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A Review on Vacuum Bagged Natural Fiber Reinforced Polymer Composites

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ABSTRACT

To lessen dependency on synthetic fibers, researchers are looking at eco-friendly natural fiber composites, which are becoming more and more popular in industrial applications because to their low cost, low density, biodegradability, and non-abrasive qualities. However, comparing various aspects of the composite fabrication, manufacturing method affects the characteristics of the prepared samples. Among various manufacturing methods, vacuum bagging is one of the prominent techniques to fabricate composites. Vacuum pressure, fiber-matrix ratio, thickness of the mold are crucial factors that are needed to be considered for proper manufacturing of samples. Reviewing available literature, this article summarizes the characterization of the bio-composites manufactured using vacuum bagging technique and hence, provided significant factors to look after while using it. Moreover, practical uses of vacuum-bagged natural fiber reinforced composites have been discussed.

Keywords: Natural Fiber, Vacuum Bagging, Chemical Treatment, Mechanical Properties.

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1. Introduction

Increasing efforts to produce advanced materials with high strength and modulus, reduced density, improved thermal conductivity, lower thermal expansion, and reduced costs to fulfill rising performance expectations, which are driven by the critical role materials play in engineering design and applications [1]. The increasing interest in employing bio-composites is drawing researchers to investigate their fabrication [2]. Incompatible materials are combined to produce composites, which are perfect for a variety of advanced applications since they have high strength and specific modulus [3]. Synthetic fibers like glass, carbon, and aramid are frequently used in polymer composites because of their exceptional strength and stiffness. Nevertheless, these fibers present problems such as limited recyclability, high energy consumption, health hazards, and expensive production [4-5].

Researchers and manufacturers are interested in natural fiber-based composites, as they are relatively stronger, lightweight, nontoxic, and biodegradable that might be utilized in the building, automotive, and furnishings sectors [6]. Cotton, jute, sisal, wool, silk, and asbestos are examples of natural fibers that come from plants, animals, and minerals. They are extensively utilized in composites, paper, textiles, and insulation. Composed of cellulose, hemicellulose, lignin, and waxy materials, plant-based lignocellulosic fibers have several benefits, including affordability, sustainability, effective insulation, and safety for human health [2, 7-8].

A variety of problems, such as hydrophilia, low thermal stability, and poor interfacial adhesion between fibers and the matrix, can be resolved using compatibilizers or chemical treatments that increase the fiber-matrix adhesion [9]. Researchers have tested numerous chemical treatments, including alkaline, silane, acetylation, acrylation, maleated coupling agent, and others. The fiber's surface treatment technique significantly enhances the polymer-fiber connection, resulting in improved material properties [10-12]. The primary determinants of natural fibers' capacity to reinforce are their surface properties, mechanical strength, and polarity. Additional determinants include harvest maturity, retting degree, fiber treatment, ambient conditions, and processing techniques including carding and spinning [13]. Since natural fiber composites (NFCs) show promise as substitutes for carbon and glass fiber composites, research on them has expanded quickly. NFCs may reduce vehicle weight by up to 80% in the automobile sector, which improves fuel economy and lowers production and energy costs [14].

The manufacturing method is a further significant aspect that significantly affects composite characteristics. Vacuum bagging is renowned for its mass production capabilities among many composite manufacturing techniques. Other well-known techniques include injection molding, vacuum-assisted resin transfer molding (VARTM), hand layup, pultrusion, and others [2]. This review article will cover the effect of vacuum bagging fabrication technique on the mechanical, thermal, physical, and morphological characteristics of natural fiber reinforced polymer composites. A thorough literature search was conducted using keywords such as "vacuum bagging," "natural fiber composite," and "mechanical, thermal and morphological properties" in Scopus, Web of Science, and Google Scholar. Studies from 2005–2025 focusing on vacuum-assisted fabrication of flax, kenaf, sisal, bamboo, and jute composites were reviewed. Key characteristics (tensile strength, flexural strength, thermal degradation temperature and so on), resin system, stacking sequence, and fiber type data were gathered for comparison. It is believed that the composite research community would greatly benefit from this type of work.

