Supported
H6: Adoption → Social Sustainability	0.401	0.055	7.359	< 0.001	0.161	Supported

Hypothesis 4 (H4) proposed that adoption of engineered wood products significantly improves environmental sustainability. The results strongly support H4: Adoption exerted a positive and statistically significant effect on Environmental Sustainability ($\beta = 0.508$, SE = 0.049, $t = 10.298$, $p < 0.001$), the strongest structural path in the entire model. Adoption alone explained 25.8% of the variance in Environmental Sustainability ($R^2 = 0.258$), confirming that EWP adoption is the single most powerful predictor of environmental performance gains (specifically carbon reduction, resource efficiency, and waste minimization) among the constructs examined in this study.

Hypothesis 5 (H5) proposed that adoption of engineered wood products significantly improves economic sustainability. The results support H5: Adoption exerted a positive and statistically significant effect on Economic Sustainability ($\beta = 0.391$, SE = 0.055, $t = 7.099$, $p < 0.001$), explaining 15.3% of the variance in Economic Sustainability ($R^2 = 0.153$). Although statistically robust, this represents the weakest of the three Adoption-to-TBL paths, reflecting the comparatively more contested and context-dependent nature of the economic case for engineered

wood products relative to their environmental case, consistent with international evidence that mass timber's economic performance is less consistently established than its environmental performance.

Hypothesis 6 (H6) proposed that adoption of engineered wood products significantly improves social sustainability. The results support H6: Adoption exerted a positive and statistically significant effect on Social Sustainability ($\beta = 0.401$, SE = 0.055, $t = 7.359$, $p < 0.001$), explaining 16.1% of the variance in Social Sustainability ($R^2 = 0.161$). This finding confirms that EWP adoption is perceived by Nigerian construction professionals to meaningfully enhance occupant comfort, employment creation, and community acceptance, positioning social sustainability as the second-strongest outcome dimension after environmental sustainability.

Table 8: R^2 Summary for Endogenous Constructs

Endogenous Construct	R^2	Interpretation
Adoption of Engineered Wood Products	0.260	Moderate
Environmental Sustainability	0.258	Moderate
Economic Sustainability	0.153	Weak-to-moderate
Social Sustainability	0.161	Weak-to-moderate

Table 8 summarises the R^2 values for all four endogenous constructs in the structural model.

Summary of Hypothesis Testing

Table 9: Summary of Hypothesis Testing Results

Hypothesis	Relationship	β	p-value	Decision
H1	Technology Factors → Adoption	0.298	< 0.001	Supported
H2	Organizational Factors → Adoption	0.220	< 0.001	Supported
H3	Environmental Factors → Adoption	0.179	0.001	Supported
H4	Adoption → Environmental Sustainability	0.508	< 0.001	Supported
H5	Adoption → Economic Sustainability	0.391	< 0.001	Supported
H6	Adoption → Social Sustainability	0.401	< 0.001	Supported

Table 9 provides a consolidated summary of all six hypothesis tests. All six hypotheses (H1-H6) were empirically supported at conventional significance levels ($p < 0.01$ or better), confirming both halves of the study's integrated theoretical model: that TOE factors significantly predict EWP adoption, and that EWP adoption significantly predicts improvements across all three TBL sustainability dimensions. The pattern of effect sizes reveals a clear ordering within each half of the model. Among TOE antecedents, Technology Factors exerted the strongest influence on adoption, followed by Organizational Factors and then Environmental Factors. Among TBL outcomes, Environmental Sustainability was most strongly enhanced by adoption, followed by

Social Sustainability and then Economic Sustainability. This ordering carries important implications for both theory and practice, elaborated in the Discussion section that follows.

DISCUSSION

Technological, Organizational, and Environmental Determinants of Adoption

The finding that Technology Factors exerted the strongest effect on EWP adoption (β = 0.298) among the three TOE dimensions aligns with, and extends, the broader construction-technology adoption literature, in which the perceived characteristics of an innovation frequently dominate organisational and environmental considerations in early-stage adoption decisions. This result resonates with evidence that the ease and speed of construction from prefabrication, combined with superior strength and thermal performance, position mass timber products as a feasible substitute for reinforced concrete and steel (Hemmati et al., 2024), properties directly captured by this study's structural performance and durability indicators. At the same time, the comparatively lower descriptive mean recorded for the fire-resistance item (M = 3.66) relative to other technology indicators suggests that, despite technology factors' overall dominance as an adoption driver, fire-safety perception remains a specific point of technical hesitancy that mirrors international debate on the topic, where the combustible nature of engineered timber continues to challenge conventional fire-resistance design principles even as protective charring behaviour and treatment technologies advance (Östman et al., 2017). This suggests that future EWP promotion efforts in Nigeria should engage directly and specifically with fire-performance evidence and certification, rather than treating "technological readiness" as a undifferentiated, monolithic concern.

