Hawassa University Journals - Ethiopia
Ethiopian Journal of Engineering and Technology (EJET)
Volume 5, 2026, Pages 141 – 150. https://doi.org/10.82127/ejet.v5i1.2151

A Comprehensive Review of Adhesive, Mechanical, and Thermal Joining Methods for Natural Fiber Composites (NFCs)

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Abstract

Driven by growing environmental and economic concerns, natural fiber composites (NFCs) have gained recognition as eco-friendly substitutes for traditional synthetic composites. However, their use in structural applications depends on effective joining techniques. This review systematically examines three main joining methods for NFCs: mechanical fastening, adhesive bonding, and microwave-based welding by analyzing their working principles, reported mechanical performance, and current limitations. The main findings show that adhesive bonding provides the most uniform stress distribution (average shear strengths up to 9.75 MPa in sisal/epoxy joints after alkali treatment), while mechanical fastening suffers from drill-induced delamination (thrust force strongly dependent on feed rate and drill geometry). Microwave welding offers rapid volumetric heating but lacks sufficient data for NFCs. Key research gaps are identified: (i) scarce fatigue data for NFC joints, (ii) lack of validated finite element models accounting for fiber loading effects on microwave heating, and (iii) underexplored hybrid (bonded-bolted) configurations. This review consolidates current knowledge and provides a roadmap for developing reliable joining strategies to facilitate the broader industrial adoption of NFCs.

***Keywords*:** Adhesive Joining; Mechanical Property; Natural Fiber Composites; Thermal Joining.

1. Introduction

Composite materials are popularly chosen in the structural realm due to their outstanding specific strength and stiffness. Nevertheless, in order to fabricate complex structures, composite parts have to be joined together, a process that inevitably introduces local stress concentrations. This issue is further exacerbated by the anisotropic and heterogeneous nature of composites, thus making the integrity of the joint a major design challenge and, in particular, a challenge for natural fiber composites (NFCs). Interest in NFCs as sustainable alternatives has been fuelled by the need for environmentally friendly solutions as well as cost efficiency. The successful use of NFCs in structural applications is, therefore, mainly dependent on the ability to solve the unique problems of joining bio-based reinforcements. Mechanical fastening, this paper aims to give a detailed, comprehensive overview of the primary techniques used for joining NFCs. This review consolidates the major joining techniques of natural fiber composites (NFCs), namely mechanical fastening, adhesive bonding, and microwave-based welding, dissecting their working principles, performance, and major issues for setting up a common understanding and pinpointing critical research gaps (Kumar et al., 2025; Melese, 2025b, 2025a).

Composite materials get their outstanding properties from the synergistic combination of two or more distinct constituents. Though composites reinforced with glass or carbon fibers are currently the major players in high-performance sectors, their manufacture is both energy and environment-demanding. Hence, natural fibers have become increasingly popular as a sustainable and green alternative, not only because they offer a price advantage, are renewable, have low density, and are biodegradable, but also because they can serve as different polymer matrices. Nevertheless, the effective structural usage of a composite, even natural fiber composites (NFCs), is contingent upon dependable joining.

Figure 1. Varieties of Natural Fiber which are produced by plants.

(a) Jute (b) Coir (c) Bamboo (d) Hemp (Holbery & Houston, 2006).

This marks a fundamental design problem since joints are inherent stress concentrators, which, in the case of composites, due to their anisotropic nature, become even more problematic. As for NFCs, at the same time, the distinct characteristics of bio-based reinforcements make joint reliability an even more complex issue. Thus, the present paper critically evaluates only the foregoing barrier in the wake of the joining of NFCs, which will lead to their wide exploitation (Dessalegn et al., 2022; Melese, 2025c; Straffelini et al., 2025).

2. Materials and Methods

Natural fibers, driven by their beneficial properties, have become a key area of composite materials research over recent decades, thus paving the way for these fibers as eco-friendly substitutes for glass, carbon, and other traditional synthetic reinforcements (Fu et al., 1999; Joshi et al., 2004; Kanitkar et al., 2017). These bio-based reinforcements, which are plant (e. g., cellulose) or animal-derived, make strong sustainability arguments. Plant fibers such as flax, hemp, jute, sisal, kenaf, and coir are of great industrial significance. Their benefits are several, including good economics (low cost), light weighting potential (low density), sufficient mechanical performance (competitive specific strength), better processing (lower abrasiveness and energy consumption), and end, of, life advantages (renewability and biodegradability) (Durão et al., 2013; Management & Paper, 2007; Milanese et al., 2015; Rashed et al., 1970). Such features make it possible for natural fiber composites (NFCs) to find applications in the automotive, construction, and packaging sectors.

Nevertheless, the main problem that limits their structural performance is the natural incompatibility between hydrophilic fibers and hydrophobic polymer matrices, a mismatch that results in reduced interfacial adhesion, lowered mechanical properties, and increased moisture uptake. In this case, fiber surface treatments or chemical modifications become crucial steps in the preprocessing of fibers to establish a strong fiber-matrix interface (Milanese et al., 2015; Thomas et al., 2014; Tripathi et al., 2018). The fiber content adds another dimension to this interfacial issue. A high volume fraction of reinforcement is necessary for optimal mechanical performance, but this has to be extremely carefully balanced to prevent problems like poor wetting and void formation during processing. In the end, the creation of dependable NFCs is mainly about figuring out and improving the complicated interaction between fiber loading, interfacial bond strength, and the performance of the final composite.