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2. Vacuum Bagging

Highly effective natural fiber-reinforced polymer composites may be produced in large quantities with little tooling cost using a closed-mold process known as vacuum bagging. The present hand lay-up is expanded upon by vacuum bagging method. Vacuum bagging is a technique that puts mechanical pressure on a laminate as it cures [15]. The vacuum bagging method employs air pressure to compress and encapsulate wet laminates in a flexible opaque film [16]. It plays a crucial part in removing any trapped air between the laminates, maintaining the fiber orientation position during curing, lowering humidity, and maximizing the fiber to resin ratio in the composite product [15]. Figure 1 shows the schematic diagram of vacuum bagging method. The first layer in a standard vacuum bagging process is a release film or peel ply that is draped onto the mold followed by laminates, release film, bleeder and breather fabric, and vacuum bagging film as a last layer. The bagging film is then fitted with a vacuum gauge, and vacuum suction pressure is applied to a standard 25 mmHg [16].

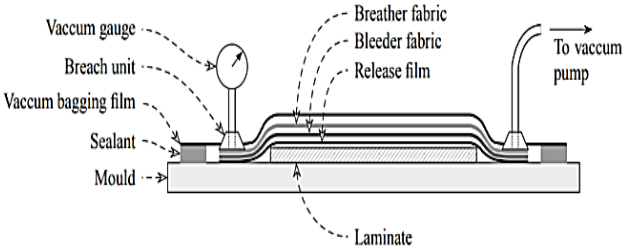


Fig.1 Schematic diagram of Vacuum Bagging process [16]

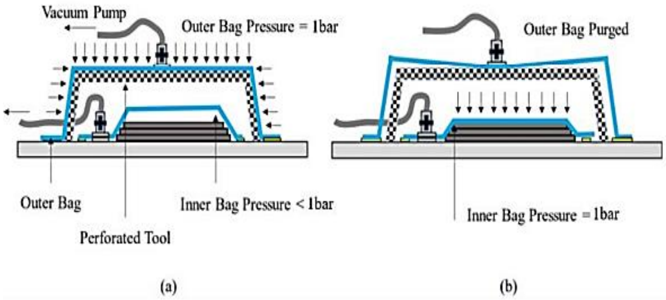


Fig.2 A double vacuum bagging set-up with a perforated device throughout (a) degassing phase and (b) compaction phase [19]

Vacuum bagging was initially employed to create large, superior composite parts. Because of its versatile tooling and material choices, vacuum bagging makes it possible to fabricate huge, intricate, and superior composite parts. Like the hand lay-up approach, it is easily adaptable to different forms. However, its primary disadvantages are limited resin injection pressure because of vacuum and ambient conditions, non-recyclable materials, and air leaks that rely on worker skill [17-18]. Double vacuum bagging (DVB) and single vacuum bagging (SVB) are the two varieties of vacuum bagging procedures. The SVB process involves stacking prepregs between the caul and the tool, and then sealing the assembly with a vacuum bag. In contrast, the DVB effectively removes volatiles created during curing by using a double vacuum bag. Using the standard SVB configuration, the DVB places an outer vacuum bag over the assembly and inserts a perforated steel tool between the two bags. When the vacuum is drawn, the perforated steel tool keeps the outer bag from collapsing into the inner bag, as seen in Figure 2. The outside bag undergoes a complete vacuum, while the inside bag undergoes a partial vacuum. The "ballooning effect" caused by the pressure differential facilitates the release of trapped air and volatiles. The inside bag is sucked as much as possible to consolidate the laminates during the last curing cycle, while the outside bag vacuum is purged to air pressure. The DVB approach is more effective than the SVB technique at allowing volatiles and trapped air to escape, according to research [16, 19].

3. Composites Fabricated by Vacuum Bagging Process

Vacuum bagging is a widely used process for producing both simple and complex composites in large quantities. A variety of natural fibers has been used as a reinforcement for composite in vacuum bagging process.