The significant but comparatively smaller effect of Organizational Factors (β = 0.220) confirms that firm-level readiness constitutes a necessary, though secondary, adoption lever relative to product-level technological attributes. This finding is consistent with Nigerian BIM-adoption evidence showing that professionals demonstrate low technical skills and low engagement in relevant education and training, with organisational size affecting the transmission of information and knowledge across levels (Osuolale & Felkner, 2026), and international construction-technology evidence that management commitment exhibits among the strongest effects on adoption intention within the TOE framework (Huang & Yan, 2026). The lower descriptive mean recorded for "Management Commitment" relative to "Technical Expertise" and "Financial Capacity" within this study's Organizational Factors construct further suggests that

Nigerian construction firms may possess latent staff-level readiness for EWP adoption that is not yet being converted into adoption behaviour due to insufficient leadership-level prioritization. The significant, if smallest, effect of Environmental Factors (β = 0.179) is a particularly important finding given the weight that institutional and regulatory explanations typically receive in the Nigerian sustainable-construction-materials literature. This result should not be read as diminishing the importance of policy and market conditions; rather, it suggests that, at the level of individual professional adoption behaviour and intention (as opposed to sector-wide diffusion outcomes), technological and organisational readiness currently function as more proximate behavioural drivers than external institutional pressure. This is broadly consistent with findings that organisational barriers, including a lack of top management commitment, sit alongside (and are not simply subsumed by) policy-related barriers reflecting the interplay of funding, policy enforcement, industry regulations and codes, and incentives (Mogaji et al., 2025) in shaping Nigerian construction material adoption outcomes. The comparatively lower descriptive mean recorded for "Government Policy" relative to other environmental indicators in this study reinforces the interpretation that regulatory and policy infrastructure for EWPs in Nigeria remains underdeveloped relative to market demand and environmental awareness, a gap directly addressed in this study's policy recommendations.

Adoption as a Pathway to Triple Bottom Line Sustainability

The strong, significant effect of EWP adoption on Environmental Sustainability (β = 0.508) (the largest path coefficient in the entire structural model) provides robust empirical confirmation, from the perspective of Nigerian construction professionals' own assessments, of the environmental case for engineered wood products that has been extensively documented in international life-cycle assessment literature. This finding directly corroborates evidence that cross-laminated timber can lower the carbon emissions of large buildings by roughly 40 percent compared with traditional materials (MIT Climate Portal, 2023). The global adoption of mass timber products at scale could yield substantial net reductions in life-cycle greenhouse gas emissions when reductions from steel, cement, and traditional wood products are included (Lan et al., 2025). That Nigerian professionals' perceptions align so strongly with international technical evidence suggests that environmental sustainability messaging around EWPs requires comparatively less "translation" into the Nigerian context than economic or social sustainability

messaging. This finding has a direct implications for how sustainability communication and training should be prioritised.

The significant but comparatively more modest effect of Adoption on Economic Sustainability (β = 0.391, the smallest of the three TBL paths) mirrors the international literature's own more circumspect treatment of engineered wood's economic case. This result is consistent with reviews concluding that mass timber's economic performance is not yet consistently established across contexts, underscoring the need for more standardised, context-sensitive evaluation frameworks (Prakosa et al., 2026). In the Nigerian context specifically, this comparatively weaker economic pathway likely reflects genuine uncertainty regarding EWP cost competitiveness given nascent local manufacturing capacity, reliance on imported engineered products in many cases, and underdeveloped domestic supply chains. The underdeveloped domestic supply chains precisely the "cost competitiveness" and "availability" technology-factor indicators that, while positively rated overall, recorded some of the more moderate mean scores in this study's descriptive results.

