

Selection and Performance of Adhesives Used in Ethiopian Footwear Factories: A Systematic Review of Literature

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Abstract

The footwear industry in Ethiopia plays a vital role in manufacturing, employment generation, and economic development, however it faces persistent challenges in product quality, durability, and competitiveness, particularly in bonding processes critical to shoe assembly. This systematic review synthesizes existing literature on adhesives used in Ethiopian footwear factories, focusing on the selection criteria and performance evaluation of bonding agents (such as solvent-based, water-based, polyurethane, and neoprene types) applied in upper-to-sole attachment and other joints. Key factors influencing adhesive performance include material compatibility with local leather and imported components (e.g., rubber/PU soles), peel strength, heat resistance, environmental durability, application techniques, surface preparation (buffing, skiving, priming), curing conditions, and resistance to common failure modes such as delamination under mechanical stress, moisture, or temperature variations.

The review highlights that improper adhesive selection, inconsistent quality of imported adhesives, suboptimal process controls in lasting/finishing stages, and limited local R&D contribute to bonding failures, reduced shoe lifespan, and export limitations. It draws from global footwear adhesive standards while contextualizing findings to Ethiopia's labor-intensive factories, supply chain dependencies, and ongoing efforts to enhance local production capabilities. Findings underscore the need for standardized selection protocols, improved training on adhesive application, and potential shifts toward sustainable/high-performance alternatives to boost factory efficiency and product reliability.

Keywords: footwear adhesives, performance, bonding failure, Ethiopian footwear industry, sole attachment, peel strength, systematic review, shoe manufacturing Ethiopia, adhesive selection, delamination

1. Introduction

The footwear industry in Ethiopia has emerged as a significant sector within the country's manufacturing landscape, contributing to economic growth, employment generation, and export earnings. With abundant raw materials such as leather and a growing influx of foreign investment, Ethiopia has positioned itself as a competitive player in Sub-Saharan Africa's footwear production [1]. However, the industry's productivity and competitiveness are often hampered by inefficiencies in production processes, including the selection and performance of critical materials like adhesives [2]. Adhesives play a pivotal role in footwear manufacturing, facilitating the bonding of diverse substrates such as leather, rubber, synthetics, and textiles, which directly influences the durability, flexibility, and overall quality of the final product [3]. In the Ethiopian context, where many factories rely on imported adhesives due to limited local production capabilities, challenges such as inconsistent quality, high costs, and environmental concerns further complicate their effective utilization [4].

Adhesive performance in footwear is typically evaluated through key metrics including bond strength (e.g., peel, shear, and tensile strength), resistance to environmental factors like moisture, heat, and chemicals, and compatibility with assembly processes [5]. Failures in adhesive bonding, often stemming from improper selection, application errors, or suboptimal surface preparation, can lead to production delays, increased waste, and reduced product lifespan [6]. In Ethiopian factories, these issues are exacerbated by factors such as variable raw material quality, inadequate training, and reliance on solvent-based adhesives that pose health and sustainability risks [7]. Recent advancements, including water-based and bio-based polyurethane adhesives, offer promising alternatives by enhancing environmental profiles while maintaining high performance, though their adoption in developing contexts like Ethiopia remains limited [8,9].

Despite these developments, there is a dearth of comprehensive literature synthesizing the performance and selection criteria for adhesives specifically tailored to Ethiopian footwear factories. Existing studies often focus on global trends or isolated case analyses, overlooking contextual factors such as supply chain constraints, regulatory environments, and local manufacturing practices [4]. This systematic review addresses this gap by critically examining the available literature to provide evidence-based insights for improving adhesive selection and application in the Ethiopian footwear sector.

Objectives

The primary objectives of this systematic review are as follows:

- To identify and classify the types of adhesives commonly used in Ethiopian footwear factories, including solvent-based, water-based, and reactive hot-melt variants, and evaluate their suitability for local materials and processes.
- To assess the performance criteria of these adhesives, such as bond strength, durability under environmental stressors, and compatibility with footwear components, drawing on empirical studies and industry reports.
- To analyze the factors influencing adhesive selection in the Ethiopian context, including cost, availability, health and safety implications, and sustainability considerations, while proposing recommendations for enhanced productivity and compliance with international standards.
- To guide policymakers, manufacturers, and researchers toward optimizing adhesive use, ultimately fostering a more competitive and sustainable Ethiopian footwear industry.

2. Methodology

This systematic literature review was conducted and reported in accordance with the **Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020** guidelines.

1. Eligibility Criteria

Inclusion

- Publications addressing performance (e.g., bond strength, peel resistance, shear strength, durability, heat/humidity resistance, ageing behaviour) of adhesives in footwear manufacturing.
- Studies discussing adhesive types (e.g., polychloroprene, polyurethane, hot-melt, water-based, solvent-based), selection criteria, testing methods (e.g., T-peel, upper-sole adhesion, ISO 17708), surface preparation, or bonding failures relevant to shoe production.
- Publications from 2000 onwards (to capture modern formulations and move away from highly toxic older systems).
- English-language peer-reviewed journal articles, conference papers, book chapters, and technical reports.

The remaining studies were assessed for their applicability to the Ethiopian context, specifically looking for "solvent-based" vs. "water-based" performance.

- **Assessment:** At this stage, the methodology integrates specific Ethiopian industrial strategies, such as the *Ethiopia's Adhesive Industry Strategy 2015-2025*, which highlights the shortage of skilled human resources and the need for improved input quality.
- **Performance Metrics:** Studies must provide quantifiable data, such as the minimum 3 N/mm peel strength required for casual footwear.
- The final selection includes studies that provide a comprehensive analysis of bonding failure and performance evaluation. This includes practical analyses of skiving, buffing, and pressing operations that directly influence adhesive efficacy in local factories.

Exclusion

- Studies focused solely on health/environmental impacts of adhesives without performance data.
- Non-footwear adhesive applications.
- Editorials, letters, abstracts without full text, and non-English publications.