3.1 Flax Fiber Based

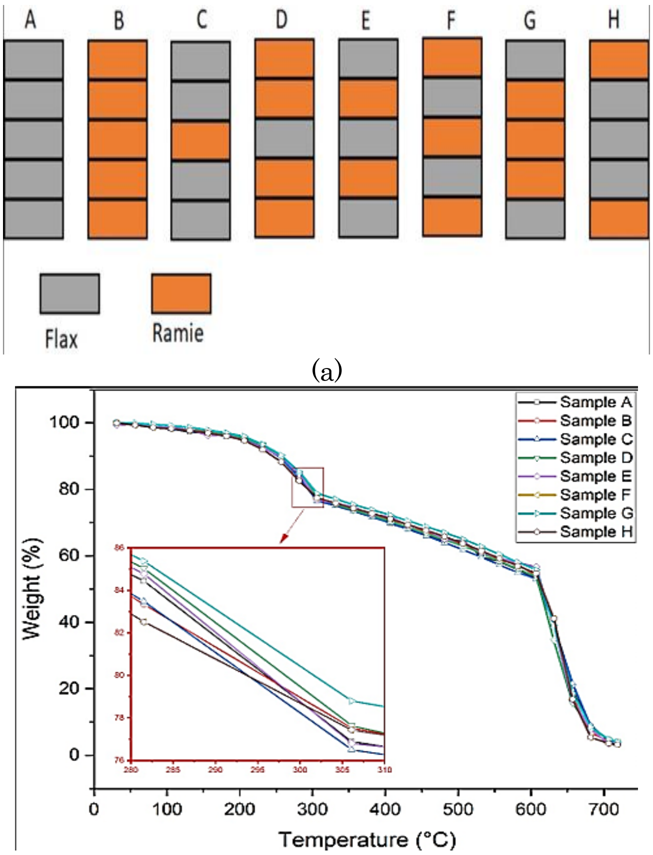
Rajendran et al. [20] conducted an experimental investigation to evaluate the tensile, flexural, and low-velocity impact characteristics of ±45 bi-axially positioned flax and its hybrid composite laminates. In order to enhance matrix–fiber interfacial bonding and reduce void content, the specimens underwent three hours of processing. The hybrid composites showed improvements in tensile strength and Young's modulus of 3.5 and 2.7 times, respectively, whereas flax composites obtained tensile and flexural strengths of 85.56 MPa and 102.97 MPa. Dal Pont and his colleagues [21] experimented on innovative flax fiber/epoxy composites that had a higher percentage of bio-based content. Three biobased epoxy resin systems reinforced with 30% twill flax fibers- MT1 (petro/biobased), MB1 (biobased/biobased), and BB1 (biobased/petro)-were created using vacuum bagging. The method produced void-free laminates with tensile moduli of 2.7–6.3 GPa, tensile strengths of 44–71 MPa, and impact strengths of up to 19.16 kJ/m² while ensuring uniform resin distribution and excellent fiber–matrix adhesion.

In a different study of mechanical properties of flax fiber reinforced hybrid composites, Karacor et al. [22] found that samples created by hand lay-up method had more hollow gaps and bubbles than those made using vacuum assisted techniques. Along with strength and stiffness, vacuum bagging also improves vibration damping properties. The damping capability of vacuum-bagged flax/epoxy samples is greater than that of compression-molded samples [23-24]. Rajesh et al. [25] used the vacuum bagging procedure to examine the thermal behavior of flax fiber-reinforced polymer composites hybridized with ramie fiber. TGA study showed a three-stage weight loss pattern with greatest thermal stability at 630 °C: cellulose degradation between 270-630 °C, entire disintegration up to 720 °C, and moisture and volatile loss below 270 °C.

