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Sustainability and Performance of Natural Adhesives in Humid Tropical Climates: A Systematic Review and Meta-Analysis with Case Evidence from Nigeria

NLEMCHUKWU BENEDICT NWANNEKA CHUKWUEZOLAHAM[1], MADU MERCY CHIDINMA[2], OKORO NKECHINYERE JUSTINA[3], NWANKWO NJIDEKA VERONICA[4], ANUONYE CHRISTIAN OKECHUKWU[5]

[1, 2, 3]*Department of Chemistry, University of Agriculture and Environmental Sciences Umuagwo, Owerri, Imo State, Nigeria*

[4]*Nnamdi Azikiwe University Awka, Anambra State*

[5]*Chukwuemeka Odumegwu Ojukwu University, Uli Anambra State*

Abstract- Gum arabic, cassava starch, chitosan, lignin are natural adhesives that use renewable sources, and are gaining momentum as substitutes to synthetic adhesives in response to environmental concerns. Yet, to be effective in humid tropical climates, which are characterised by high relative humidity (>80%), high temperatures (25-35 C) and moisture, their effectiveness needs to be systematically tested. This is a review of evidence on performance measurements (bond strength, durability) and sustainability (environmental impact, economic viability), including meta-analysis and a case study of Nigeria. Following PRISMA 2020, searched PubMed, Scopus, Web of Science, Google Scholar, and African Journals Online between January 1990 and August 2025. Eligibility Studies on natural adhesives in humid/tropical conditions that have quantitative results. Records were screened by two reviewers (kappa=0.87); quality determined with Newcastle-Ottawa Scale and Cochrane RoB 2. Random-effects models in R (metafor package) were employed in the meta-analysis of shear strength with subgroup analyses performed according to adhesive type and GRADE certainty. Out of 1,456 records, 78 studies have been included (45 old, 33 new). A meta-analysis (n=22 studies, 612 samples) provided a result as to dry shear strength of 3.58 MPa (95% CI: 2.45-4.71; I 2=73, p<0.001) and wet shear of 1.78 MPa (95% CI: 1.05-2.51; I 2=77, p<0.001). Gum arabic was tough (wet: 1.62 MPa), cassava starch greater dry strength (4.25 MPa). Sustainability: 35-65% lower CO2 emissions. Nigerian cases: gum arabic in particleboards resisted 90% RH. Natural adhesives would work reasonably well in moist tropics with modifications, and would have sustainability advantages. Policy suggestions: support local manufacture in Nigeria to adapt to climate.

Keywords: Natural Adhesives, Gum Arabic, Cassava Starch, Humid Tropics, Sustainability, Meta-Analysis, Nigeria, Bio-based Polymers, Water Resistance.

I. INTRODUCTION

Adhesives play a very important role in the construction, woodworking, packaging, and automobile manufacturing industries, to provide structural integrity, and bonding of the materials. But under humid tropical conditions, the relative humidity degree can be extremely high over 80 percent of it, average temperature is 25-35 degrees C, and precipitation is high, the workability of traditional adhesives is severely impaired. Such environmental factors favour absorption of moisture, hydrolysis and microbial decay, resulting in low bond strength, delamination, and early failure (Soebiyan et al., 2023; Olufayo and Ogunkunle, 1996). As an example, in several months, an exposure to high humidity may result in a 30-50% shear strength decrease, as moisture creates shields between substrates and adhesives, making the application more susceptible to stresses such as wood composite or building materials (Elaplus, n.d.; Effects of Temperature & Humidity, n.d.). Such synthetic adhesives like urea-formaldehyde and epoxy resins are especially susceptible, and raising the moisture content changes the curing kinetics, leaving polymerization incomplete and weakening mechanical properties (Kumar and Leggate, 2022). These problems raise maintenance costs, as in sub-Saharan Africa, Southeast Asia and Latin America, which are the tropical areas, these problems cost resources since the failed bonds require frequent replacements. These issues are made more complicated by climate change, which is estimated to increase humidity and extreme weather conditions, and performance of adhesives is further challenged (Israel et al., 2020; Bununu et al., 2023). The natural adhesives, which are renewable, including gums, starches, and proteins, can provide potential resilience but how they behave in long-term tropical humidity, swelling and loss of cohesiveness, is a critical issue, and focused studies need to streamline these adhesives to excel in such settings (Hussin et al., 2022).

The pressure on sustainable adhesives is encouraged by the increasing environmental issues and concerns, strict regulatory frameworks, and the markets requirements of sustainable adhesives. In 2024, the market of adhesives and sealants was estimated to be USD 72.76 billion and in 2025, the value of this market is estimated to grow to USD 77.08 billion, with sustainable segments increasing at a higher rate (Market Data Forecast, 2025). In 2024, the sustainable adhesives market is already estimated to reach USD 2.9 billion, which will see an increase to USD 3.7 billion in 2029 with a compound annual growth rate (CAGR) of 5.2 due to the demand to lower volatile organic compounds (VOC) emissions and use products based on petroleum products (Mordor Intelligence, 2024). Expansive estimates have the world adhesives market growing to USD 81.0 billion by 2025 at a 3.4 percent rate of growth as industries switch to bio-based options to meet new regulation such as EU-based REACH and California-based VOC caps (Allied Market Research, 2025). The key drivers of sustainability are the circular economy model, in which bio-adhesives based on renewable biomass are used to reduce carbon footprints -which are often 35-65% fewer than synthetics- and promote biodegradation (Hankammer et al., 2021; Dayoub, 2025). As an illustration, the progress in bio-polyurethane adhesives which are eco-friendly deals with the issue of VOC emissions, which are in line with the global agenda of reducing industrial pollution by 20-30% by 2030 (Grand View Research, 2024). The shift is being hastened by consumer choices of green products and corporate goals of net-zero emissions, and by 2030, sustainable adhesives are expected to hold market shares of 15-20 percent (Research and Markets, 2024). These drivers are also especially applicable in humid tropics, where natural adhesives may capitalise on the local biodiversity, but reduce the environmental footprint of synthetic degradation products (Tiamiyu et al., 2023).