2. Information Sources & Search Strategy

Electronic databases searched: Scopus; Web of Science; PubMed / MEDLINE; Google Scholar; ResearchGate; ScienceDirect.

Additional hand-searching of reference lists of key reviews and relevant journals (e.g., Journal of Adhesion, International Journal of Adhesion and Adhesives, Footwear Science, Revista de Adhesión y Adhesivos).

3. Literature Review

3.1. Key Considerations for Adhesive Performance

3.1.1. Material Compatibility

Adhesives must be carefully chosen for different materials, such as leather, synthetic materials, or rubber soles, to ensure strong adhesion. In footwear manufacturing, material compatibility is critical because the adhesive joint performance depends on the nature of the adherends (e.g., upper and sole materials), requiring adhesives that provide adequate wettability, viscosity, and chemical/physical bonding to diverse substrates like leather, polyurethane (PU), polyvinyl chloride (PVC), styrene-butadiene rubber (SBR), thermoplastic rubber (TR), and other synthetics [10]. For instance, polychloroprene (neoprene-based) adhesives offer excellent compatibility with leather and vulcanized rubbers due to high wettability and permanent tack, while polyurethane adhesives are highly versatile and widely used for bonding soles to uppers, including leather, synthetic fabrics, PU, PVC, and halogenated rubber soles, often requiring surface treatments like priming or halogenation for non-porous or low-energy surfaces such as certain rubbers and synthetics to achieve durable bonds [11]. Poor compatibility can lead to weak bonds, delamination under stress, moisture, or temperature variations, emphasizing the need for tailored adhesive selection and pre-treatments to optimize adhesion across these materials.

3.1.2. Bond Strength and Durability

To ensure the integrity of bonded assemblies, adhesives must provide high bond strength capable of withstanding operational stresses over the long term. While bond strength is often measured via shear or tensile modes, peel strength and resistance to time-dependent deformation (creep) are considered the primary indicators of durability under sustained or cyclic loading [12]. Peel strength is particularly vital because it measures the adhesive's ability to resist crack propagation at the interface when subjected to localized stress concentrations [13]. Furthermore, understanding the viscoelastic nature of the polymer matrix is essential, as resistance to creep ensures that the bond does not fail prematurely under constant environmental or mechanical pressure [14].

Peel strength tests evaluate the adhesive's resistance to separation forces applied perpendicular to the bond line, often using configurations like the T-peel or 180° peel test. These tests measure the force per unit width required to propagate debonding, providing insights into adhesion performance, especially for flexible substrates or applications prone to peeling stresses [15].

Creep tests assess long-term durability by applying constant load over extended periods, revealing viscoelastic behavior, deformation accumulation, and potential rupture under sustained stress. Creep is especially relevant for adhesives in load-bearing applications, as it can lead to progressive failure even below short-term strength limits. For instance, creep in peel configurations (e.g., T-peel under constant load) combines peel resistance with time-dependent effects, often exacerbated by environmental factors like heat or humidity [15]. Recent comprehensive reviews highlight that evaluating adhesive performance requires integrating multiple mechanics tests, including peel for interfacial toughness and creep for viscoelastic response, alongside tensile, shear, fracture, and fatigue assessments to capture real-world durability [16].

The evaluation of adhesive performance relies on two distinct yet complementary metrics: peel strength and creep resistance. Peel strength is the primary indicator of immediate debonding resistance, measuring the energy required to initiate a fracture at the interface under specified loading conditions [17]. Conversely, creep testing assesses the material's ability to maintain structural integrity under prolonged, sub-critical loads, which is vital for predicting long-term service life in demanding environments [18]. Together, these tests provide a comprehensive profile of an adhesive's mechanical limits, allowing engineers to mitigate the risk of catastrophic failure in real-world applications [19].

3.1.3. Application Method

Adhesives must be suitable for the production process, whether **manual** or **automated**, and exhibit good **workability** to ensure efficient, reliable, and high-quality bonding in manufacturing environments. Workability refers to properties such as viscosity, flow characteristics, open time (pot life), thixotropy, and ease of dispensing or spreading, which directly influence how well an adhesive can be applied without defects like voids, uneven coverage, or excessive waste [20]. These factors become critical when matching the adhesive to the specific demands of the assembly line or workbench setup.

In **manual application** processes common in low-volume production, prototyping, or complex geometries adhesives with moderate to higher viscosity and good open time are often preferred, allowing operators to brush, roll, or dispense the material precisely while maintaining control over placement and thickness. Manual methods, such as brushing or cartridge application, require adhesives that offer forgiving workability to accommodate variations in operator technique, but they can introduce inconsistencies if the adhesive's flow or cure characteristics are mismatched [21]. For instance, adhesives with poor workability may lead to uneven bonds or require excessive rework.

Conversely, **automated** processes such as robotic dispensing, spray systems, roll coating, or jetting demand adhesives optimized for high-speed, repeatable application. These require low to medium viscosity for smooth flow through nozzles, consistent rheology to prevent stringing or dripping, and rapid yet controlled cure profiles to align with cycle times. Automated systems enhance precision, reduce waste, and improve uniformity but are sensitive to variations in adhesive properties; for example, high thixotropy aids in preventing sag during robotic application, while poor workability can cause clogs or inconsistent bead formation [22]. Selection must also consider dispensing equipment compatibility, as viscosity and shear-thinning behavior affect pumpability and transfer efficiency.

Overall, mismatched application methods can compromise bond performance through defects like porosity, incomplete wetting, or weak interfacial adhesion, ultimately affecting structural integrity and durability. Early consideration of production-scale factors such as throughput, operator skill level, equipment constraints, and environmental conditions helps avoid costly downstream issues [22,23].

3.1.4. Environmental Impact

The adhesive industry is experiencing a significant shift toward **eco-friendly**, **non-toxic**, and **water-based** formulations, driven by environmental regulations, consumer demand for sustainability, and the need to reduce harmful emissions such as volatile organic compounds (VOCs). Traditional solvent-based adhesives often release high levels of VOCs, contributing to air pollution and health risks, prompting industries like packaging, construction, woodworking, and automotive to adopt greener alternatives [24,25].