Figure 3 illustrates that sample B had the lowest heat deflection temperature (76.0 °C), whereas sample D had the greatest (80.1 °C). Sample A's thermal conductivity was 0.182 W/mK, whereas sample E's was 0.213 W/mK, with the latter showing better heat transmission capabilities3.2 Kenaf Fiber Based

An optimized vacuum-bagging process for kenaf fiber reinforced epoxy composites was developed by Owen et al [26]. Compared to hand lay-up, a double-bag method produced a 15.3% higher hardness and a 112.6% higher flexural strength, while a single-bag method increased tensile and impact strengths by 16% and 38.5%, respectively.

It's noteworthy that the double vacuum-bagging method produced the best thermal stability at high temperatures. SEM evaluation verified that the vacuum processing methods resulted in well-consolidated composite structures with reduced void content, entire wettability, enhanced fiber-matrix interface, and uniform fiber distribution, all of which improved material characteristics. Zakaria et al.[27] additionally found greater mechanical characteristics utilizing vacuum bagging, noting that double-bagged kenaf fiber laminates obtained up to 54.1% higher flexural modulus than single-bag and wet lay-up laminates. Their investigation using scanning electron microscopy (SEM) showed that the double-bagged composites had a denser microstructure that was almost void-free, full fiber impregnation, and an excellent fiber–matrix interface. By compressing the lay-up using atmospheric pressure, Huang et al. [28] have confirmed that the vacuum bagging process improves matrix impregnation of kenaf fiber preforms and creates denser composites with less porosity. They add that autoclave molding, which may be used in conjunction with vacuum bagging, can be used if a higher compaction pressure is needed to improve mechanical and thermal qualities (up to around 5 bar). The hybrid kenaf/basalt fiber epoxy composites were created by Rajendiran and Palanivel [29] using vacuum bagging. In order to compare with five stacks of layered composite composed of individual basalt and kenaf fiber, respectively,



(a)

(b)

Fig.3 (a) Stacking sequences and (b) TGA curves of flax/ramie hybrid composites [25]

six hybrid composites with five stacks in six distinct stacking sequences were created. In comparison to pure kenaf composites, their hybrid laminates demonstrated noticeably better tensile, flexural, and compressive qualities, demonstrating that the vacuum-bagging technique can consistently create well-bonded multi-fiber polymer composites (as shown by SEM images of fracture surfaces). By incorporating carbon nanotubes (CNTs) into kenaf fiber epoxy laminates and consolidating them using vacuum bagging (600 mmHg vacuum pressure), Hidayah et al. [30] showed a hierarchical approach that resulted in notable increases in flexural stiffness and strength. These gains were ascribed to the improved interfacial bonding from the CNT reinforcement and the efficient removal of air voids under vacuum.3.3 Sisal Fiber based

According to Fajrin et al. [31] vacuum-bagged sisal fiber/epoxy composites have better mechanical qualities. The tensile, flexural, shear, and compressive stresses of the epoxy composite reinforced with unidirectional oriented sisal (UOS) fiber are 40.25 MPa, 62.16 MPa, 23.26 MPa, and 60.88 MPa, respectively. In contrast, the tensile, flexural, shear, and compressive stresses of the epoxy composite reinforced with randomly oriented sisal (ROS) fiber are 22.52 MPa, 51.5 MPa, 22.34 MPa, and 49.12 MPa, respectively. Kovuru and Schuster [32] experimented with alkali and fungal treatments to improve the mechanical characteristics of hemp and sisal fiber-reinforced composites for sustained uses. With the aid of vacuum bagging and a hand lay-up, they were able to achieve uniform fiber impregnation with low void content, enhanced fiber–matrix adhesion, and consistent laminate thickness in 48 hours. These results translated into a marked improvement in composite strength and quality. An investigation on the mechanical characteristics of polyester composites reinforced with sisal/banana hybrids was carried out by Naik et al. [33]. Hand lay-up, film stacking, and vacuum bagging were the methods used in the study to produce polyester composites reinforced with natural fiber sisal/banana hybrid composite. Different stacking sequences were used to create composite laminates, which are 3 mm thick and made up of five layers of fabric and resin mixture. These laminates were subjected to impact and hardness tests. In a laminate of 19.35 weight percent sisal fiber, the maximum impact strength and hardness were found to be 198.62 J/m and 13.8 Kgf/mm^2, respectively. A study on the flexural characteristics of epoxy composites reinforced with tropical natural fibers, including jute, sisal, hemp, and bamboo, made by vacuum bagging was carried out by Pathurahman et al. [34]. The flexural strength and modulus of sisal-based natural fiber composites were enhanced to 54.35 MPa and 2322 MPa, respectively. A prevalent failure mechanism of natural fiber composites evaluated under three point bending force was fracture at the bottom of the specimens, which is why the majority of the specimens failed.