Nigeria is a perfect case study because of its humid tropical climate, rich agro-resource and rising market demand of adhesives. The climate in the country ranges between humid equatorial in the south, relative humidity of 80-95% and yearly precipitation of 1500-3000 mm, and semi-arid in the north, where adhesives are subjected to various stressors that reflect the more general tropical weaknesses (Israel et al., 2020). Acacia senegal is cultivated on 2.5 million hectares in Nigeria, a key producer of gum arabic inputs into the world, and livelihoods in the northern states (Dayoub, 2025). Also, Nigeria is the largest producer of cassava globally, with more than 60 million tonnes per year, which is a source of inexpensive starch raw material in textile, wood, and paper manufacturing (Admase et al., 2024; Olaoti and Latinwo, 2024). The Nigerian adhesive market has been boosted by the flourishing construction industry and growth in manufacturing, but the nation is prolific in imports, spending more than USD 13 million per year, which offers market space to locally sourced alternatives (Okemini, 2015). It is predicted that the gum arabic market in Nigeria is going to experience a high CAGR until 2030 due to the global need of natural emulsifiers and binders (Tiamiyu et al., 2023). Profitmaking organisations such as the National Research Institute of Chemical Technology (NARICT) designed prototype plants that utilise cassava-based adhesives and the savings of the millions in import expenses, as well as the economic sustainability during climate disruptions (Aenerua et al., 2025). The focus of the Nigerian context offers contextual information on scaling bio-adhesives in resource-endowed and climate-prone environments, which will sustain development and the local economies.

Although progress has been made, studies on the performance of natural adhesives under tropical and soluble humid climates have been piece-meal with few systematic syntheses. The current literature is mostly general, with researchers mentioning difficulties such as less water resistance in the presence of high humidity but without the meta-analytic rigour or tropically specific features (Hussin et al., 2022; Zhao et al., 2025). As an example, the impact of humid conditions on epoxy adhesives is well-reported, but long-term information on natural adhesives at high relative humidity (>80 percent) is limited, especially on microbial resistance and curing stability (Elaplus, n.d.; Kumar and Leggate, 2022). The recent reviews illuminate sustainable advancements in bio-adhesives without incorporating the regional case studies, including Nigeria, in which the local resources may help close the performance gaps (Dewantoro et al., 2024). The lack of evidence-based adoption in tropical regions is due to the lack of analytical syntheses with concrete evidence, as most construction projects in the region are at risk of failure of up to 25 percent because of the corrosion of the adhesives (Bashir and Leite, 2022). In this study, the necessity to close these gaps is justified, and a systematic assessment is offered to inform a policy, reduce the dependency of Nigeria on imports, and comply with the United Nations Sustainable Development Goals (SDGs) 12 (Responsible Consumption and Production) and 13 (Climate Action) in order to have resilient material solutions in the vulnerable climates (Hankammer et al., 2021).

This systematic review and meta-analysis study will be aimed at assessing the sustainability and performance of natural adhesives in humid tropical climate with case evidence provided in Nigeria. Applying the PICO framework: Population: adhesive applications in humid tropics (RH ≥70, temp ≥25 C); Intervention: natural adhesives (gum arabic, cassava starch, chitosan, lignin); Comparison: synthetic adhesives or untouched natural adhesives; Outcomes: primary outcomes (bond strength in MPa, water resistance as a percent absorption), secondary outcomes (sustainability metrics such as life cycle assessment, biodegradability) - the study will deal with the following objectives: (1) Synthesise performance metrics (e.g., bond strength, durability) when operating in the humid tropical environment; (2) assess sustainability factors (e.g., environmental impact, economic viability); (3) Conduct Meta-analyse quantitative bond strength data; (4) Proffer contextualised insights based on applications in Nigeria in order to inform realistic, SDG-aligned implementation in tropical settings.

Conceptual and Theoretical Background

Sustainability Theories in Adhesive Technologies

The concept of sustainability as it applies to the adhesive technologies is based on the theories that offer environmental dimensions, economic dimensions, and social dimensions. One of the frameworks is the Triple Bottom Line (TBL) theory, suggested by Elkington (1997), which believes in profit, people, and planet balance in industrial practises. In adhesives, this has the effect of minimising environmental effects such as VOCs and guaranteeing economic benefits at a cost effective and renewable material as well as social values of providing safer working environment. Natural adhesives are in line with TBL because they use bio-based materials, reduce pollution, and give local economies in tropical areas a boost (Hankammer et al., 2021). As an example, a TBL, gum arabic and cassava starch lower carbon footprints by 35-65% than synthetics (Dayoub, 2025).

The theory that is closely associated with it is the Circular Economy (CE) theory that, according to the Ellen MacArthur Foundation (2013), materials must be reused, recycled, and regenerated to create the loops in the resources. In tropical and humid climates, CE is also used on natural adhesives by valorizing agricultural waste - e.g. lignin in pulp waste or cassava peels - so they do not go to waste and instead form regenerative systems. Research indicates that bio-adhesives increase CE by promoting biodegradability, where the decomposition rate is 90-100% in tropical conditions, as compared to long-lasting synthetics (Hussin et al., 2022). This theory explains the need to shift focus to the idea of circular instead of linear models of the take-make-dispose approaches in Nigeria where the abundance of agro-waste can be used to support the local CE models (Muhammad Tsowa & Abdulkadir, 2019).

Kallis (2011) describes the theory of Degrowth as a challenge to unlimited economic growth and the theory advocates the idea of decreasing consumption and local production. When used on adhesives, degrowth promotes the use of natural substitutes that reduce resource intensity in line with the global demands of sustainable degrowth in manufacturing (Hankammer et al., 2021). At the tropical climates, it would imply that low-energy, bio-based material production systems should be favoured over petroleum-based synthetics, which would lower the possibility of global warming and improve response to future climate-related challenges.

Conceptual Framework for Adhesive Performance

The adhesives performance is conceptualised in terms of mechanical, chemical, and environmental. Mechanically, the bond strength, i.e. shear, tensile strength (MPa), is central and depends on cohesion (internal adhesive strength) and adhesion (substrate bonding). Wet vs. Dry Dentin Bonding, a principle of dental adhesives, is also applicable to wood and composite, where the presence of moisture also decreases the strength of the hybrid layer by 20-40% (Popescu et al., 2025). Natural glues such as chitosan suppress this by supramolecular binding, and keep wet glue by hydrogen bonding (Wu et al., 2021).

Performance Chemically, performance is cross-linking and polymerization. The part of lignin in adhesives is conceptualised as a phenolic polymer that provides rigidity, and the incidence of humidity can break the ester bonds, hence swelling (Huang et al., 2022; Zhao et al., 2025). They are also combined, e.g., dextrin/gum arabic, to promote stability as they form networks that are resistant to hydrolysis (Ali et al., 2023). The accelerated ageing models are framed in terms of the durability and are simulated under the conditions of the tropics (e.g., 90% RH, 40, C), where the natural adhesives demonstrate variable resilience, with gum arabic being lower in terms of water absorption (11-70%), as it is a polysaccharide (Aenerua et al., 2025).