Water-based adhesives, which use water as the primary carrier instead of organic solvents, offer low-VOC emissions, reduced toxicity, and improved workplace safety while maintaining strong bonding performance in many applications. This transition aligns with stricter global environmental standards on VOC limits and sustainability initiatives, making water-based options increasingly dominant [26]. Market analyses indicate strong growth in this segment, with water-based adhesives holding substantial shares (e.g., around 34% in sustainable categories) due to their environmental compliance, biodegradability potential in some formulations, and lower carbon footprint compared to petroleum-derived counterparts [25,27].

Beyond water-based systems, the broader push includes **bio-based** and **sustainable adhesives** derived from renewable resources such as vegetable oils, proteins, starches, lignin, and tannins, which further minimize reliance on fossil fuels and enhance non-toxicity [28,29]. These developments address not only ecological concerns but also performance demands, with in-

novations focusing on formaldehyde-free, low-emission, and recyclable solutions to support zero-waste goals and circular economy principles [30,31]. The shift toward sustainable materials in manufacturing is driven by a convergence of legal mandates and innovation. This industry-wide movement reflects a combination of regulatory pressures, particularly concerning the mitigation of volatile organic compounds (VOCs) and formaldehyde [32], heightened environmental awareness among global consumers [33], and technological advancements that enable comparable or superior performance from greener materials [34].

3.1.5. Key Types

Polyurethane (PU) adhesives are widely used in athletic footwear due to their excellent flexibility, which accommodates the dynamic stresses and repeated flexing experienced during sports activities, while also providing strong, durable bonds to diverse materials such as synthetic uppers and rubber soles [35,36]. This flexibility contributes to enhanced comfort, impact absorption, and overall performance in high-movement applications. In contrast, neoprene (polychloroprene) adhesives are commonly applied for general bonding in the footwear industry, offering reliable adhesion for a range of substrates, including leather, rubber, and certain synthetics, often in less demanding or traditional shoe constructions where high initial tack and heat resistance are prioritized [3,5]. PU adhesives have become particularly prominent in modern athletic and performance footwear for their versatility and superior mechanical properties under flexure, whereas neoprene remains a staple for broader, general-purpose shoe assembly.

3.2. Common Failures in Ethiopian Context

3.2.1. Key Adhesive Failures & Causes

Sole Adhesion Failures (Bond Failure): It is well-established that sole adhesion failures—colloquially known as "bond failures" remain the most pervasive defect in footwear manufacturing both globally and within the Ethiopian industry [37]. This structural detachment typically originates from suboptimal bonding protocols, where a critical failure point is the selection of an adhesive chemically incompatible with the specific substrate materials [38]. Specifically, mismatches frequently occur when adhesives optimized for the fibrous structure of leather uppers are erroneously applied to the non-polar or high-surface-energy surfaces of synthetic or rubber outsoles, leading to a weak interfacial bond [39].

In Ethiopia's footwear industry, which includes both large factories and numerous micro/small enterprises, challenges in adhesive selection and application are exacerbated by factors like outdated techniques, limited access to modern materials, and reliance on imported adhesives that may degrade during transit or have limited shelf life [40]. For instance, improper bonding of thermoplastic rubber soles without required pre-treatments (e.g., halogenation) has been noted as a specific technical oversight leading to weak adhesion [40]. Broader studies on footwear production highlight that poor adhesive selection for specific processing needs, combined with issues like improper surface preparation (e.g., inadequate roughing or buffing of surfaces), incorrect adhesive application methods, and suboptimal control of drying temperatures or pressing during sole attachment, frequently result in bond failures [41].

These problems align with global observations in the sector, where sole adhesion failure is documented as the most prevalent mode of footwear degradation. Research indicates this is frequently triggered by the use of incompatible adhesive systems, inadequate mechanical surface roughing, or insufficient curing times [42,43]. Furthermore, environmental stressors such as high humidity and temperature fluctuations can significantly compromise bond strength during both production and consumer use.

In resource-constrained environments like Ethiopia's shoe SMEs, these issues are compounded by specific systemic barriers. Inconsistent quality of imported adhesives and a lack of standardized application protocols often lead to high rates of sole detachment [44]. These technical gaps are exacerbated by operator training deficiencies and a lack of modern testing equipment, which are common hurdles identified in regional leather and footwear quality assessments across East Africa [45].

Improper Application Techniques

The integrity of an adhesive bond is not solely a product of the chemical formulation of the adhesive; it is a direct result of the application process. In the context of Ethiopian manufacturing and construction, the transition from theoretical material strength to practical bond durability is often undermined by inconsistent manual techniques, poor surface preparation, and environmental mismanagement. Research indicates that even high-performance structural adhesives fail prematurely when surface contaminants like oxides or moisture are not rigorously removed a common challenge in unregulated industrial environments [46]. Furthermore, the lack of standardized curing protocols and the prevalence of manual application lead to significant variations in bond line thickness, which directly compromises the mechanical load-bearing capacity of the joints [47]. Environmental factors, particularly the high-altitude UV exposure and fluctuating humidity levels characteristic of the Ethiopian highlands, further accelerate the degradation of improperly applied polymers [48].

The Interfacial Region: The Point of Failure

As noted by [49], adhesive failure is distinct from cohesive failure in that the separation occurs precisely at the interface between the adhesive and the substrate. This critical region, which [50] describes as a "delicate zone" only two to three molecules thick, is where the primary molecular forces Van der Waals forces, hydrogen bonding, and covalent bonding must be established. When application techniques are improper, this region fails to develop. Inconsistent manual application leads to variable bond line thickness. If the layer is too thin, it cannot achieve wetting the ability of a liquid to maintain contact with a solid surface resulting in a lack of mechanical interlocking. Conversely, excessively thick layers can trap internal stresses during the curing process, ultimately reducing the overall cohesive strength of the joint [51].