3.4 Bamboo Fiber Based

Using the vacuum bagging technique, bamboo, rattan, and rattan–bamboo fiber composites were fabricated and compared by Parvez et al. [35]. Among them, rattan–bamboo composites exhibited the highest flexural **(**57.66 MPa**)** and impact **(**44.49 kJ/m²**)** strengths, surpassing ABS plastics and showing strong potential for automotive applications. Adil et al. [36] investigated the thermal and physical characteristics of a bamboo and rattan fiber reinforced polymer composite utilizing vacuum bag molding. They discovered that the composite reinforced with bamboo fiber had the greatest swelling thickness, the lowest density, and the largest water absorption. At 358°C and 414°C, respectively, the bamboo fiber reinforced hybrid composite exhibited the highest disintegration rate of 2.42 and 6.11 mg/min. For the same composite, the highest thermal conductivity of 0.266 W/m.K. was recorded. Similar vacuum bagging techniques were used by Oliveira et al. [37] to construct bamboo fiber/epoxy laminates. They discovered that improved fiber–matrix adhesion and the removal of air voids resulted in greater tensile, flexural, and impact strengths than manual lay-up techniques. Additionally, they found that utilizing the same vacuum method to combine bamboo with glass/carbon layers of synthetic fibers increased the composite's thermal stability (higher decomposition temperature in TGA) because of better interface bonding.

3.5 Jute Fiber Based

Ferreira et al. [38] described the static mechanical characteristics and impact reactions of a set of epoxies laminated composite plates made with various jute fiber types (coarse, medium, and fine) that were vacuum bagged. Both the thickness of the specimens and the proportion of fiber influenced the mechanical response to bending and impact loadings. In the initial days of immersion, mechanical characteristics were significantly lost, particularly for composites with smaller fiber grammage. Additionally, increasing the grammage of the mats encouraged a significant rise in peak load, impact energy for perforation, and recovered energy, as well as a noticeable decrease in deformation. The physical, mechanical, and thermal characteristics of epoxy resin unidirectional void-less composites reinforced with jute and bamboo fibers were thoroughly examined by Biswas et al. [39]. In the vacuum-bagged composites, bamboo fiber-reinforced epoxy had greater tensile strength, whereas jute fiber-reinforced epoxy demonstrated a higher Young's modulus and improved flexural strength because of the transverse fiber distribution. Additionally, TGA studies showed that epoxy composites reinforced with jute fibers were more thermally stable than their bamboo. Karthikeyan et al. [40] looked at how the mechanical characteristics of jute-reinforced polymer composites were affected by brown algae particles. The impact strength increased to 101.24 J/m^2, the tensile strength to 34.39 MPa, and the flexural strength to 73.16 MPa with the addition of 6 wt.% brown algae filler. However, overall mechanical performance declined when the filler level was increased beyond 6 wt. %.