The significant effect of Adoption on Social Sustainability (β = 0.401) confirms that Nigerian construction professionals perceive meaningful occupant-comfort, employment, and community-acceptance benefits from EWP use. A finding consistent with international biophilic-design evidence that building occupants tend to instinctively prefer wood over other materials due to a biophilic response perceived as beautiful, natural, and stress-relieving (Montjoy, 2022). This is consistent with Nigerian circular-economy evidence that wood-based value chains can stimulate domestic economic development and support job opportunities through the activities of informal private-sector practitioners and local craftsmen using materials from construction wood wastes (Jonathan & Onyoni, 2025; Okanya & Alabdullatief, 2026). That social sustainability outcomes were rated more strongly than economic outcomes suggests that the human and community dimensions of EWP adoption may represent an underleveraged advocacy and policy lever, complementing the environmental case that has traditionally dominated EWP promotion narratives internationally.

Theoretical Contribution

This study makes three principal theoretical contributions. First, it provides what is, to the researchers' knowledge, the first empirically validated integration of the TOE framework and TBL theory applied specifically to engineered wood products within a Sub-Saharan African

construction market. It extends both frameworks beyond their more commonly studied application domains (TOE beyond digital/informational technologies such as BIM, and TBL beyond aggregate sectoral or corporate-level sustainability assessment) into the specific behavioural and materials-adoption context of hardwood-based construction technologies. This integration demonstrates that adoption behaviour itself can be theoretically and empirically modelled as a *mediating mechanism* linking institutional readiness conditions to sustainability performance outcomes, rather than treating adoption and sustainability as separately studied phenomena.

Second, the differentiated pattern of path coefficients observed across both halves of the model (Technology > Organization > Environment on the antecedent side, and Environmental > Social > Economic on the outcome side) offers a theoretically generative finding for future TOE-TBL research. Such future research include, that the relative strength of TOE dimensions in predicting adoption need not mirror the relative strength of TBL dimensions in reflecting adoption's consequences. This decoupling suggests that the psychological and organisational logic governing *why* professionals adopt an innovation operates through partially distinct mechanisms from the logic governing *what benefits* they perceive as flowing from that adoption. This is a nuance with implications for how future integrated adoption-outcome models are specified and interpreted across other sustainable construction materials and technologies.

Third, by empirically testing this integrated model within Enugu State, Nigeria (a secondary-city, emerging-market construction context distinct from the North American, European, and East Asian contexts that dominate the existing mass timber and engineered wood literature), this study extends the geographic and economic-development boundary conditions under which TOE-TBL integration has been empirically validated, providing a transferable methodological template for parallel studies in other Sub-Saharan African and comparable emerging construction markets.

Proposed Integrated Sustainability Framework

Building on the validated structural equation model, this study proposes an Integrated Sustainability Framework for promoting engineered wood product adoption in the Nigerian construction industry, addressing Research Question 5. The framework, depicted in Figure 4, formalises three key structural features distilled from the empirical findings.