Variability in Manual Application

In many Ethiopian workshops, the lack of calibrated dispensing equipment leads to "spotty bonds." These are areas of insufficient coverage that act as stress concentrators [52]. Research indicates that uneven spreading is the primary culprit behind both visible and invisible bubbles, which serve as initiation points for cracks when the bond is subjected to service loads [51]. Furthermore, the "starved joint" resulting from insufficient adhesive spread is a common failure mode in furniture manufacturing. This is not a deficiency of the glue itself, but a failure of the operator to understand proper application rates [51].

Surface Preparation and "Buffing"

In the local context, "buffing" refers to the mechanical abrasion intended to increase surface roughness. However, improper buffing is a leading cause of failure:

- **Under-abrasion:** Fails to remove contaminants (oils, dust) or increase surface free energy, preventing the adhesive from "wetting out" the substrate.
- **Over-abrasion:** Can damage the substrate fibers, creating a weak boundary layer of fragmented material that shears off easily under tension.

The absence of cleanliness verification, such as contact angle measurement (a standard in advanced manufacturing), means that even monomolecular layers of contamination can proceed to bonding undetected, and effectively blocking intermolecular forces [50].

Environmental Impact on Material Integrity

In the Ethiopian highlands, the significant diurnal temperature range often fluctuating by more than 15°C within twenty-four

hours creates a volatile environment for chemical curing. Adhesives require a stable thermal window to achieve the molecular cross-linking necessary for structural integrity. When temperatures drop rapidly at night, the chemical reaction slows or halts, leading to "latent failure" where the bond appears set but lacks internal cohesion [53]. In more humid regions, such as the Gambela or Southern nations, interfacial moisture becomes the primary antagonist. Even a microscopic layer of condensation trapped between the buffing and application stages can act as a release agent. This phenomenon is exacerbated by the "skinning over" of adhesives, where the outer layer dries too quickly, trapping moisture and air pockets underneath [54].

Systemic and Economic Barriers

The failure of these bonds is rarely just a matter of chemistry; it is deeply rooted in the informal apprenticeship model prevalent in Ethiopia's vocational landscape. Without formal training in surface science specifically the concepts of surface energy and substrate preparation technicians often rely on inherited heuristics that may not account for modern synthetic materials. Furthermore, economic volatility leads to "material thinning." In an effort to maintain profit margins amidst rising import costs, practitioners often apply adhesive layers below the manufacturer's recommended thickness. This reduces the viscoelastic buffer of the bond, making it susceptible to brittle failure under mechanical stress [55].

Improper Curing/Oven Temperatures

Improper curing or uncontrolled oven temperatures represent a critical factor in adhesive failures, particularly in contexts where heat-cured adhesives, such as epoxies or certain structural formulations, are employed [56]. Failure to properly control heat during the curing process prevents the adhesive from achieving full crosslinking [57]. This lack of molecular development results in significantly reduced mechanical properties, including lower bond strength and decreased cohesive integrity [58]. Specifically, when curing temperatures fall below the optimal range, the degree of polymerization is incomplete, leading to increased brittleness and a reduction in both tensile and shear strength [59]. Conversely, excessively high temperatures can cause thermal degradation or premature hardening, which diminishes the material's flexibility and long-term durability [60]. These thermal inconsistencies often manifest as cohesive failure within the adhesive layer, interfacial weakness at the substrate boundary, or overall joint debonding when subjected to external loads [61].

Studies have consistently demonstrated that inadequate temperature control either too low, leading to under-curing, or excessively high, potentially causing thermal degradation directly compromises bond performance. For instance, low curing temperatures decelerate the crosslinking process, yielding incomplete cure and significantly lower tensile and shear strengths, while elevated temperatures beyond optimal ranges can induce brittleness or resin degradation [62,63]. In epoxy-based systems commonly used in construction, composites, or repairs, improper cure cycles result in defects such as voids, poor interlaminar strength, or reduced durability [20]. Troubleshooting analyses of bonded joints further attribute many failures to poor control or measurement of bondline temperature, where the adhesive within the joint does not experience the required time-temperature profile, leading to fractured adhesive layers or weak bonds.

Although specific literature on the Ethiopian context remains limited in publicly available academic sources, these mechanisms are highly relevant in developing regions like Ethiopia, where construction and manufacturing often face challenges such as inconsistent power supply, limited access to calibrated ovens or temperature-controlled environments, and variable ambient conditions [64]. These regions often rely on artisanal or semi-industrial practices where the lack of standardized thermal monitoring can lead to incomplete polymerization in adhesive bonds [65]. Such factors exacerbate improper curing, contributing to premature failures in applications like wood bonding, composite repairs, or structural adhesives in building and infrastructure projects [66].

Low Quality and Unreliable Supply

The Ethiopian manufacturing sector, particularly industries reliant on adhesives such as construction inputs, chemicals, and related assembly processes, faces persistent challenges rooted in low product quality and unreliable supply chains [67,68]. These systemic issues are primarily driven by inconsistent access to high-quality raw materials, which are exacerbated by a heavy reliance on imports and acute shortages of foreign currency [69,70]. Research indicates that approximately 37% of large manufacturing firms in Ethiopia suffer significant losses due to poor raw material quality and rising input prices, which directly undermine product reliability and market competitiveness [68]. Furthermore, the lack of vertical integration and the "low-quality trap" characteristic of the sector prevent manufacturers from achieving the performance benchmarks necessary for international competition [67,70]. Consequently, these supply-side risks and input inconsistencies remain the primary bottlenecks hindering the sector's overall growth and its contribution to the national economy [70,71].

The **Policy Studies Institute (PSI)** has documented these constraints in various studies on manufacturing linkages, productivity, and industrial development. For instance, local factories often struggle with **limited supply of raw materials** in terms of quantity, quality, and competitive pricing, leading to heavy reliance on imports and vulnerability to supply chain disruptions [72]. This affects sub-sectors like chemical and construction inputs, where inconsistent quality and absence of robust certification exacerbate product unreliability [72].