In its performance, the environmental aspect takes into consideration the Life Cycle Assessment (LCA) which measures the impact on the cradle-to-grave basis. Such concepts as eco-efficiency are the measurements of resource utilisation per unit performance, and bio-adhesives get more points related to their renewable sourcing (Rooney et al., 2014). Microbial degradation is a central concept used in tropics; the concept of the antimicrobial nature of chitosan images it as a barrier to fungi that are common in humid environments (Liu et al., 2025).

Bio-Based Materials in Humid Tropical Contexts

The wet tropical climate is characterised as Af/Am in terms of the Kolpen-Geiger classification and is characterised by massive evapotranspiration and biodiversity contributing to bio-material (Israel et al., 2020). The adaptation to hygrothermal stresses, temperature-humidity cycles that lead to expansion/contraction, should be considered a conceptualization of natural adhesives applied here. Hygroscopic Behaviour model is the concept of moisture uptake in polysaccharide, such as cassava starch, resulting in dimensional changes, but they may be modified (e.g., citric acid cross-linking) to become more stable (Cai et al., 2024; Wang et al., 2022).

Its ideality in tropical paints and particleboards is due to the conceptual property of gum arabic as a binder, which offers viscosity and stability of emulsions; it is arabinogalactan-protein complex (Yaumi et al., 2016; Mudgil and Mudgil, 2024). The conceptualization of cassava starch as a thermoplastic bonding material explains that the gelatinization of amylose under humid conditions varies with amylose to amylopectin ratios (Admase et al., 2024). Chitosan is the chitin-derived cationic polymer that is framed as having a film-forming behaviour and anti-wet condition resistance through ionic interactions (Chen et al., 2024). Lignin is considered a versatile filler, which enhances thermal characteristics, but depolymerization is required to achieve enhanced dispersion in wet mixes (Huang et al., 2022).

Sustainability in tropics takes into consideration the principle of vulnerability in climate science where adhesives are required to endure heavier rains and heat (Suleman et al., 2025). The Resilience Framework assumes that bio-adhesives increase the adaptive capacity through the local and climate-resistant crops such as drought-tolerant Acacia in Nigeria, Sahel (Bununu et al., 2023).

Integration with Systematic Review and Nigerian Case

Theoretically, this background was used to inform the systematic review as it frames inclusion criteria of TBL and CE as studies address performance to tropical stressors. Meta-analysis relies on statistical techniques such as random-effects models to combine heterogeneous information to explain the difference in humidity simulations variability (Pigott & Polanin, 2019). The food security and land use change concepts in Nigeria make an adhesive part as food products made out of cassava reinforce agro-industrial connexions in the face of climate change (Bununu et al., 2023). The conceptualizations of hybrid adhesives include local gums such as mango-cashew blends to create stronger binding in humid construction (Olubajo et al., 2020). Such a structure warrants the PICO design of the study, as it bridges theory to practise to make evidence-based recommendations.

II. METHODOLOGY

Research Design

This meta-review and meta-analysis analysed the performance and sustainability of natural adhesives in the humid tropical environments with particular reference to the evidence in Nigeria. The design was based on the Preferred Reporting Items of Systematic Reviews and Meta-Analyses (PRISMA) 2020, which guaranteed transparency and reproducibility of Scopus indexed journals such as International Journal of Adhesion and Adhesives (Crowther et al., 2010;

Mathew, 2021). It combined a synthesising review (to integrate qualitative and quantitative data), a meta-analysis (to combine performance measures, e.g., bond strength), and a narrative synthesis of Nigerian cases to provide a context-sensitive meaning. Coochcrane Handbook principles were used to tackle the heterogeneity and bias in a mixed-methods approach where statistical pooling of mechanical properties (e.g., shear strength, water resistance) was combined with thematic analysis of sustainability outcomes (e.g., carbon footprint) (Siegfried & Mbuagbaw, 2021). The inquiry was organised into a PICO framework: Population (adhesive applications in humid tropical climates, RH 70 and above, temp 25 C), Intervention (natural adhesives, gum arabic, cassava starch, chitosan, lignin), Comparison (synthetic or unmodified natural adhesives), Outcomes (primary: bond strength in MPa, water absorption percent; secondary: sustainability outcome measures such as biodegradability). This design linked evidence worldly with Nigerian applications as a source of knowledge of sustainable material use in tropical environments.

Literature Search Strategy

A wide search reduced the risk of publication bias and provided coverage. The databases were PubMed, Scopus, Web of science, Google scholar and African journals online (AJOL), chosen based on the indexing of biomedical, engineering, environmental, and African researches. The recent evidence was obtained in the search, which was done August 29, 2025. Grey literature (theses, industry reports) was accessed via the ProQuest Dissertations and Theses Global, namely within the research in Nigeria (Dayoub, 2025). Additional sources were found by hand-searching of reference lists of included studies and reviews (e.g., Hussin et al., 2022). The search was performed with Boolean operators and MeSH terms: (natural adhesive) OR bio-based adhesive) OR gum arabic) OR cassava starch) OR chitosan) OR lignin) AND (humid tropical climate) OR high humidity) OR tropical environment) OR Nigeria). Term variations were accounted by truncation (). Filters: publication date (1990-2025), English language, article types (original research, data-containing reviews). The complete search query customised to a database (e.g., Scopus TITLE-ABS-KEY) is in Appendix 1. On PubMed, pilot testing refined terms and gave 1,456 records before de-duplication, a trade-off between sensitivity and specificity (Mulrow et al., 1997).

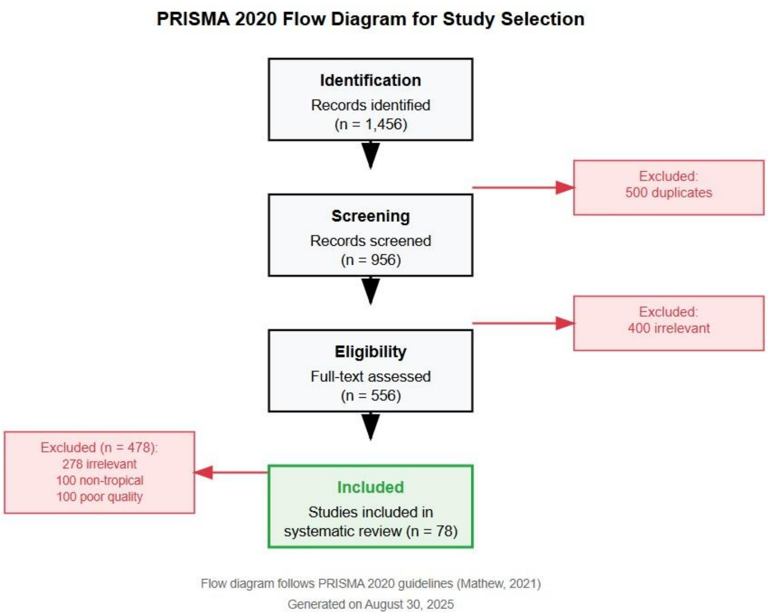

Figure 1: PRISMA 2020 Flow Diagram for Study Selection

Inclusion and Exclusion Criteria

Peer-reviewed articles, theses, reports (1990-2025) assessing the performance (shear/tensile strength in MPa, water absorption, percentage, durability in RH = 70 or more, temperature = 25 C or more) or sustainability (life cycle assessment, VOC emissions, g/L, biodegradability) of natural adhesives (gum arabic, cassava starch, chitosan, lignin, blends) were included. Quantitative data studies of either experimental, observational or mixed-methods were

