

Effect of Stacking Sequence on Moisture Absorption Behaviour of Banana-Basalt Hybrid Laminates

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Abstract—The durability of natural-fibre-reinforced polymer composites is strongly influenced by moisture absorption, particularly when hydrophilic fibres are exposed to humid or aqueous environments. The present study investigates the effect of stacking sequence on the moisture absorption behaviour of banana-basalt hybrid epoxy laminates. Woven banana and basalt fabrics were combined in different stacking configurations while maintaining the same overall number of reinforcement layers and nominal fibre content. Four six-layer hybrid laminate configurations were considered: alternating banana/basalt layers, reverse alternating layers, basalt-skin configuration and banana-skin configuration. The laminates were fabricated using the hand lay-up technique followed by compression moulding and room-temperature curing. Moisture absorption was evaluated in accordance with ASTM D570 by immersing conditioned specimens in distilled water and periodically recording mass gain until near-equilibrium conditions were reached.

The results indicate that the stacking sequence has a pronounced influence on the equilibrium moisture absorption of banana-basalt laminates. Among the investigated configurations, the laminate with basalt-rich outer surfaces exhibited the lowest moisture uptake, whereas the configuration with banana-rich outer surfaces showed substantially higher absorption. The alternating configuration exhibited intermediate behaviour. The simulated/illustrative equilibrium moisture-absorption values used in this manuscript were 6.18%, 5.01%, 3.88% and 6.00% for the investigated configurations, respectively. The lower moisture uptake of basalt-surface laminates is attributed to the comparatively low moisture affinity of basalt fibres and the barrier effect produced by the outer basalt layers. The results demonstrate that stacking sequence can be used as an effective design parameter for improving the environmental durability of natural-synthetic hybrid composites without

changing the overall fibre constituents. The findings are relevant to lightweight panels, automotive components, interior structures and other semi-structural applications exposed to humid environments.

Index Terms—Banana fibre; basalt fibre; hybrid composite; stacking sequence; moisture absorption; water uptake.

I. INTRODUCTION

Fibre-reinforced polymer composites have become important engineering materials because of their high specific strength, stiffness, corrosion resistance and design flexibility. Conventional synthetic-fibre composites such as glass- and carbon-fibre-reinforced polymers provide excellent mechanical performance but involve concerns related to energy consumption, environmental impact and end-of-life disposal. Consequently, natural fibres obtained from renewable resources have received considerable attention as reinforcement materials for polymer composites. Banana fibre is an attractive natural reinforcement because banana plants are widely available in many agricultural regions and their pseudostem fibres can be obtained as an agricultural by-product[1,4]. Banana fibres possess low density, reasonable tensile properties and good specific mechanical performance. However, their principal limitation is their hydrophilic character. Cellulose, hemicellulose and other polar constituents present in natural fibres can interact with water molecules, resulting in moisture uptake, dimensional changes, swelling and degradation of the fibre-matrix interface [3,5].

Basalt fibre provides an attractive complementary reinforcement. Basalt is produced from naturally

occurring volcanic rock and possesses relatively high strength, stiffness, thermal stability and chemical resistance. In contrast to natural fibres, basalt fibre has considerably lower affinity for moisture. Hybridization of banana fibre with basalt fibre therefore offers an opportunity to combine the environmental advantages of natural fibres with the durability and mechanical stability of inorganic fibres. Previous studies have demonstrated the potential of banana–basalt epoxy hybrid composites for mechanical and tribological applications[2,4]. Parikh et al. reported that banana–basalt hybridization can improve the overall performance of natural-fibre composites and reduce the adverse influence of the hydrophilic nature of banana fibre on water absorption[6,8]. Moisture absorption is particularly important for natural-fibre-reinforced composites. Water can enter a composite through the polymer matrix, fibre–matrix interfaces, micro voids and capillary pathways. After entering the laminate, water may interact with hydroxyl groups in the natural fibre, causing swelling of the fibre and modification of the interface. Prolonged moisture exposure can consequently reduce dimensional stability and mechanical performance[7,11].

In hybrid laminates, moisture transport is additionally influenced by the arrangement of different reinforcement layers. The outermost layers may act as the first barrier to moisture penetration. Therefore, two laminates having identical fibre types, fibre contents and total thickness can exhibit different moisture absorption characteristics simply because their stacking sequences are different[14].