Broader PSI research highlights structural issues in manufacturing, including dependency on imported raw materials (often 95% or more in some contexts like industrial parks), limited domestic value addition, and challenges in achieving consistent quality standards due to input shortages and poor backward linkages [73,74]. These factors contribute to low and inconsistent product quality across manufacturing, as firms face difficulties in sourcing reliable inputs locally, resulting in production inefficiencies and compromised output reliability [75].

In the context of construction-related manufacturing (where adhesives are critical), PSI analyses point to ongoing quality, standard, technology, and innovation challenges that hinder reliable material supply and performance [76]. Similarly, productivity reports note broader manufacturing constraints, such as input quality issues impacting efficiency and competitiveness [77]. These adhesive-related failures manifesting as poor bonding strength, inconsistent application performance, or product degradation are thus tied to upstream raw material inconsistencies, import dependencies, and limited local production capacity for quality inputs.

Lack of Standardization: The lack of standardization and rigorous quality control (QC) in Ethiopia's manufacturing landscape significantly undermines the structural integrity and market competitiveness of essential products. In sectors such as construction and footwear, the absence of systematic testing for adhesive properties including viscosity, open time, and peel strength often results in catastrophic bonding failures.

Research indicates that many Ethiopian small and medium-scale enterprises (SMEs) lack the technical infrastructure and standardized protocols required to ensure adhesive consistency [78]. This technical gap leads to high defect rates, where finished goods like leather footwear or ceramic tiles suffer from delamination and separation under mechanical stress [79]. Furthermore, the reliance on varied imported and locally formulated adhesives without a unified national standard complicates the maintenance of quality benchmarks, ultimately leading to premature product failure and increased waste within the manufacturing cycle [80].

This issue stems from broader systemic challenges in Ethiopian manufacturing, including outdated equipment, poor raw material quality, unskilled labor, and limited adoption of standardized processes. For instance, studies on Ethiopian manufacturing industries highlight that factors such as lack of established quality policies, absence of incentive programs for quality improve-

ment, inefficient measuring and testing equipment, and insufficient employee awareness significantly impede product quality, directly affecting adhesive applications where precise formulation, application, and curing are critical [81].

In the chemical and adhesive sub-sector specifically, the absence of robust input/output quality control and standardization systems has been identified as a key constraint, hindering consistent adhesive performance and contributing to failures in bonding or finishing processes [82]. Related assessments of Ethiopia's adhesive industry strategy further note deficiencies in quality and standardization capacity for raw materials and outputs, exacerbating production inconsistencies and failure rates in factories lacking strict QC (Ethiopia's Adhesive Industry Strategy, as referenced in sector reports).

In construction-related applications, where adhesives are used for tiling, flooring, or surface bonding, defects often arise from poor workmanship, defective materials (including adhesives), and inadequate supervision/quality control. Common manifestations include loose tiles, adhesion failures between substrates and finishes, or separation due to non-compliance with specifications [83]. These issues align with wider patterns in Ethiopian building projects, where poor quality control contributes to material failures, including those involving adhesives or bonding agents.

Overall, the high rates of adhesive failure during production in many Ethiopian factories can be attributed to systemic gaps in quality infrastructure and technical expertise. These gaps result in variable adhesive quality, often due to the reliance on imported materials that may not meet standardized specifications for the local climate [84]. Furthermore, improper mixing and application remain prevalent because of limited specialized training for factory floor workers regarding polymer rheology and curing cycles [85]. These operational deficiencies are compounded by insufficient testing for bond strength and environmental resistance, as many local firms lack the calibrated instrumentation required to simulate long-term stress in high-humidity or high-temperature environments [86].

3.2.2. Common Factors Contributing to Failures

Technical Skill Gaps: In the Ethiopian construction industry, technical skill gaps represent a significant contributor to project failures, particularly in the context of modern building materials and techniques. These gaps often manifest as inadequate knowledge or expertise among workers, supervisors, and contractors in handling contemporary construction inputs, including modern adhesives used for applications such as tiling, flooring, bonding of structural elements, and finishing works. Research indicates that the rapid introduction of complex materials has outpaced the existing vocational training frameworks, leading to poor workmanship and frequent rework [87].

Furthermore, the lack of specialized training in chemical-based bonding agents often results in the incorrect mixing and application of adhesives, which compromises the structural integrity and aesthetic longevity of urban development [88]. This deficiency is exacerbated by a broader institutional failure to integrate modern material science into the standard operating procedures of small and medium-sized enterprises (SMEs) within the sector [89]. Consequently, the inability to effectively utilize these modern inputs not only escalates project costs but also diminishes the overall competitiveness of the local industry.

Studies on building construction failures in Ethiopia highlight that contractors' incompetence, including deficiencies in technical expertise and staff quality, ranks among the critical factors leading to defective works and overall project shortcomings [78]. Incompetence in the construction sector frequently stems from a lack of specialized training, resulting in improper application practices that compromise material performance and overall project quality [90]. Broader challenges, such as unskilled labor due to limited formal training programs and reluctance by companies to invest in skill development often driven by a fear of high workforce turnover exacerbate issues when implementing emerging materials and methods [91,92]. Research indicates that while technical challenges like resource shortages and inadequate supervision are prevalent, the use of unskilled labor directly leads to poor workmanship and diminished material efficiency [90,134]. Furthermore, the temporary and insecure na-

ture of construction employment often discourages long-term investment in human capital, creating a cycle where untrained workers struggle to meet the requirements of modern, complex construction technologies [92,93].

The integration of advanced chemical bonding agents into the Ethiopian construction sector has been characterized by a "technological mismatch." According to [94], the prevalence of finishing defects in Addis Ababa is frequently rooted in the lack of specialized skills required for modernized materials. This is compounded by the findings of [95], who identified that a significant portion of construction rework in Ethiopia stems from poor workmanship and a lack of adherence to technical specifications.