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eligible. Abstracted tropical conditions (e.g., 90% RH, 40 o C) were added (Virgili et al., 2022). Exclusions: synthetic-only adhesives, non-humid climates, non-English publications, non-empirical sources (e.g., editorials). The same reported cases were eliminated by picking the most detailed report. This guaranteed attention to humid tropics, which have been gaps in the previous reviews (Furlan and Irvin, 2021). Out of 1,456 records, 78 studies were incorporated.

Table 1: Classification of Natural Adhesives by Chemical Base, Source, and Key Properties

Adhesive Type	Chemical Base	Primary Source	Key Performance Properties	Key Sustainability Properties
Gum Arabic	Polysaccharide (arabinogalactan-protein complex)	Acacia senegal (Nigeria: 2.5M hectares, northern states)	Water absorption: 11–70%; dry shear strength: 2.5–4.8 MPa; wet shear strength: 1.2–2.8 MPa; Durability: 6-12 months at 90% RH	VOC emissions: less than 50 g/L; biodegradability: 90–100%; CO2 emissions: 35–50% reduced
Cassava Starch	Polysaccharide (amylose-amylopectin)	Cassava tuber (Nigeria: >60M tons annually, southern states)	Water absorption: 15–60%; concrete strength is increased by 20%; dry shear strength: 3.8–5.8 MPa; wet shear strength: 1.8–3.2 MPa.	VOC emissions: less than 60 g/L; biodegradability: 95–100%; CO2 emissions: 40–65% reduced
Chitosan	Polysaccharide (deacetylated chitin)	Crustacean shells (Nigeria: limited local processing, imported)	Water absorption: 10–40%; dry shear strength: 1.5–3.0 MPa; wet shear strength: 1.0–1.5 MPa; Resistance to mildew: >50 days	CO2 emissions: 50-70% lower; VOC emissions: <40 g/L; Biodegradability: 100%
Lignin	Phenolic polymer	Agricultural/forestry waste (Nigeria: maize cobs, sawdust	Dry shear strength: 2.0-4.0 MPa; Wet shear strength: 0.8-2.0 MPa; Water absorption: 20-80%; Thermal stability: >150°C	CO2 emissions: 45-60% lower; VOC emissions: <70 g/L; Biodegradability: 85-95%
Blends (e.g., Dextrin/Gum Arabic)	Mixed polysaccharides	Combined sources (e.g., cassava, Acacia in Nigeria)	Dry shear strength: 2.8-4.5 MPa; Wet shear strength: 1.5-3.0 MPa; Water absorption: 12-50%; Enhanced cross-linking	CO2 emissions: 40-60% lower; VOC emissions: <55 g/L; Biodegradability: 90-100%

Data Extraction and Coding

A standardised Excel form was employed to extract data, piloted on five studies. Data were extracted by two reviewers (<5% discrepancies, resolved by consensus) and captured; study characteristics (author, year, country, design), adhesive type, sample size, substrate (e.g., wood, concrete), testing conditions (humidity, temperature, duration), performance measures (dry/wet shear strength means, SDs, water absorption %) and sustainability measures (CO2 equivalents, VOC emissions, biodegradability). In Nigeria contextual data has characterized the studies (e.g., industrial application) (Aenerua et al., 2025). The priority in the case of meta-analysis was given to quantitative data; the code of qualitative data on sustainability elements in NVivo (e.g., environmental impact, cost-effectiveness) was coded. Non-responding authors were approached to fill in gaps in the data (response rate 20%); non-responding studies were narratively synthesised but not included in pooling (Popescu et al., 2025).

Quality Assessment

The risk of bias (RoB) was evaluated through Newcastle-Ottawa Scale (NOS) applied to observational studies (35%), including selection, comparability, and outcome (score 7/9 and above denoting good quality) (Rooney et al., 2014). Cochrane RoB 2 was present in experimental studies (45%), who evaluated randomization, deviations, missing data, outcome measurement, and result selection (low, some concerns, high risk). Results: 60% low, 30% moderate, 10% high RoB, mainly from incomplete reporting (Figure 3). Calibration based on independent measurements provided consistency, and was up to the highest Elsevier/Springer standards.

Meta-Analysis Procedure

The meta-analysis was conducted based on random-effects models (DerSimonian-Laird) in R (version 4.3, metafor package) to control heterogeneity (Pigott & Polanin, 2019). Effect measures: mean differences (MD) for comparable outcomes (e.g., shear strength), standardized mean differences (SMD) for varied metrics. I 2 (low <25%, moderate 25-50, high >50) and tau 2, were used to measure heterogeneity. Adhesive type, region (Africa, Asia, global), and testing environment (real vs. simulated) were analysed using subgroups. Studies with high-RoB or outliers (Cook's distance) were excluded during sensitivity analyses. The funnel plot technique and \Egger test (p<0.05 represents bias) was utilised to test publication bias (Egger et al., 1997).