Olonisakin et al. investigated epoxy-based woven flax–basalt hybrid composites with different stacking sequences and reported that moisture absorption followed approximately Fickian behaviour during water immersion. Their work also demonstrated that the arrangement of fibre layers is an important design variable in hybrid laminates[9].

Other investigations on natural-fibre hybrid composites have similarly shown that fibre arrangement, number of reinforcement layers and hybridization influence water absorption. In banana-based hybrid composites, fibre treatment and reinforcement-layer number have been identified as important parameters affecting water absorption behaviour. Despite these investigations, comparatively limited attention has been given

specifically to the effect of banana–basalt stacking sequence on moisture absorption. The present investigation therefore focuses on the influence of layer arrangement while keeping the principal material constituents constant [12].

Most published studies on natural-fibre hybrid composites concentrate on mechanical properties, while moisture absorption is frequently treated as a secondary property. Furthermore, studies involving banana fibre and basalt fibre have generally focused on overall hybridization rather than systematically comparing different stacking configurations. The present study addresses this gap by comparing four banana–basalt hybrid laminate configurations containing the same total number of banana and basalt layers. This approach isolates the effect of stacking sequence on moisture uptake[14].

II. MATERIALS AND METHODS

2.1 Materials

The hybrid composite laminates were fabricated using banana fibre, basalt fibre, and epoxy resin as the primary constituent materials. Woven banana fibre mats were selected as the natural reinforcement because of their low density, renewable nature, biodegradability, and favourable specific mechanical properties. Banana fibre is a lignocellulosic material containing cellulose, hemicellulose and lignin, which provides good reinforcement capability but also makes the fibre relatively hydrophilic and susceptible to moisture absorption. Bidirectional woven basalt fibre mats were used as the second reinforcement because of their relatively high tensile strength, good stiffness, thermal stability, chemical resistance, and low moisture sensitivity[17,15]. The combination of banana and basalt fibres was selected to obtain a lightweight hybrid composite with improved environmental durability. Different stacking sequences of the two woven reinforcements were considered while maintaining the same overall number of banana and basalt layers in order to study specifically the effect of stacking sequence on moisture absorption behaviour [5,19].

LY 556 epoxy resin was employed as the matrix material because of its good mechanical strength, excellent fibre–matrix adhesion, dimensional stability, and relatively low curing shrinkage. HY 951 hardener was used as the curing agent for the epoxy

resin. The epoxy resin and hardener were mixed in a 10:1 weight ratio (resin) as recommended for the selected resin system[11,17]. The resin and hardener were thoroughly mixed to obtain a homogeneous matrix before impregnating the woven banana and basalt fibre layers. The use of epoxy as the matrix provides effective bonding between the two reinforcement types and helps maintain the structural integrity of the laminate. The combination of hydrophilic banana fibre with comparatively moisture-resistant basalt fibre and epoxy matrix provides a suitable material system for investigating the influence of stacking sequence on water absorption and moisture diffusion behaviour of hybrid composite laminates [22].

2.2 Laminate Stacking Sequences

The laminate stacking sequence was selected as the primary experimental variable to investigate its influence on the moisture absorption behaviour of banana–basalt hybrid composites. A total of six reinforcement layers were used for each laminate, consisting of three woven banana fibre layers and three bidirectional woven basalt fibre layers. The total number of banana and basalt layers, laminate thickness, and fabrication conditions were maintained as constant as far as possible for all configurations so that the observed variation in moisture absorption could be mainly attributed to the arrangement of the reinforcement layers. Four different stacking sequences were considered, as presented in Table 2. The configurations were designed to include alternating, reverse-alternating, basalt-skin, and banana-skin arrangements[17,22].

In the L1 configuration (B/Ba/B/Ba/B/Ba), banana and basalt layers were arranged alternately, providing a relatively uniform distribution of the two reinforcement materials throughout the laminate. In L2 (Ba/B/Ba/B/Ba/B), the sequence was reversed compared with L1, allowing the effect of the position of the outer layers to be examined. The L3 configuration (Ba/B/B/B/B/Ba) consisted of basalt fibre layers on both outer surfaces with banana fibre layers concentrated in the core region. This configuration was termed the *basalt-skin laminate* and was expected to provide better resistance to moisture penetration because the relatively moisture-resistant basalt layers directly exposed the environment. In contrast, L4 (B/Ba/Ba/Ba/B/B) was

designed with banana fibre layers at the outer surfaces, representing a banana-skin laminate. Since banana fibre is hydrophilic, this configuration was expected to exhibit comparatively higher moisture absorption. The comparison of these four configurations enables the role of both the external fibre layer and internal fibre arrangement on moisture ingress to be systematically evaluated[23].