Furthermore, research focusing on the North Shoa Zone suggests that quality management systems are often bypassed to meet aggressive deadlines, leading to the misapplication of chemical components that require precise environmental conditions to cure [96]. These skill gaps directly correlate with the "premature degradation" observed in adhesive-dependent finishing works across the region.

Table 1: Critical Analysis of Adhesive Performance in Ethiopia

Performance Criteria	Adhesion Type / Substrate	Synthesis of Performance Limitations	Leading Source
Bond Strength Durability	Solvent-based Polychloroprene (PCP)	Provides high initial "green strength" (tack), which is vital for the manual lasting processes common in Ethiopian small and medium enterprises (SMEs). However, it often fails under cyclic mechanical stress.	[104]
Moisture Heat Resistance	Polyurethane (PU) Adhesives	Essential for Ethiopia's climate and export requirements. PU adhesives offer tensile strengths up to 30 MPa and heat resistance to 150°C, preventing sole detachment during transport in high-heat containers.	[105]
Material Compatibility	Natural Leather vs. Synthetics	Traditional Ethiopian bovine leather requires roughing (buffing) for mechanical interlocking. Synthetic uppers (PVC/PU) often require chemical primers to increase surface energy for effective bonding.	[106]
Environmental Safety	Water-based Dispersions	Transitioning to water-based systems reduces Volatile Organic Compounds (VOCs), which is a key barrier for Ethiopian factories seeking to enter European markets. These require longer drying times and controlled ovens.	[107]
Production Efficiency	Hot-Melt Adhesives (EVA/PUR)	Targeted at high-speed automated lines. While costly, they eliminate the "open time" (drying time) required by solvent glues, potentially increasing Ethiopia's factory line efficiency from 75% to over 80%.	[108]

Workforce-related barriers significantly impede the modernization of the Ethiopian construction industry, where a persistent shortage of skilled labor and inadequate vocational training programs hinder the effective use of advanced materials [97,98]. These deficiencies often lead to systemic inefficiencies, project delays, and technical failures [97]. Recent studies indicate that while Ethiopia has expanded its Technical-Vocational Education and Training (TVET) systems, many graduates still lack the specific technical competencies required by the industry, creating a "vicious cycle" of incompetence [99].

Addressing these gaps requires targeted training initiatives designed to modernize the workforce's capabilities in handling so-

phisticated technologies, such as industrialized building systems [98]. Critical areas for intervention include:

- **Surface Preparation:** Ensuring substrates are properly conditioned to maximize bond strength [100,101].
- **Environmental Awareness:** Understanding how local climate conditions affect the curing and durability of materials [102].
- **Application Techniques:** Implementing rigorous standards for adhesive and composite material use to prevent mechanical failure [100].

Such training is essential for ensuring adhesive efficacy and the long-term structural integrity of modern infrastructure in the region [97,103].

Synthesis of Key Findings

1. The "Quality Gap" in Sole Attaching

Critical analysis suggests that sole detachment remains the primary reason for quality rejection in Ethiopian footwear [104]. This is often not due to the adhesive's chemical failure but to inadequate surface preparation, such as improper skiving or failure to control the temperature of activating ovens.

2. The Move toward Sustainability

The Ethiopian Adhesive Industry Strategy (2015-2025) emphasizes a shift toward green chemistry. Solvent-based glues, while cheaper and easier to apply in poorly equipped workshops, pose severe respiratory risks to workers and hinder compliance with international environmental standards [107]. Synthesis of recent data suggests that factories adopting water-based PU dispersions see a 23% increase in finished shoe output performance when integrated with proper line balancing [108].

3. Material Sensitivity

Selecting the performance of adhesives must account for the diversity of substrates used in Ethiopian hubs like Modjo. While leather is naturally porous and receptive to adhesives, the increasing use of EVA and TPR (Thermoplastic Rubber) soles necessitates specialized primers or halogenation treatments to prevent "peel-off" failures [106].

Inadequate Machinery: Historical assessments of the Ethiopian shoe industry highlight the persistence of outdated machinery, such as tack lasting systems that have been largely superseded in modern production but continue to cause adhesion-related issues due to incompatibility with contemporary cement-based methods. For instance, problems arise when cement does not properly adhere to certain materials (e.g., plastic shanks), necessitating fallback to antiquated tack lasting, which compromises quality and efficiency. Recommendations have long emphasized replacing such equipment with modern pulling-over, lasting, and cementing machines to improve bonding outcomes [40].

Broader challenges in the Ethiopian leather and footwear value chain exacerbate these machinery limitations. Systemic issues include dependence on imported inputs (e.g., adhesives and chemicals), limited access to modern technology, and underutilization of installed equipment, which collectively hinder consistent adhesive application and controlled drying processes [109]. Obsolete machinery contributes to low productivity, poor workflow organization, and difficulties in achieving uniform adhesive coverage or proper drying conditions, leading to failures like insufficient penetration, premature cooling, or uneven curing (UNIDO, as cited in various sector reports).

In the context of footwear assembly, inadequate or outdated adhesive application equipment (e.g., manual or semi-automated systems lacking precise control) and drying setups (e.g., insufficient ovens or reactivation units) often result in bonding weaknesses. These are compounded by environmental factors and material incompatibilities, but machinery deficiencies remain a root cause in resource-constrained settings like Ethiopia's small- and medium-scale enterprises [110].

While global footwear literature identifies adhesive failures as stemming from improper application, curing, or equipment settings, the Ethiopian context uniquely amplifies these through outdated infrastructure and limited technological upgrades (e.g., challenges in upgrading machinery and equipment noted in national roadmaps; [111]).

Environmental Factors: In the Ethiopian manufacturing sector, environmental factors specifically elevated relative humidity and temperature fluctuations are primary drivers of adhesive bond degradation. In regions like the central highlands or during the Kiremt (rainy) season, moisture can infiltrate the adhesive-adherent interface, leading to plasticization of the polymer matrix or the hydration of oxide layers on metallic substrates [112]. Without standardized climate control in many local industrial facilities, adhesives often cure under sub-optimal conditions, which compromise their long-term shear strength and chemical stability [113].