According to a comparative analysis of research, by increasing fiber wetting and decreasing voids, the vacuum bagging technique dramatically improves mechanical and thermal characteristics for all varieties of natural fiber composites. Tensile and flexural values for flax/epoxy laminates are 85.6 MPa and 102.9 MPa, respectively, while kenaf/epoxy composites exhibit gains of 16% in tensile strength and 122.6% in flexural strength when compared to hand lay-up. Bamboo fiber composites have a flexural strength of 57.7 MPa at thermal breakdown temperatures up to 414 °C, whereas sisal/epoxy laminates attain tensile and flexural strengths of 40.25 MPa and 62.16 MPa. In the same way, jute/epoxy composites exhibit flexural strength of around 73 MPa along with good stiffness and thermal stability over 400 °C

4. Critical Parameters of Vacuum Bagging Technique

Processing parameters have a significant impact on the performance of vacuum-bagged natural fiber/polymer composites. During bagging, for instance, a high vacuum (around 1 bar) compacts the laminate by squeezing out extra resin, decreasing porosity, and increasing the fiber volume fraction. This uniform compaction reduces voids and significantly increases fiber–matrix contact, which in turn increases mechanical characteristics [41-42]. Strength and stiffness are significantly impacted by the type of natural fiber used. Stiffer laminates are made from stronger fibers, such as hemp (30–60 GPa modulus); for example, hemp has a greater tensile strength (250–900 MPa) than sisal (400–700 MPa) [32]. Strength and rigidity are increased by more fiber content, but only to a practical extent. Vacuum bagging allows for negligible voids and high fiber fractions (typically 25-30%). For instance, the stiffness and tensile strength were best in hemp/sisal laminates that contained 25% sisal by weight (as well as treated fibers). While modulus and load capacity increase with increasing volume percentage, voids and partial wet-out become problematic if vacuum and resin viscosity are not properly managed [32, 41]. Properties are significantly impacted by the layup sequence, which includes stacking order and symmetry. In a vacuum-bagged epoxy composite, Nag et al. [43] showed that the best tensile strength was obtained from a symmetric hybrid stack consisting of layers of palmyra, jute, and luffa with a 45° fiber orientation. Similarly, by sandwiching natural fiber plies between synthetic fibers (or vice versa), the composite properties may be altered.

5. Practical Application

Many different industries currently employ vacuum bagged natural fiber reinforced polymer composites (NFRPCs). For instance, natural-fiber panels (such as jute, flax, hemp, kenaf, sisal, etc.) are utilized for dashboards, door panels, headliners, seat backs, and other interior components in the automobile and aerospace industries [35-36, 44-45]. The use of vacuum-treated flax or jute/epoxy sandwich hulls and decks in maritime boats, such as racing skiffs and catamarans, has been established. Bio-epoxies have also been vacuum-infused into flax, hemp, or bamboo laminates to create bicycle frames, surfboards, canoes, and other recreational sports equipment [46-47]. NFRPC panels can be used for low-weight, vibration-damped constructions in consumer products and building applications (e.g., doorframes, partition panels, furniture, and packaging) [48]. Importantly, these parts are of higher quality because of vacuum bagging: the applied vacuum removes air and extra resin, resulting in very low porosity (often less than 2% voids) and good fiber wetting. Consequently, compared to hand-laminated parts, vacuum-bagged NFRPC laminates have better fatigue/endurance and greater tensile and flexural strength [44, 49].

6. Conclusion

For natural fiber-reinforced polymer composites, vacuum bagging is a sustainable and efficient production technique that provides better quality and consistency than traditional hand lay-up. The technique reduced void content to 2%, improved thermal stability to as high as 630 °C, increased flexural strength, hardness, and flexural modulus by 112.6%, 15.3%, and 54.1% respectively throughout the examined investigations. Compared to single-bag systems, double-vacuum bagging consistently produced superior consolidation and interfacial bonding. Having been considered, the procedure ensures increased fiber wetting, enhanced strength-to-weight ratio, and enhanced durability of flax, kenaf, sisal, jute, and bamboo composites, establishing vacuum bagging as a dependable and environmentally friendly method for producing bio-composite materials on a big scale. Future studies should concentrate on modeling resin flow and curing kinetics to forecast laminate quality, incorporating nano-fillers or bio-based resins, and creating adaptive vacuum control systems to manage compaction pressure.

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