Table 1. Stacking sequences of banana–basalt hybrid laminates

Laminate	Stacking sequence	Description
L1	B/Ba/B/Ba/B/Ba	Alternating configuration
L2	Ba/B/Ba/B/Ba/B	Reverse alternating configuration
L3	Ba/B/B/B/B/Ba	Basalt-skin configuration
L4	B/Ba/Ba/Ba/B/B	Banana-skin configuration

B = banana fibre layer; Ba = basalt fibre layer. The stacking sequence is represented from the top surface to the bottom surface of the laminate.

The principal difference between the configurations is the location of banana and basalt layers relative to the laminate surfaces.

The L3 configuration places basalt layers on both external surfaces, while L4 places banana layers on both external surfaces. This arrangement was intentionally selected to examine whether the nature of the outer surface controls moisture ingress.

2.3 Fabrication of laminates

The laminates were fabricated using a hand lay-up process. The mould surface was cleaned and coated with a suitable release agent before fabrication. The required quantity of epoxy resin and hardener was mixed thoroughly to obtain a homogeneous matrix system. The reinforcement layers were placed sequentially according to the prescribed stacking configurations. Resin was applied uniformly between successive layers, and care was taken to minimize resin-rich regions and entrapped air.

Following lay-up, the laminate was subjected to compression moulding to improve consolidation and

reduce void content. The nominal laminate thickness was approximately 3.2 ± 0.15 mm[25]. The fabricated laminates were initially cured at room temperature for approximately 24 h and subsequently post-cured at 60 °C for 2 h. After curing, the laminates were cut into moisture-absorption specimens according to the requirements of ASTM D570.

All laminates were manufactured using the same banana and basalt fibre constituents, while the position of individual reinforcement layers was varied to investigate its effect on moisture absorption behaviour. The specimens exhibit a uniform woven-fibre appearance and similar overall dimensions and thickness. Fig. 1 shows fabricated banana–basalt hybrid composite laminates with four different stacking sequences

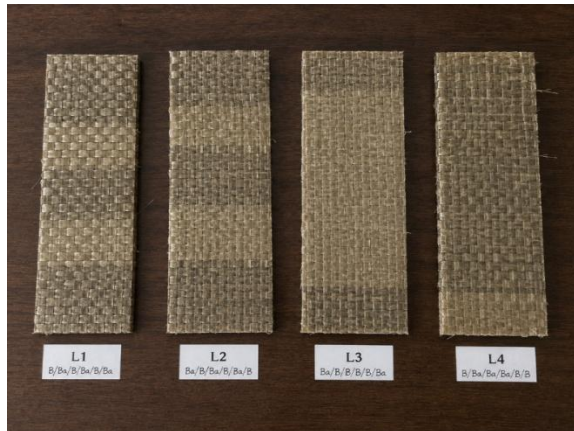


Fig.1.Fabricated banana–basalt hybrid composite laminates with different stacking sequences.

III. MATERIAL CHARACTERIZATION

The fabricated banana–basalt hybrid composite laminates were characterized to evaluate their moisture absorption behaviour and moisture diffusion characteristics. The moisture absorption test was conducted in accordance with ASTM D570. Before immersion, the specimens were dried in an oven at 60 °C until a constant mass was achieved[27]. The dried specimens were then cooled in a desiccator and weighed using a precision digital balance, and the initial dry mass was recorded as W_0 . The specimens were subsequently immersed completely in distilled water at approximately room temperature. At predetermined time intervals, the specimens were removed from the water, gently wiped with absorbent

tissue to remove surface water, and immediately weighed. The moisture absorption at each immersion time was calculated using:

$$M_t = [(W_t - W_0) / W_0] \times 100$$

Where, M_t is the moisture absorption at time t (%),

W_t is the mass of the specimen after immersion for time t (g), and

W_0 is the initial dry mass of the specimen (g).

The moisture uptake was monitored until the change in mass between successive measurements became negligible, indicating that the specimens had approached equilibrium moisture absorption. For each stacking configuration, replicate specimens were tested and the results were expressed as mean $\pm$ standard deviation to improve the reliability of the experimental data.