High humidity often leads to prolonged or inconsistent adhesive drying times, as excessive moisture in the air hinders evaporation in water-based adhesives or interferes with curing mechanisms in others [114,115]. For instance, in water-based systems common in industries like footwear, packaging, or wood products manufacturing, elevated humidity slows solvent evaporation, potentially causing issues such as incomplete drying, reduced bond strength, or defects like blocking (unintended sticking during storage) [61,115]. This is exacerbated in manufacturing facilities lacking regulated temperature and humidity controls, leading to inconsistent production quality and higher failure rates [116,117].

Moreover, uncontrolled high-humidity environments can accelerate degradation in certain adhesive types, such as moisture-cure polyurethanes or others sensitive to hydrolysis, where excess moisture diffuses into the bond line, softening the adhesive or promoting chain scission and reduced mechanical properties over time [118]. Studies on adhesive joints under coupled temperature-humidity-load conditions show that high humidity significantly decreases failure loads, with effects compounded in tropical or subtropical climates similar to parts of Ethiopia [118,119].

In local contexts, such as footwear manufacturing in Ethiopia, improper environmental controls during adhesive application and curing combined with ambient humidity variations contribute to bonding failures, as processes like oven drying or open-air curing become unreliable without humidity management (e.g., as noted in discussions of adhesive processes in regional industries; *Journal of Chemical Research and Application*, 2017). Similar challenges appear in studies involving natural adhesives or wood bonding in Ethiopia, where environmental moisture influences bond durability [120]. These factors underscore the need for better-controlled manufacturing environments, such as dehumidification or humidity-resistant adhesive formulations, to mitigate failures in Ethiopia's industrial settings.

3.3. Strategic Recommendations

Enhance Quality: To enhance quality in adhesive bonding processes, manufacturers should prioritize improvements in adhesive quality specifically through strategic formulation selection, chemical consistency, and optimized material properties and application techniques, including rigorous surface preparation, dispensing precision, thickness control, and controlled curing conditions [121]. These focus areas directly contribute to superior bond strength and a significant reduction in structural defects such as voids, porosity, and interfacial adhesion failure [122]. By refining these variables, manufacturers achieve enhanced overall production performance, characterized by higher throughput, lower scrap rates, and improved long-term product durability in demanding environments [123].

Research emphasizes that advancements in adhesive formulations such as tailored polymer chemistries with enhanced toughness and environmental resistance combined with optimized application methodologies, significantly boost bonding reliability and strength [20]. For instance, precise control over adhesive application parameters, including bond line thickness and dispensing methods, minimizes defects originating from inconsistencies in surface preparation or curing, thereby integrating process parameters with long-term joint performance [23].

Effective strategies include adopting automated or optimized dispensing systems to ensure uniform application and consistent bond line thickness, which enhances mechanical performance in high-volume manufacturing [124]. Surface preparation techniques, such as laser texturing combined with resin pre-coating, have been shown to improve interfacial adhesion through better mechanical interlocking, leading to substantial increases in load-bearing capacity (e.g., ~25% improvement in some composite joints) [125]. Additionally, multilayer adhesive application techniques can increase bond strength to dentin or similar substrates by improving penetration and reducing technique sensitivity, with multiple layers yielding higher microshear bond strength compared to single-layer applications [126].

In industrial contexts, holistic quality control encompassing surface energy optimization, pretreatment (e.g., plasma or mechanical methods), and in-process monitoring addresses root causes of adhesion failure, elevating product quality and operational efficiency [127]. These integrated approaches link application techniques directly to reduced failure modes and enhanced manufacturing outcomes.

Address Process Weaknesses: Implementing rigorous **quality control** measures, such as continuous monitoring of **viscosity** during adhesive or coating application processes, is essential to ensure consistent flow behavior, uniform thickness, and optimal wetting of substrates, thereby minimizing defects like voids, poor adhesion, or inconsistent film build that contribute to bond or coating failures (Bonner, as cited in *Assembly Magazine*, 2024; see also discussions in rheological control for dispensing adhesives). Viscosity variations, often induced by temperature fluctuations or improper formulation, can lead to uneven dispensing, sagging, or insufficient penetration into substrate surfaces, directly impacting long-term **durability** and increasing the risk of interfacial failures [20]. Real-time viscosity monitoring and control systems enable adjustments to maintain stable rheological properties, reducing process variability and enhancing overall product reliability in manufacturing environments.

Furthermore, ensuring proper **drying** and **activation** (curing) times is critical to achieving complete polymerization or cross-linking, which directly influences mechanical properties, adhesion strength, and resistance to environmental degradation. Inadequate curing times can result in incomplete cross-linking, leading to defects such as porosity, voids, poor cure, and reduced durability under stress or exposure to moisture and temperature variations [23]. For instance, controlled curing conditions minimize residual stresses and improve bond integrity, while extended or optimized activation protocols enhance long-term performance by preventing issues like plasticization or hydrolytic degradation in polymer systems [128]. In waterborne or epoxy-based systems, precise management of drying rates and curing kinetics through factors like evaporation control and coalescing agents promotes robust film formation and superior protective qualities [129].

By integrating these process controls viscosity monitoring alongside strict adherence to validated drying and activation protocols manufacturers can significantly reduce failure rates, improve product consistency, and extend service life in demanding applications.

Strategic Alignment and Industrial Growth: The strategic planning for adhesive selection in Ethiopia should be closely aligned with the broader Ethiopian Industrial Development Strategic Plan (IDSP) 2013–2025, which serves as the foundational framework for industrial transformation during the relevant period. This plan emphasizes structural economic change through industrialization, aiming to increase the industrial sector's share of GDP from approximately 13% to 27% and the manufacturing sector's from 4% to 17% by 2025 [130].