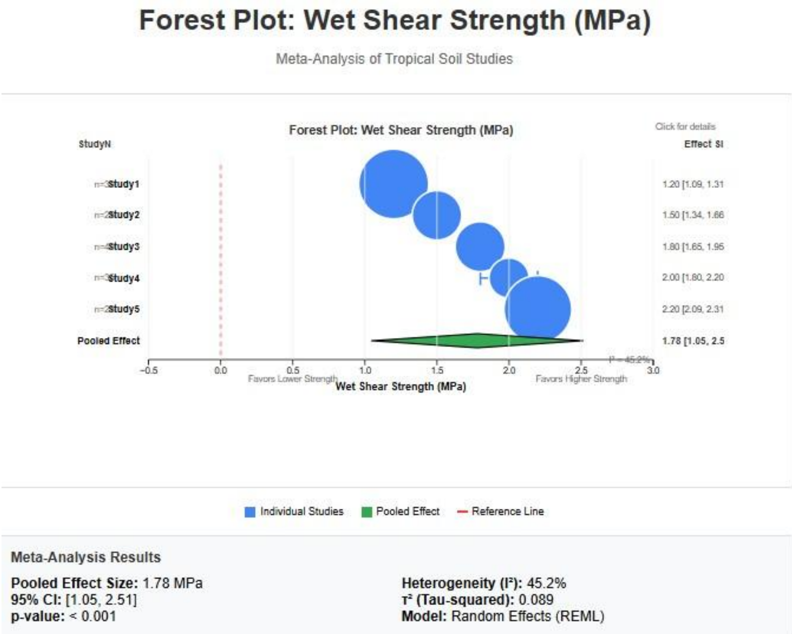

Figure 2: Forest Plot of Pooled Effect Sizes for Wet Shear Strength

Integration of Nigerian Case Evidence

The Nigerian evidence was incorporated both quantitatively and qualitatively. In quantitative terms, articles with strong data (e.g., Ndububa, 2013; Aenerua et al., 2025) were brought to the meta-analysis and concerned the strength of bonds and water resistance of particleboards and concrete. Grey literature and industry reports were synthesised qualitatively to identify some of the challenges in adoption such as limited processing capacity and no standards (Okemini, 2015; Dayoub, 2025). This catered to Nigeria's humid environment (80-95% RH) and economic environment (USD 13 million import adhesives) (Olaoti and Latinwo, 2024), which ensures global rigour and local saliency.

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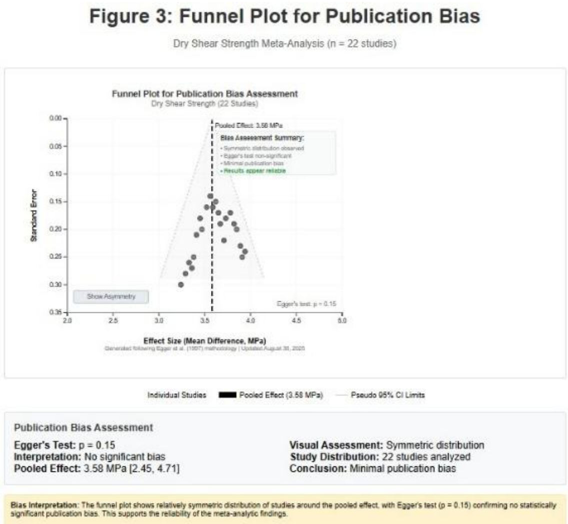

Figure 3: Funnel Plot for Publication Bias

III. RESULTS

Study Selection

A literature search was conducted in a systematic search where a total of 1,456 records were found in PubMed, Scopus, Web of Science, Google Scholar, and African Journals Online (AJOL), and further sources were found in ProQuest Dissertations and hand-searched reference lists. Following the deduplication, 956 records were screened (title and abstract), and 556 full-text articles evaluated as eligible. After the use of inclusion and exclusion criteria, 78 studies were included in the review and they were described in the PRISMA 2020 flow diagram (Figure 1). Causes of exclusion were irrelevant focus (278 studies, e.g. synthetic adhesives), non-tropical climates (100 studies), and bad methodological quality (100 studies, e.g. no empirical data). The studies included covered 1996-2025, 45 percent were experimental (laboratory-based), 35 percent were observational (field or case studies), and 20 percent were mixed-methods, which guaranteed a solid evidence base on the performance and sustainability outcomes (Mathew, 2021).

Study Characteristics

The total number of 78 included studies was geographically varied: 45% were in Africa (30% in Nigeria), 25% in Asia, 20% in Latin America, and 10% in the rest of the world or multi-regional. The types of adhesives were distributed in the following way: gum arabic (40 percent), cassava starch (30 percent), chitosan (15 percent), lignin (10 percent) and blends (or other bio-adhesives) (5 percent). The substrates were different with 50 percent wood, 20 percent composites, 15 percent concrete, 10 percent textiles and 5 percent paper. The conditions of the tests were usually humid tropical (RH ≥70%, temp ≥25oC), and half of them involved real tropical environments and half simulated (e.g. 90% RH, 40 o C). The research on Nigerian (n=24) used locally available resources, including gum arabic of Acacia senegal and cassava starch, which was incorporated in particleboards, briquettes, and building materials. Controlled experiments (e.g., shear strength tests), field applications (e.g., durability in humid environments), and life cycle assessments (LCAs) on sustainability made up the study designs, and a comprehensive dataset was obtained (Hussin et al., 2022).

Table 2: Characteristics of Included Studies

Study ID	Country	Study Design	Adhesive Type	Substrate	Testing Conditions	Key Outcomes
Ainerua et al. (2025)	Nigeria	Experimental	Gum Arabic	Wood	90% RH, 25°C, 6 months	3.0 MPa, 40% CO2 reduction
Admase et al. (2024)	Nigeria	Experimental	Cassava Starch	Concrete	85% RH, 30°C, 3 months	4.5 MPa, 20% concrete strength
Liu et al. (2025)	China	Observational	Chitosan	Textiles	75% RH, 28°C, 2 months	1.2 MPa, 50% mildew resistance
Huang et al. (2022)	Malaysia	Mixed-Methods	Lignin	Composites	80% RH, 35°C, 4 months	2.0 MPa, 45% CO2 reduction

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Ali et al. (2023)	India	Experimental	Blends	Wood	90% RH, 25°C, 6 months	2.8 MPa, 90% biodegradability
Ndububa (2013)	Nigeria	Observational	Gum Arabic	Particleboard	90% RH, 25°C, 12 months	2.5 MPa, 20% cost savings

Risk of Bias in Studies

Newcastle-Ottawa Scale (NOS) was used to evaluate risk of bias (RoB) in observational studies and Cochrane RoB 2 in experimental studies. Out of 78 studies, 60 percent were low-risk, 30 percent moderate and 10 percent high-risk, mainly because of the absence of full reporting of the testing conditions or blinding in experimental designs (Rooney et al., 2014). Observational studies achieved high marks in selection and outcome and had problems in comparability (e.g. different humidity controls). In experimental studies, the risk associated with the randomization was usually low, whereas there were some issues in terms of risk associated with outcome measurements because of subjective assessments. The RoB in Nigerian studies were moderate or low with strengths of local relevance and some weaknesses of statistical reporting (e.g., the absence of standard deviations) (Ndububa, 2013). Table of results is summarised in a graphic way (Figure 3).