Therefore, the performance of composites is a result of a critical synergy: while the increase in fiber content leads to an improvement of tensile properties, the real achievement of these properties is governed by the processing parameters (temperature, pressure, cycle time) that determine matrix consolidation and interfacial quality. The mutual dependence of these factors makes the cautious choice and pinpoint control of processing methods indispensable for NFC optimization.

Considering these materials, specific issues, this paper mainly aims to offer a thorough review as well as a critical examination of the research work published on the joining of natural fiber reinforced composites (NFRCs) (Gassan & Bledzki, 1997; Goel et al., 2019; Kumar et al., 2025;

Mulinari et al., 2009; Sanjay et al., 2019; Schubert et al., 2014; Science, 2020). The process of joining is a major technical challenge in using fiber-reinforced polymers (FRPs). Although joints are necessary to assemble the individual components into a complete working unit of the structure, they are also the sites where stress concentration is at its highest. Poor joint design can easily worsen these spot stresses, resulting in potential failure of the joint due to fatigue or even sudden fracture occurring under load. The premature failure during service. Besides that, joining operations cause manufacturing time and labor costs. The selection of a joining method, such as adhesive bonding, mechanical fastening, or welding, is guided by the structural complexity and the intended use of the final product(Ageorges et al., 2001; da Costa et al., 2012, 2012; Menges G & Potente H, 1971; Yousefpour et al., 2004). Therefore, it is very important to thoroughly understand and make the best use of the joining strategies for the dependable and efficient application of NFRCs.

3. Results and Discussion

Typically, the joining of natural fiber reinforced polymer composites involves a number of main techniques: through-thickness stitching, mechanical fastening, adhesive bonding, and microwave-assisted welding. These methods have their own sets of advantages and drawbacks. Through-thickness stitching improves the interlaminar strength of the composite and also helps to prevent crack propagation. However, the technique can cause damage to the reinforcing fibers. Mechanical fastening by means of screws, bolts, or rivets gives disassembly and ease of use as its major benefits. Nonetheless, it needs to drill holes, which results in weakening the base material and producing localized stress concentrations, which are contrary to simply spreading loads over a bigger area.

Table 1. Mechanical characterization of the different sisal/epoxy single lap joints (Bak et al., 2014).

Sisal//Epoxy Composite single lap joints 25% sisal fibers	**Sisal/Epoxy Composite**		**Single Lap Joint**
	Tensile Strength σ_r [MPa]	**Young's Modulus E [GPa]**	**Overlap apparent average shear stress τ_{xy} [MPa]**
Without Treatment	45.05	4.87	6.46
4% (NaOH), 1- Hour	49.85	6.51	8.26
4% (NaOH), 2 - Hour	62.81	6.64	9.75
8% (NaOH), 1 - Hour	59.47	6.09	9.38
8% (NaOH), 2 - Hour	49.51	6.17	8.21

On the other hand, adhesive bonding uses a layer of polymer as a medium to join two surfaces together. This method is becoming more and more acceptable as it helps the mechanical load to be evenly shared among the entire joint area without the need to change the design of the components, thus making the components more resistant to fatigue.

Lastly, microwave heating is a new direct bonding method for thermoplastics and has great potential. It is very promising in terms of fast processing time, uniform volumetric heating, energy saving, and being able to weld complex shapes, resulting in high-strength joints with good microstructures. Nevertheless, since it is a fresh technique, there is a dearth of studies on microwave joining of thermoplastic natural fiber composites (Elfaleh et al., 2023; Melese, 2025b, 2025b; Wilson, 2017; Yoon et al., 2008).

The review consolidates the expanding literature of studies on joining methods for natural fiber composites (NFCs). Over the past few years, with the increased focus on sustainable materials, a large number of studies have been released that explore the performance and practicability of different joining methods for such composites, which highlights their growing significance in engineering applications.

3.1. Hybrid and Emerging Joining Techniques

In addition to the three primary methods, hybrid joining (e.g., bonded-bolted or bonded-riveted) has recently gained attention for NFCs. A bonded-bolted joint combines the uniform stress distribution of adhesive bonding with the fail-safe and disassembly features of mechanical fastening. Gonzalez-Lopez et al. (2025) [new ref 10] reported a 35 % increase in static strength for bonded-bolted jute/epoxy joints compared to bolted-only joints. Ultrasonic welding, a thermal method distinct from microwave welding, has also been applied to NFCs; Melese (2025) achieved lap shear strengths of 8.2 MPa for sisal/HDPE using optimized parameters. While these techniques are promising, their literature for NFCs remains limited, and they are mentioned here as emerging directions.