Within this framework, the chemical and pharmaceutical sub-sector encompassing adhesives is prioritized for import substitution and value addition using local resources, such as agricultural and mineral inputs [131]. Strategic adhesive selection is therefore not merely a technical choice but a means of fostering essential linkages with downstream sectors like construction, leather, textiles, and packaging, which are pivotal to the nation's export-led growth strategy [132].

Adhesives fall under consumer and industrial chemicals, where the IDSP identifies opportunities for products such as industrial adhesives and natural adhesives to support import substitution, reduce foreign exchange outflows, and enhance inter-industrial linkages [82]. The plan's strategic objectives include expanding priority industries (e.g., chemicals), diversifying manufacturing, enhancing entrepreneurship, attracting investment (public, private, and foreign), and developing industrial zones [130]. Aligning adhesive selection with these involves prioritizing formulations that utilize locally available raw materials (e.g., starch-based or natural adhesives from agricultural byproducts, or synthetic ones leveraging emerging petrochemical inputs), target high-demand sectors (construction inputs, footwear/leather, and packaging), and support export-oriented or import-substituting production to contribute to foreign exchange savings and job creation.

Later strategies, such as the **National Import Substitution Strategy for Manufacturing Industry Sectors** (developed post-2013 IDSP but building on its foundations), further reinforce this by identifying chemicals and construction inputs (including adhesives) as priority areas for reducing import dependency through domestic production enhancement, regulatory improvements, market access, finance, infrastructure, and efficiency interventions [133]. Adhesive manufacturing can thus be selected and developed to address persistent imports in related categories (e.g., construction materials and chemicals), promoting local value chains and competitiveness.

Key recommendations for alignment include:

- **Prioritize import-substituting and resource-based adhesives:** Focus on natural or hybrid adhesives derived from local agricultural/mineral resources to minimize imported inputs and align with the IDSP's emphasis on broad economic linkages and technology transfer [82,130].
- **Integrate into industrial zones and investment incentives:** Locate production in designated industrial parks to benefit from infrastructure support and attract FDI, as outlined in the plan's objectives for zone development and investment enhancement [130].
- **Support human resource and technology development:** Invest in skilled labor and technology acquisition to improve capacity utilization and quality, addressing constraints like inadequate human resources noted in the IDSP and chemical sector analyses [82].
- **Link to downstream sectors:** Select adhesives that serve priority industries (e.g., leather products, construction), fostering value addition and reducing reliance on imports, consistent with import substitution pillars [133].

4. Conclusion and Recommendation

4.1. Conclusion

The systematic review of literature on the performance of adhesives used in Ethiopian footwear factories highlights that adhesive selection and application remain critical yet underexplored factors in the sector's overall quality and competitiveness. Existing studies and reports indicate that Ethiopian footwear manufacturing faces persistent challenges, including bond failures (such as delamination or sole detachment), which stem from improper adhesive selection, suboptimal application techniques,

inadequate surface preparation (e.g., poor buffing, skiving, or lasting), inconsistent environmental controls during bonding (e.g., oven temperature), and reliance on imported materials. Many factories depend heavily on imported adhesives, glues, and related chemicals, often solvent-based types, which contribute to quality inconsistencies, higher production costs, supply chain vulnerabilities, and potential health risks for workers due to volatile organic compounds (VOCs). While global literature emphasizes high-performance options like polyurethane reactive (PUR) hotmelts, water-based adhesives, and one-side or two-in-one systems for superior durability, flexibility, and efficiency, the Ethiopian context shows limited adoption of these advanced solutions. Broader industry analyses reveal that adhesive-related issues compound other problems, such as low line efficiency, import dependency for raw materials (including ~50–60% of components like glues and polymers), and inconsistent local leather quality, ultimately hindering export competitiveness and domestic market satisfaction. Despite government strategies (e.g., the 2015–2025 Adhesive Industry Strategy) aiming to boost local production and reduce imports, the literature suggests that adhesive performance continues to be a bottleneck in achieving higher productivity, product durability, and international standards in Ethiopian footwear factories.

4.2. Recommendations

To improve adhesive performance and overall footwear quality in Ethiopian factories, the following practical, evidence-informed actions are recommended:

- **Prioritize systematic adhesive selection criteria tailored to local materials and conditions:** Factories should evaluate adhesives based on bonding strength to common substrates (e.g., leather, synthetic uppers, rubber/PVC soles), heat resistance, flexibility, early green strength for production speed, and environmental durability (e.g., resistance to moisture and flexing). Shift toward globally proven high-performance adhesives, such as water-based or low-VOC polyurethane systems, to reduce bond failures and health risks.
- **Invest in standardized training and process optimization for adhesive application:** Implement protocols for proper surface preparation (buffing, skiving, cleaning), precise adhesive spreading, controlled drying/activation temperatures, and adequate pressing. Training programs for operators and quality controllers can significantly reduce common failure causes identified in footwear bonding literature.
- **Promote local adhesive production and supply chain localization:** Building on Ethiopia's adhesive industry strategy, encourage investment in domestic manufacturing of quality adhesives (including eco-friendly variants) to cut import dependency, lower costs, stabilize supply, and enable faster adaptation to factory needs.
- **Foster collaboration and knowledge transfer:** Ethiopian footwear manufacturers, research institutions (e.g., leather engineering departments), and international partners should conduct joint testing and trials of modern adhesives under local conditions. Government incentives could support pilot projects introducing PUR hotmelts or automated dispensing systems to boost efficiency and bond reliability.
- **Integrate adhesive performance monitoring into quality management:** Establish routine testing (e.g., peel strength, flex tests, aging simulations) and feedback loops to track bond failures in finished products, enabling continuous improvement and alignment with export market requirements.

Declarations

Author's Contribution

All authors contributed equally to this work from its inception up to final preparation of the Manuscript.

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Conflicting Interests

The authors declare that there is no conflict of interest with respect to the authorship or publications of this manuscript.

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