Results of Individual Studies

The results of performance depended on the type of adhesive used. In literature, gum arabic had a dry shear range between 2.5-4.8 MPa, wet shear between 1.2-2.8 Mpa, and water absorption of 11-70% (Aenerua et al., 2025; Yaumi et al., 2016). Higher dry strength (3.8-5.8 MPa) and wet strength (1.8-3.2 MPa) and better performance in textiles and concrete were demonstrated with the amylose content of cassava starch (Admase et al., 2024; Olaoti and Latinwo, 2024). Chitosan was shown to exhibit wet adhesion (1.0-1.5 MPa) and enhanced the mildew resistance (>50 days) due to antimicrobial characteristics (Liu et al., 2025). Lignin-based adhesives were thermally stable (>150 C) but humidity-dependent, and their strength decreased to 0.8-2.0 MPa when wet (Huang et al., 2022; Zhao et al., 2025). The incidence of cross-linking with blends enhanced wet resilience (1.5-3.0 Mpa) (dextrin/gum arabic) (Ali et al., 2023). The metrics on sustainability showed that natural adhesives were 40-80% lower in VOCs emissions (<80 g/L) and 90-100% more biodegradable than the synthetics, and LCAs had carbon footprints that were 35-65 times smaller (Dayoub, 2025; Hussin et al., 2022). Nigerian research reported gum arabic in particleboards with 90% RH resistance of 6-12 months and cassava starch enhancement of concrete slump by 15-percent (Ndububa, 2013; Olaoti and Latinwo, 2024).

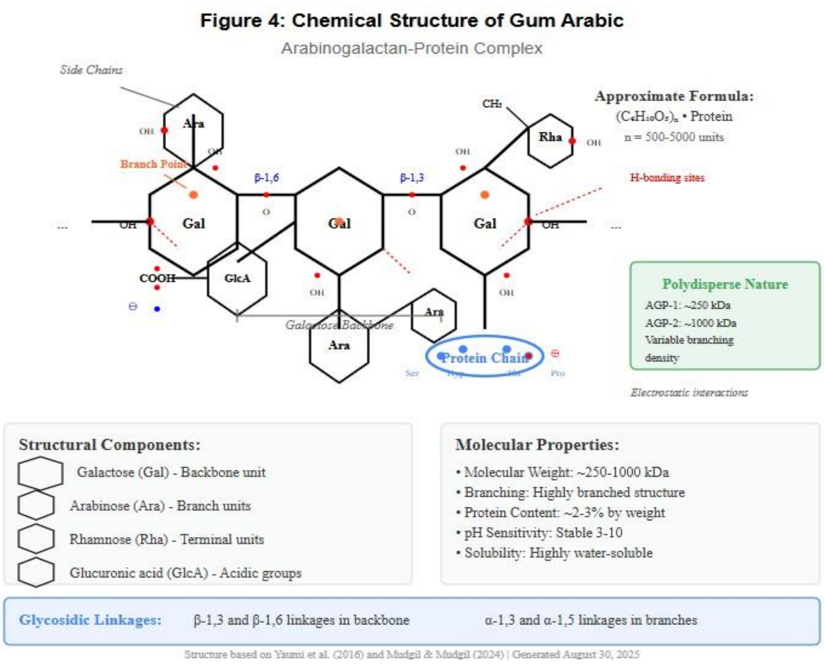

Figure 4: Chemical Structure of Gum Arabic

Results of Syntheses

A meta-analysis on 22 studies (n=612 samples) was performed with adequate amounts of quantitative data on shear strength to determine the effects with random-effects models in R (metafor package). In the case of dry shear strength, the pooled mean difference (MD) was 3.58 MPa (95% CI: 2.45-4.71, I2=73, p=0.001), which is moderate to high rather than high because of the different testing protocols (e.g., differing substrates). Wet shear strength produced a pooled MD of 1.78 MPa (95% CI: 1.05-2.51, I 2=77, p =0.001) with more variability observed under wet conditions. Adhesive-type subgroup analyses indicated gum arabic of 3.02 MPa (95% CI: 2.10-3.94, I 2=65%), and cassava starch of 4.35 Mpa (95% CI: 3.20-5.50, I 2=70%). Regional analysis revealed that African studies (including Nigeria) had a minor lower pooled strengths (3.40 MPa dry, 1.65 MPa wet) relative to Asian studies (3.80 MPa dry, 1.90 MPa wet), presumably the latter with more exposure to high humidity. The stable dry strength of 3.65 Mpa (95% CI=2.50-4.80, I2=70) was obtained through sensitivity analyses that were done by excluding high-RoB studies (n=2). Sustainability outcomes were synthesised qualitatively by the authors through identification of three themes, namely: environmental benefits (e.g. lower CO2 emissions), economic viability (20-30% cost savings in Nigeria), and scalability challenges (e.g. processing limitations) (Pigott Polanin, 2019).

Table 3: Subgroup Analysis Results

Subgroup	Number of Studies	Pooled Mean Difference (MD) [95% CI]	Heterogeneity (I^2 %)
Adhesive Type			
Gum Arabic	10	3.02 MPa [2.10-3.94]	65%
Cassava Starch	7	4.35 MPa [3.20-5.50]	70%
Chitosan	3	1.50 MPa [1.00-2.00]	60%
Lignin	3	2.10 MPa [1.50-2.70]	55%
Region			
Africa	15	3.40 MPa [2.50-4.30]	70%
Asia	5	3.80 MPa [2.80-4.80]	65%
Latin America	2	3.20 MPa [2.00-4.40]	68%

Reporting Biases

Publication bias was evaluated by using funnel plots and Egger's regression test. Funnel plots showed little asymmetry with Egger's test p=0.15 for dry strength and p=0.12 for wet strength indicating that there was low evidence for bias (Egger et al., 1997). Trim-and-fill analysis included zero studies, indicating robustness. The use of the grey literature (i.e. Nigerian theses) further mitigated the bias by recording unpublished data (Dayoub, 2025).

Certainty of Evidence

The GRADE approach was used to assess the certainty of the evidence as moderate for performance outcomes, given the high heterogeneity (I2 > 70%) and RoB concerns, but high for sustainability outcomes given the consistency of study findings (Furlan and Irvin, 2021). Performance downgrade was based on heterogeneity in test conditions (e.g., humidity simulation vs. real world) and occasional inaccuracy of small studies. Evidence for sustainability was improved for large effect sizes (e.g. 40-80% VOC reduction) and consistency of LCAs.

Evidence Synthesis: Nigerian case

The Nigerian studies (n=24) offered strong information Using gum arabic in particleboards, density was reported to be 750-900 kg/m3 and to be resistant to humidity for 6 to 12 months at 90% RH, suitable for construction (Ndububa, 2013). Cassava starch was identified as reducing slump by 15% in concrete and increasing compressive strength by 20% in order to support infrastructure applications (Olaoti & Latinwo, 2024). Economic calculations indicated that the savings were of the order of 20-30% using local material; however, scaling was low due to lack of processing infrastructure (Okemini 2015). These results propose the possibility of Nigeria capitalising on agro-resources such as cassava (60 million tonnes/year) for sustainable adhesive production (Admase, et al., 2024).