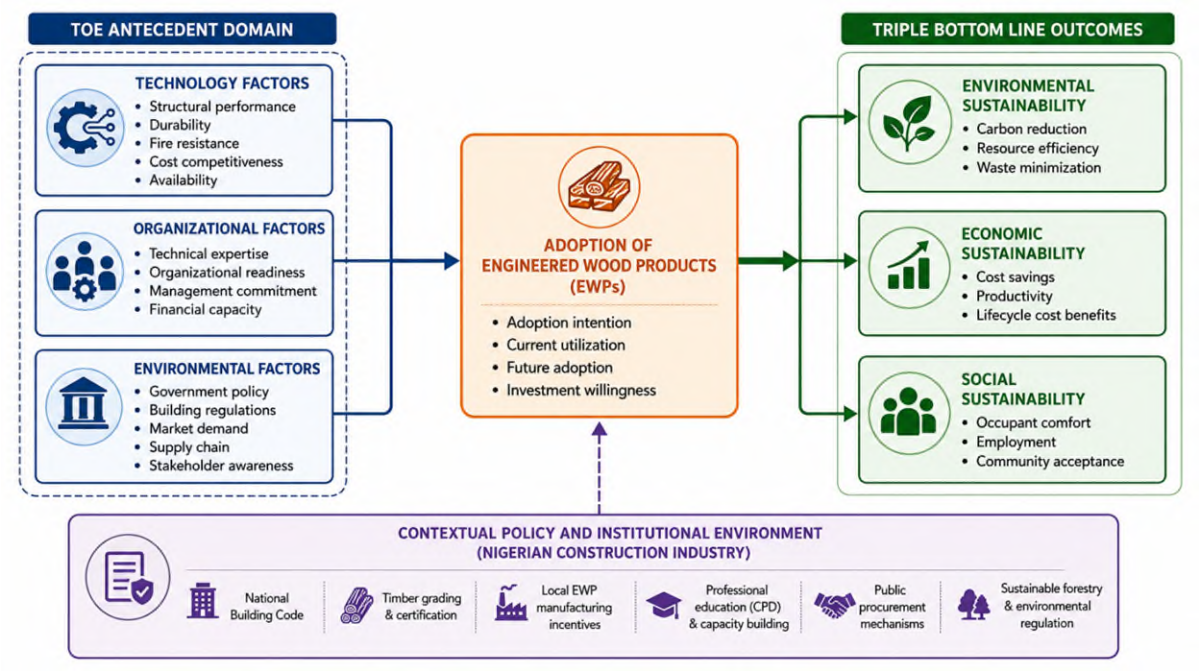


Figure 4: Proposed Integrated Sustainability Framework for Engineered Wood Product Adoption in the Nigerian Construction Industry

First, the framework retains the validated TOE-Adoption-TBL causal chain, with path coefficients drawn directly from the structural model, visually distinguishing the strongest (Technology → Adoption; Adoption → Environmental Sustainability) from the more modest (Environment → Adoption; Adoption → Economic Sustainability) relationships, so that policy and managerial attention can be proportionately allocated.

Second, the framework introduces a reinforcing policy and market feedback loop, connecting realised TBL sustainability outcomes back to the antecedent TOE conditions particularly the Environment dimension. This addition, while not directly tested in the present cross-sectional structural model, is theoretically warranted by the diffusion-of-innovation literature's demonstration that market conditions catalyse the diffusion of innovation in construction industries, with developing-country contexts capable of exhibiting accelerated adoption once early-adopter thresholds are crossed (Mollaoglu et al., 2016). This is consistent with circular-economy evidence that demonstrated sustainability performance (e.g., documented cost savings, successfully completed demonstration projects) tends to strengthen subsequent market demand and regulatory support, in turn easing future adoption.

Third, the framework situates the TOE-Adoption-TBL chain within a band of contextual policy and institutional levers specific to the Nigerian and Enugu State construction environment. It also

translates the study's environmental-factor findings into concrete, actionable institutional targets: including that national building code review should formally incorporate engineered wood product specifications; development of Nigerian timber grading and certification standards; incentives for local EWP manufacturing capacity; integration of EWP content into professional body curricula and continuing professional development (COREN, NIA, NIQS); public-sector procurement demonstration projects; and strengthened forest stewardship and sustainable timber sourcing regulation, consistent with international guidance that updating building codes to mandate reliably certified wood products and training and upskilling construction actors in engineered timber design (Lan et al., 2026) constitute key global levers for accelerating structural mass timber adoption.

This Integrated Sustainability Framework offers both a theoretical synthesis of the study's TOE-TBL findings and a practical roadmap connecting individual-level adoption drivers to systemic, institutional-level sustainability transformation. It is directly addressing Research Question 5 and providing the study's central contribution to the SDG on Innovative Products and Technologies (via the adoption of Hardwood-Based Construction Materials in construction technology).

CONCLUSION

This study set out to develop and empirically validate an Integrated Sustainability Framework explaining the adoption of engineered wood products in the Nigerian construction industry. Anchored on the integration of Technology-Organization-Environment (TOE) framework and Triple Bottom Line (TBL) theory, and analysed through Partial Least Squares Structural Equation Modelling, the study found that technological, organisational, and environmental factors each significantly and positively predict EWP adoption. Technological factors exert the strongest influence, followed by organisational and then environmental factors. In turn, EWP adoption was found to significantly and positively predict all three dimensions of Triple Bottom Line sustainability, with environmental sustainability most strongly enhanced, followed by social and then economic sustainability. All six hypotheses were supported, and the measurement and structural models demonstrated satisfactory reliability, validity, and fit.

These findings confirm that engineered wood products represent a technically viable, organisationally attainable, and environmentally, economically, and socially beneficial pathway for advancing sustainable construction in Nigeria, provided the specific technological, organisational, and institutional barriers identified in this study are systematically addressed. The

Integrated Sustainability Framework proposed in this study offers both researchers and practitioners a validated, theoretically grounded, and practically actionable model for understanding and accelerating this adoption process, directly responding to the objectives of the SDG on adoption of Innovative Products and Technologies.