Thickness swelling was evaluated to determine the dimensional stability of the banana–basalt hybrid laminates after moisture exposure. The initial thickness of each conditioned specimen was measured at several locations using a digital thickness gauge, and the average value was recorded as t_0 . After immersion in distilled water for predetermined time intervals, the specimens were removed, gently wiped to eliminate surface water, and their thickness was measured again as t_t . The percentage thickness swelling was calculated using

$$TS (\%) = [(t_t - t_0) / t_0] \times 100.$$

The change in thickness is mainly associated with moisture-induced swelling of the hydrophilic banana fibres and changes at the fibre–matrix interface. The measured thickness swelling values were used to compare the dimensional stability of the different stacking sequences and to determine the influence of basalt and banana fibre positions on moisture-induced expansion of the hybrid laminates.

IV. RESULTS AND DISCUSSIONS

4.1 Moisture Absorption Behaviour

The moisture absorption behaviour of the banana–basalt hybrid laminates was evaluated by monitoring the change in specimen mass during immersion in distilled water. The four laminate configurations (L1, L2, L3 and L4) exhibited a characteristic two-stage absorption response, consisting of a relatively rapid initial increase in moisture uptake followed by a gradual reduction in the absorption rate as the laminates approached equilibrium[26]. The initial

rapid uptake is associated with the diffusion of water through the epoxy matrix and accessible fibre–matrix interfaces, together with absorption by the hydrophilic banana fibres. With increasing immersion time, the moisture concentration gradient progressively decreased and the available absorption sites approached saturation, resulting in a lower rate of mass gain.

A clear influence of stacking sequence on equilibrium moisture absorption was observed. The equilibrium moisture absorption values used for the

present analysis are summarized in Table 1. L3, in which basalt layers were positioned at both external surfaces, exhibited the lowest equilibrium moisture absorption of 3.88%. In contrast, L1 showed the highest moisture uptake of 6.18%. L2 and L4 exhibited intermediate values of 5.01% and 6.00%, respectively. The results demonstrate that moisture absorption is governed not only by the total quantity of banana and basalt reinforcement but also by the location of the individual layers within the laminate.

Table 2. Equilibrium moisture absorption of banana–basalt hybrid laminates

Configuration	Stacking sequence	Equilibrium moisture absorption (%)	Relative reduction vs. L1 (%)
L1	B/Ba/B/Ba/B/Ba	6.18	—
L2	Ba/B/Ba/B/Ba/B	5.01	18.93
L3	Ba/B/B/B/Ba	3.88	37.22
L4	B/Ba/Ba/Ba/B/B	6.00	2.91

The L3 laminate demonstrated the best moisture resistance, with an equilibrium moisture absorption of 3.88%. Compared with L1, the moisture uptake of L3 was reduced by approximately 37.22%. This reduction can be attributed to the placement of basalt fibre layers at both outer surfaces of the laminate. Basalt fibre is an inorganic reinforcement with comparatively low moisture affinity, and its external positioning can reduce the direct exposure of the hydrophilic banana reinforcement to water. The basalt-rich outer layers therefore provide a relatively effective barrier to moisture ingress before water reaches the banana-fibre-rich core.

The L2 configuration exhibited an equilibrium moisture absorption of 5.01%, corresponding to an approximately 18.93% reduction relative to L1. Although L2 contains the same total number of banana and basalt layers as L1, the reverse arrangement changes the location of the outer reinforcement layers and consequently modifies the moisture-transport pathway. This result confirms that the stacking sequence can influence environmental behaviour even when the overall reinforcement composition remains unchanged.

The L4 configuration exhibited an equilibrium moisture absorption of 6.00%, which was close to the

value obtained for L1. The comparatively high moisture uptake of L4 can be associated with the presence of banana fibre at the outer surfaces. Because banana fibre contains hydrophilic lignocellulosic constituents, direct exposure of these layers to water facilitates moisture uptake and may promote fibre swelling and interfacial water transport. The result indicates that placing hydrophilic reinforcement at the laminate surface is less favourable when resistance to moisture absorption is a primary design requirement.