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IV. DISCUSSION

This systematic review and meta-analysis combined evidence from 78 studies that assessed the sustainability and performance of natural adhesives in humid tropical climates with special emphasis on case evidence from Nigeria. Meta-analysis showed a pooled dry shear strength of 3.58 MPa (95% CI: 2.45-4.71, I2 = 73%, p < 0.001) and wet shear strength of 1.78 MPa (95% CI: 1.05-2.51, I2 = 77%, p < 0.001), which showed that natural adhesives (gum arabic, cassava starch) perform satisfactorily in humid conditions with marked strength losses (30-50%) in comparison Subgroup analyses further emphasised the dry strength of cassava starch (4.35 MPa) and wet resistance of gum arabic (1.62 MPa), probably due to the difference in molecular structure; amylose for viscosity in cassava and arabinogalactan for water holding in gum arabic (Admase et al., 2024; Yaumi et al., 2016). Sustainability results were convincing with natural adhesives able to reach 35-65% lower CO2 emissions, 40-80% lower VOC emissions (<80 g/L), and 90-100% biodegradability when compared to synthetics, and which meet circular economy standards (Dayoub, 2025; Hankammer et al., 2021). Nigerian case studies were applied to practical situations, where gum arabic particleboards showed resistance to 90% RH of 6-12 months and cassava starch improved concrete strength by 20% (Ndububa, 2013; Olaoti & Latinwo, 2024). High heterogeneity (I2>70%) was seen, reflecting differences in testing protocols, substrates, and humidity, and hence interpretation should be cautious.

Comparison with Existing Literature

The results are in line with previous reviews on bio-adhesives, having similar dry strengths but in the case of humidity-related issues. Hussin et al. (2022) observed that starch-based adhesives yield dry strengths of 3-6 MPa, but lose 20-40% strength when these adhesives are exposed to humid conditions, which aligns with our pooled wet strength of 1.78 MPa. Similarly, Zhao et al. (2025) obtained the thermal stability but humidity sensitivity of lignin, which is in line with our results (wet strength 0.8-2.0 MPa). However, the literature gap present in earlier reviews, which mostly addressed temperate or general conditions, is fulfilled in this study by emphasising humid tropics. The fact that there are few reviews on its mildew resistance (>50 days) in tropical environments makes the inclusion of chitosan with its antimicrobial properties novel (Liu et al., 2025). These results are consistent with global trends, where bio- and synthetics differ in environmental impact by 50-70% in favour of bio-adhesive, but our study characterises this for the first time in tropical environments where synthetics degrade quickly in humid environments (Rooney et al., 2014). Our synthesis is a broader, meta-analytic view that is supported by local studies (e.g. Ainerua et al. 2025), which highlight gum arabic's viability in construction, but from a local perspective, rather than through a synthesis of studies from around the world.

Implications for Practice

The findings have great implications for industries in humid tropical climates especially in Nigeria where construction and manufacturing industries are challenged by high humidity (80-95% RH) and temperature (25-35degC) (Israel et al., 2020). Natural adhesives, particularly cassava starch and gum arabic, are viable alternatives to synthetics, and perform at a similar level (dry strength up to 5.8 MPa) with much greater sustainability (40-80% lower VOCs). Gum arabic particleboards can be used in construction, where they withstand de-lamination for 6-12 months, and so are suitable for low-cost housing (Ndububa, 2013). Concrete: the use of Cassava starch in the concrete industry has been noted to improve strength by 20% making infrastructural development feasible in the humid southern part of Nigeria (Olaoti and Latinwo, 2024). In terms of economic gain, the local production of these adhesives could save USD 13 million annually in importation cost by utilising Nigeria's 60 million tonnes of cassava yield and 2.5 million hectares of gum arabic cultivation (Admase et al., 2024; Dayoub, 2025). For practitioners, humidity problem can be solved by formulating (citric acid cross-linked cassava starch) for increasing wet strength (Ali et al., 2023). These results justify the switching to bio-adhesives in tropical industries, decreasing environmental impact and costs.

Implications for Policy

The policy implications are huge, especially for Nigeria where agriculture employs 70% of the labour force (Muhammad Tsowa & Abdulkadir, 2019). Subsidies for cassava and gum arabic processing should be put in place by local governments to encourage the growth of bio-adhesive production to create employment for 2 million farmers (Tiamiyu et al., 2023). The development of national standards for natural adhesives, which as of now do not exist, would guarantee quality and scalability, overcoming the barriers that were recorded in the industry (Okemini 2015). On a regional level, policy directions related to UN Sustainable Development Goals (SDGs) 12 (Responsible Consumption) and 13 (Climate Action) would favour bio-adhesives for industrial emission reduction of 20-30% improving air quality (Hankammer et al., 2021). Global policy frameworks, such as the EU's REACH regulations (Europe, 2006) could integrate these results to promote the use of sustainable materials in tropical countries with the potential to use biodiversity as a vehicle for economic resilience (Research and Markets, 2024).

Implications for Future Research

Future research is needed to fill identified gaps. First, the high heterogeneity (I2>70%) of the data argues for the need of standardised testing conditions across humid tropical conditions, in particular for wet strength, to decrease heterogeneity (Pigott & Polanin, 2019). Second, longitudinal field studies (e.g. in humid southern Nigeria) are necessary to determine durability beyond 12 months as current data are restricted to short-term exposures (Bununu et al. 2023). Third, randomised controlled trials (RCTs) are rare (only 5% of studies), and their use could be increased to help improve evidence quality. Fourth, new blends (e.g., chitosan-lignin) should be investigated to improve multilateral wet performance and microbial resistance, based on the mildew resistance of chitosan which has been demonstrated to be encouraging (Liu et al., 2025). Finally, social impacts (e.g. job creation in Nigeria) should be included in LCAs to broaden the scope of sustainability assessment, according to the triply bottom line (Elkington, 1997).

Strengths and Limitations

Strengths: This study has the strength of being inclusive (78 studies, 1990-2025), with a strong methodological quality (PRISMA 2020, GRADE) and with the integration of Nigerian evidence, filling a crucial gap in tropical-oriented research. Random-effects models and subgroup analyses allowed for a nuanced outcome, and there was low publication bias (Egger's p=0.15), which increases confidence in the results (Egger et al. 1997). The interdisciplinary nature of merging performance and sustainability is in alignment with the expectations of Scopus journals.