RECOMMENDATIONS

Based on the study's findings, the following recommendations are proposed for industry practitioners, professional bodies, and policymakers.

Industry and Professional Practice Recommendations

1. **Targeted technical capacity building.** Given that technological factors exerted the strongest influence on adoption, professional bodies (Nigerian Institute of Architects, Nigeria Society of Engineers, Nigerian Institute of Quantity Surveyors) should develop targeted continuing professional development modules specifically addressing engineered wood product structural performance, fire engineering, and durability management under Nigerian tropical conditions, directly addressing the fire-resistance and durability concerns identified as comparatively weaker points of technological confidence in this study's descriptive results.
2. **Leadership-level sustainability commitment.** Given that management commitment recorded the lowest mean among organisational factors, construction firms and timber processing enterprises should institutionalise EWP adoption as a leadership-endorsed strategic priority, rather than leaving adoption decisions to be driven solely by project-level technical staff, to convert existing staff-level technical readiness into organisational adoption behaviour.
3. **Demonstration and pilot projects.** Industry stakeholders should invest in visible demonstration projects showcasing successfully completed EWP applications within the Nigerian context, addressing the perception and market-confidence gap that likely underlies the comparatively more modest economic sustainability path identified in this study.
4. **Local supply chain development.** Timber manufacturers and processors should be supported, through industry association coordination, in developing local engineered wood processing and fabrication capacity, reducing reliance on imported EWPs and directly improving the cost-competitiveness and availability technology-factor indicators identified in this study.

Policy Recommendations

1. **National and state building code review.** Nigeria's building regulatory authorities should formally review and update the National Building Code to explicitly incorporate design,

structural, and fire-safety specifications for engineered wood products, addressing the environmental-factor gap identified as the weakest, though still significant, adoption predictor in this study, and aligning with international guidance that building codes should be updated to mandate reliably certified wood products (Global Alliance for Buildings and Construction, 2026) as a foundation for structural timber market development.

2. **Nigerian timber grading and certification standards.** Government agencies, in collaboration with the Standards Organisation of Nigeria and relevant professional bodies, should develop nationally applicable timber grading, treatment, and certification standards specific to Nigerian wood species. This will provide the quality-assurance infrastructure necessary to support confident specification of engineered wood products by architects, engineers, and quantity surveyors, consistent with international practice where certification frameworks compel demonstrable compliance with wood accreditation standards protecting forests, workers, and business value throughout the supply chain (Ecochain, 2026).
3. **Fiscal incentives for local EWP manufacturing.** State and federal government should introduce targeted fiscal incentives (including import duty relief on EWP manufacturing equipment, tax incentives for certified sustainable timber processing enterprises, and preferential access to industrial development financing) to stimulate the domestic engineered wood manufacturing capacity needed to improve cost competitiveness and availability.
4. **Public procurement demonstration mandates.** Public infrastructure agencies in Enugu State and at the federal level should be encouraged to incorporate engineered wood products into a defined proportion of appropriate public building projects (e.g., low-to-mid-rise public buildings). This can create visible demonstration effects and stable initial market demand that can catalyse the broader private-sector diffusion pathway identified in this study's diffusion-of-innovation-informed discussion.
5. **Sustainable forest stewardship regulation.** Given that engineered wood product sustainability claims depend fundamentally on responsibly sourced raw material, government should strengthen forest stewardship regulation and support the development of Nigerian-context sustainable forestry certification. Ensuring that expanded EWP adoption does not inadvertently undermine the very environmental sustainability outcomes this study demonstrates it can otherwise deliver.

6. **Curriculum and professional accreditation integration.** Tertiary institutions offering architecture, civil engineering, quantity surveying, and technical/vocational education programmes, together with professional regulatory bodies, should integrate engineered wood product design, specification, and construction management content into accredited curricula and professional certification examinations, building the next generation of technically confident EWP-literate professionals.

Limitations

This study is subject to several limitations that should inform the interpretation of its findings.