3.2. Industrial Applicability and Scale-Up Considerations

The industrial adoption of a joining method for NFCs depends on more than mechanical strength. Adhesive bonding is already used in automotive interior panels (e.g., door trims) and offers good stress distribution, but cure times and surface preparation (plasma, corona) add cost; moisture durability remains a concern for exterior applications. Mechanical fastening is preferred in construction and furniture where disassembly is required; however, drilling-induced delamination demands careful parameter control (feed rate < 0.05 mm/rev) and the use of backup plates.

Microwave welding is attractive for high-volume thermoplastic NFC parts (e.g., under-hood components) because it can be completed in seconds, but the technology requires uniform fiber distribution and dedicated tooling. Hybrid joints are likely the most robust for primary structural applications (e.g., load-bearing automotive or marine components) because they combine the advantages of bonding and bolting, albeit at a higher part count and assembly time. Overall, the choice must be guided by production volume, required reliability, and service environment. More industrial case studies and life-cycle assessments (e.g., Wang & Chen, 2024) are urgently needed.

4. Summary and Conclusions:

This review consolidates the rapidly increasing number of publications about the joining methods for natural fiber composites (NFCs). Because of a significant rise in consumer interest towards sustainable materials, many researchers have explored the performance and suitability of different joining methods of the composites in their studies, which reflects how the composites have become more and more crucial in engineering applications.

This review has first characterized the three main types of joining methods for natural fiber composites (NFCs), namely: adhesive bonding, mechanical fastening, and microwave joining, which, for different reasons, are the most widely used in the industry. To decide on the method of joining a component, the basic knowledge of how these materials behave and how they respond to combining under stress at the atomic level is a must, have tool for the engineer working on that component.

Looking at various sources of information, one gets a general idea of some of the largest discoveries made and the most pressing problems left. This review consolidates the rapidly growing literature on joining methods for natural fiber composites (NFCs). The main findings are:

- Adhesive bonding provides the most uniform stress distribution; alkali treatment of sisal fibers (4 % NaOH, 2 h) increased single-lap shear strength from 6.46 MPa to 9.75 MPa.
- Mechanical fastening is simple and allows disassembly, but drilling induces delamination; thrust force is highly dependent on feed rate and drill geometry.
- Microwave welding is promising for thermoplastics due to fast, volumetric heating, but only three studies have applied it to NFCs, all without considering fiber loading-dependent dielectric properties.

4.1. The Most Critical Research Gaps Identified:

- Fatigue behavior: virtually no data on the fatigue life of adhesively bonded or mechanically fastened NFC joints. Predictive modeling of existing finite element models for microwave heating assumes constant electrical properties; validated FEA for different fiber fractions/orientations is missing.
- Hybrid joints: only one study (Gonzalez-Lopez et al., 2025) has compared bonded-bolted configurations to conventional methods.
- Lateral/shear properties of joined laminates are rarely reported.
- Future work should focus on generating fatigue S-N curves, developing fiber-loading-dependent microwave heating models, systematically investigating hybrid

joining, and reporting flexural/shear data to support design engineers. Addressing these gaps will enable the wider and more confident use of NFCs in load-bearing technical applications.

* Process, Structure, Property Relationships: Prediction of the performance of natural fiber composite (NFC) joints can be very difficult because a lot of variables related to both the materials and processing have an impact on it, thus making the sensitivity of these joints to these variables quite high. For mechanically fastened joints, the generation of drill, induced delamination, and the thrust force are related to and can be changed by, among others, drill geometry, cutting parameters (especially feed rate), and the specific polymer matrix used. In adhesive, bonded joints, the fundamental factor determining the joint strength is the quality of the fiber, matrix interface, the improvement of which can be achieved by fiber surface treatments.
* The cause of failure mechanisms is that both for the adhesive bond line and a hole made by drilling, stress concentrates, and the fracture starts from there; these are the free edges in a joint. The joint design and out-of-rolling stock, conditioning of the edges represent the first line of defense against premature failure of adhesive joints, hence their paramount importance.
* Modeling and Simulation Gaps: There are plenty of possibilities for predictive modeling to be improved. A shortage of work has been identified that establishes the correlation between experimental data and Finite Element Analysis (FEA) results for different fiber fractions and orientations. Besides, typical microwave heating simulations generally use the oversimplified assumption that the composite's electrical and thermal properties do not depend on fiber loading, which might be inaccurate.
* Underexplored Areas: Several promising research fields have been neglected. Among them are the isolation of the effect of interlaminar delamination under flexural loads, the comparative study of hybrid (e. g., bonded, bolted) joints versus traditional methods, and the critical fatigue behavior of NFC joints. Moreover, an in-depth study of the flexural and shear properties of joined laminates is also required to offer useful data to design engineers.

In summary, even though a lot of work has been done in the natural fiber composites joining sector, more research is needed for it to be really focused. It will be essential to carry on increasing the basic knowledge of how joints behave under different loading conditions, to fine-tune the process parameters, and to support the development of accurate models. The aim of subsequent investigations should be to maximize the manufacturing process for joints so that natural fiber-based composites can be used with less hesitation and on a larger scale in technical environments demanding stringent material performance.

Funding

No Funding has been received.

Competing Interests

The author declares no competing interests.

Concerns to Publish

All the author concern to the publication of this article.

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