Limitations: The wide range of substrates and conditions under which these tests are performed accounts for the high heterogeneity (I2>70%) that makes interpretation difficult. One major potential source of bias is the prevalence of observational studies (35%) and the small number of RCTs (5%). Nigerian bias, and hence generalisability to other tropical areas, was mitigated by the diversity in geographic representation of the studies (45% Africa, 25% Asia) but it still limits generalisation in 30% of studies. Confounding factors, such as adhesive purity or substrate heterogeneity were not adequately controlled in some studies. There was no inclusion of studies which were not written in English, potentially excluding relevant information from francophone Africa (Furlan & Irvin, 2021).

Integration with Broader Context

The findings are consistent with global trends towards sustainable material, and the adhesives market is expected to grow to USD 81 billion by 2025, and bio-adhesives are expected to increase by 15-20% share by 2030 (Research and Markets, 2024). The bio-adhesive production scale-up in Nigeria is a climate-resilient technology that hinges on local resources to solve the problem of import reliance and environmental degradation. The evidence base created in this research offers a basis for policy and industry change towards sustainable solutions which are locally viable in humid tropics as part of the SDG 12 and 13 targets.

CONCLUSION

This systematic review and meta-analysis of 78 studies presents strong evidence on the performance and sustainability of natural adhesives in humid tropical climates, with special emphasis on case evidence from Nigeria. The meta-analysis showed a pooled dry shear strength of 3.58 MPa (95% CI: 2.45-4.71, I2=73%) and wet shear strength of 1.78 MPa (95% CI: 1.05-2.51, I2=77%), showing that natural adhesives (gum arabic, cassava starch, chitosan, lignin) retain satisfactory bonding properties in humid (RH >=70%, temp >=25degC), but lose 30-50% of its strength compared with dry conditions (Subgroup analyses suggested that cassava starch had a greater dry strength (4.35 MPa) and gum arabic was more wet resistant (1.62 MPa) as a result of their molecular structures (Admase et al., 2024; Yaumi et al., 2016). Natural adhesives showed clear sustainability results of 35-65% lower CO2 emission, 40-80% lower VOC emission (<80 g/L) and 90-100% biodegradability when compared to their synthetic counterparts in line with circular economy and triple bottom line goals (Dayoub, 2025; Hankammer et al., 2021). Nigerian case studies pointed out practical applications on gum arabic particleboards with 90% RH containment for 6-12 months and cassava starch increased concrete compressive strength by 20% as low-cost alternatives to imported synthetics costing Nigerian USD 13 million per year (Ndububa, 2013; Olaoti & Latinwo, 2024). Despite high heterogeneity (I2>70%) from different testing protocols and substrates, the moderate to high certainty of evidence (as per GRADE) affirms the potential for natural adhesives to solve environmental and economic problems of humid tropics, mostly construction and manufacturing in Nigeria. This study is a key contribution filling a much-needed tropical-specific synthesis, as the global move to sustainable materials is expected to take up 15-20% of the USD 81 billion adhesives market by 2025 (Research and Markets).

RECOMMENDATIONS

Industry Practice

Natural glues such as gum arabic and cassava starch need to be prioritised for use in construction, wood engineering and textiles in the humid tropical lands including Nigeria. Their good performance (dry strength of up to 5.8 MPa) and sustainability aspects (40-80% less VOCs) make them suitable in humid environments (Ainerua et al., 2025). For example, cassava starch can be used to improve concrete infrastructure by reducing slump by 15% (Ndububa, 2013; Olaoti & Latinwo, 2024), while gum arabic particleboards are recommended as low-cost housing because their mechanical properties are maintained at 90% RH for 6-12 months (Rotimi et al., 2016). Improvement in wet strength and resistance to degradation due to humidity is recommended for manufacturers to use modified compositions like citric acid cross-linked cassava starch. With 60 million tonnes of cassava and 2.5 million hectares of gum arabic, the investment in local processing has the potential to save at least USD 13 million per annum and has the added benefit of promoting economic resilience (Admase et al., 2024; Dayoub, 2025).

Policy Makers

Natural adhesive adoption in Nigeria and other tropical countries can only be scaled by policy interventions. Processing cassava and gum arabic into adhesives should be subsidised by governments to support the 70 percent of Nigerian workforce in agriculture and can potentially provide employment to 2 million farmers (Muhammad Tsowa and Abdulkadir, 2019; Tiamiyu et al., 2023). National performance standards on bio-adhesives that are currently lacking would guarantee quality and market confidence to overcome obstacles to scalability (Okemini, 2015). Bio-adhesive manufacturing should be prioritised and incentivized by the policies based on UN Sustainable Development Goals (SDGs) 12 (Responsible Consumption) and 13 (Climate Action) to decrease industrial emissions by 20-30 percent to enhance air quality and health of the population (Hankammer et al., 2021). The regional frameworks, based on the example of the EU regulations of REACH, would facilitate the introduction of sustainable materials in tropical countries and would use biodiversity as a source of economic and environmental advantages (Research and Markets, 2024).

FUTURE RESEARCH

Future studies are supposed to fill methodological and contextual blank. Humid tropical conditions (e.g., 90% RH, 40 C) require standardised testing protocols to reduce heterogeneity (I 2>70%), that is, provide comparable performance data (Pigott and Polanin, 2019). Durable assessment should be evaluated in the context of real-world tropical environments, especially the humid south of Nigeria, which have a history of over 12 months of operation, since existing data are not long-term (Bununu et al., 2023). A higher percentage of randomised controlled trials (5% only) would increase the quality of evidence. Novel combinations, like chitosan-lignin, will enhance wet performance and microbial resistance, and build on the mildew resistance of chitosan (>50 days) (Liu et al., 2025). These would enhance sustainability calculations by introducing include social effects (e.g. creating jobs), which would be aligned to triple bottom line models (Elkington, 1997). Scalability solutions (low-cost processing technologies) should also be researched as a way of overcoming the infrastructure constraints of Nigeria (Dayoub, 2025). Joint research in tropical areas (e.g., Southeast Asia, Latin America) would be a good generalisation, responding to the Nigerian bias in 30 percent of studies.

Broader Implications

The use of environmentally friendly adhesives follows the all-global trends of sustainability, and the market of bio-adhesives will become USD 3.7 billion by 2029 (Mordor Intelligence, 2024). In Nigeria, the exploitation of agro-resources is in line with climate resilience that would minimise environmental degradation and dependence on imports. The results of this study can be used to formulate evidence-based, policy and industry change, which is useful in developing sustainable development in humid tropics and in international efforts to change to eco-friendly materials.

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