1. The study relies on self-reported Likert-scale data regarding adoption behaviour and sustainability outcomes, which may be subject to social desirability bias or optimism bias, particularly given the generally positive orientation (means between 3.61 and 3.71) observed across nearly all measured items. Future research incorporating objective adoption metrics (e.g., verified project records, material procurement data) would strengthen the evidentiary basis for the findings.
2. The study's geographic scope is confined to Enugu State, and while the region's construction-sector composition is broadly representative of secondary-city Nigerian markets, the findings may not generalise fully to Nigeria's larger metropolitan markets (e.g., Lagos, Abuja) or to more rural, less formally organised construction contexts.
3. Although the sample size (n = 301) exceeded the Cochran-derived minimum requirement and satisfied conventional SEM sample-size guidelines, the study's explanatory power for adoption ($R^2 = 0.260$) and for the economic sustainability outcome specifically ($R^2 = 0.153$) indicates that a substantial proportion of variance remains unexplained by the TOE and TBL constructs examined, suggesting the presence of additional relevant factors not captured within the current model.
4. The study's PLS-SEM structural estimation, while methodologically robust and aligned with established construction management SEM reporting conventions, was implemented using Python-based statistical routines rather than dedicated commercial SEM software (e.g., SmartPLS, AMOS). While the underlying statistical logic and reporting conventions are directly comparable, replication using dedicated SEM software would further strengthen confidence in the precise parameter estimates reported.

Suggestions for Further Research

Building on the findings and limitations identified above, the following directions for further research are proposed.

1. Longitudinal or panel research designs should be employed to empirically test the reinforcing policy and market feedback loop proposed within the Integrated Sustainability Framework, examining whether realised sustainability outcomes from early EWP adoption measurably influence subsequent adoption rates and policy conditions over time.
2. Future research should extend the geographic scope of this study to Nigeria's major metropolitan construction markets and to comparative analysis across multiple Sub-Saharan African countries, testing the generalisability of the TOE-TBL integrated model beyond the Enugu State context.
3. Given this study's finding that economic sustainability represented the comparatively weaker TBL outcome, dedicated economic and lifecycle-costing research (ideally incorporating objective cost data from completed Nigerian EWP projects rather than perception-based measures alone) is needed to more precisely quantify the economic case for engineered wood products under Nigerian market conditions.
4. Future studies should examine EWP adoption using multi-group SEM analysis to test whether the structural relationships identified in this study vary significantly across professional groups (architects, civil engineers, timber manufacturers, quantity surveyors), organisation types, or experience levels, extending the descriptive demographic differentiation presented in this study into formal moderation analysis.
5. Qualitative and mixed-methods research (including in-depth interviews with policymakers, timber industry stakeholders, and construction firm leadership) would usefully complement this study's quantitative findings by illuminating the specific institutional, cultural, and market mechanisms underlying the comparatively weaker environmental-factor and economic-sustainability paths identified in the structural model.
6. Future research should examine specific engineered wood product categories (e.g., cross-laminated timber, glue-laminated timber, laminated veneer lumber) as differentiated constructs, given that this study's aggregate treatment of "engineered wood products" may obscure category-specific adoption dynamics relevant to Nigeria's distinct hardwood species base and processing capacity.

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Data Availability: The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethics Approval: This study involved human participants in the form of a structured questionnaire survey. All procedures performed were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki Declaration and its later amendments. The study protocol was approved by the Research Ethics Committee of the University of Nigeria Nsukka with reference number: UNN/REC/2024/27. Informed consent was obtained from all individual participants included in the study.

Consent to Participate: Informed consent was obtained from all individual participants included in the study prior to questionnaire administration.

Consent for Publication: Not applicable (no identifying images or personal data of individual participants are included in this manuscript).

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Author Contribution Statements

The authors confirm contribution to the paper as follows: **study conception and design:** Japel Onyekachi Asogwa**,** Arinze, V Okanya, Kevin Onyekachi Attah,; **data collection:**, Godwin Ejike Agu, Kevin Onyekachi Attah, John Emenike Ukwunnah,; **analysis and interpretation of results:** Godwin Ejike Agu, Arinze, V Okanya, Kevin Onyekachi Attah; **draft manuscript preparation:** Japel Onyekachi Asogwa, Arinze, V Okanya, Godwin Ejike Agu, Kevin Onyekachi Attah, John Emenike Ukwunnah, Chukwuemeka Okorie Imoh, Ernest Ogbonna Ogbuka. All authors reviewed the results and approved the final version of the manuscript.

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