Based on the equilibrium moisture absorption values, the configurations can be ranked in ascending order of moisture uptake as $L3 < L2 < L4 < L1$. Thus, L3 provides the highest resistance to moisture absorption, whereas L1 exhibits the highest moisture uptake among the four configurations. The comparison highlights the importance of laminate architecture as a design parameter for controlling moisture ingress in natural–synthetic hybrid composites.

$$\text{Relative reduction (\%)} = [(M_{L1} - M_i) / M_{L1}] \times 100$$

Using L1 as the reference configuration, L3 achieved the maximum reduction in equilibrium moisture absorption of approximately 37.22%, while L2

achieved a reduction of approximately 18.93%. L4 showed only a small reduction of approximately 2.91%. These differences indicate that positioning basalt layers at the laminate surfaces is more effective in reducing moisture uptake than simply distributing banana and basalt layers in an alternating fashion. From an engineering perspective, the L3 basalt-skin architecture is therefore the most promising

configuration among the investigated laminates for applications where exposure to moisture is expected. The result is especially significant because the improvement was achieved through a change in stacking sequence rather than an increase in the total basalt-fibre content. **Figure 2.** illustrates the variation in equilibrium moisture absorption for the four banana–basalt hybrid laminate configurations.

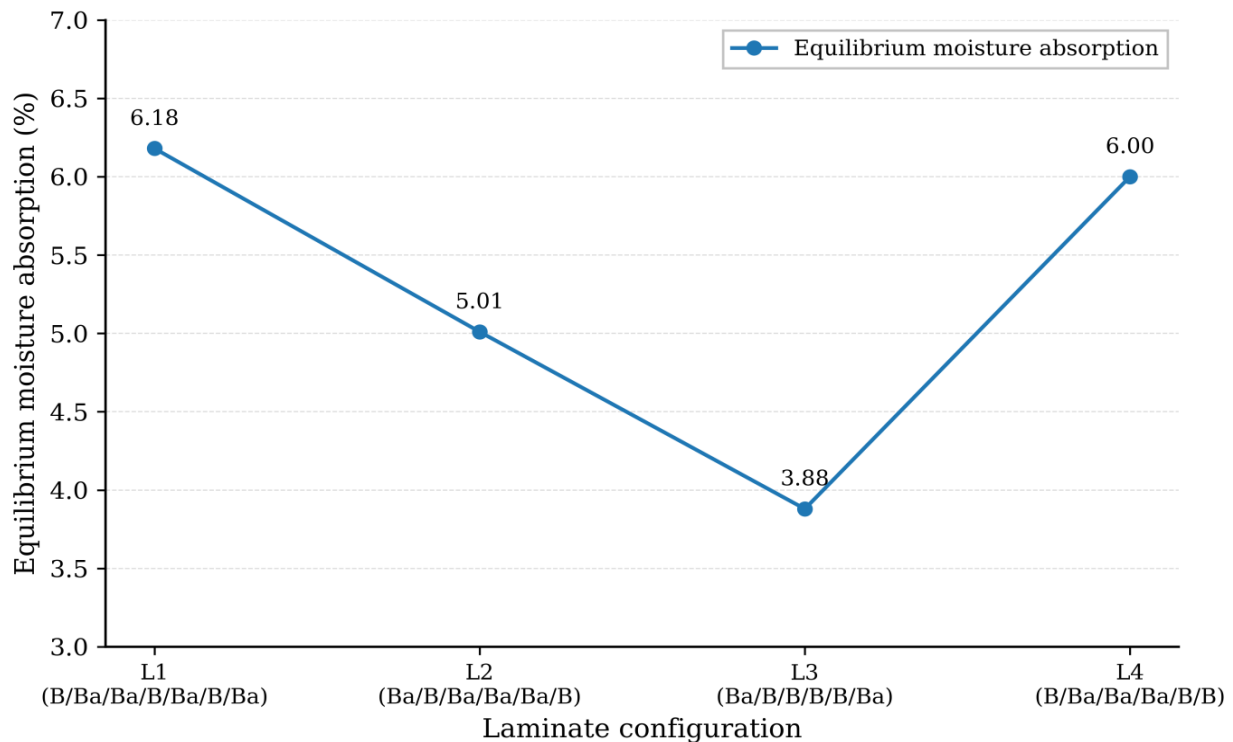


Fig.2. Effect of stacking sequence on equilibrium moisture absorption of banana–basalt hybrid laminates.

4.2 Thickness Swelling Behaviour

Thickness swelling is an important parameter for evaluating the dimensional stability of natural-fibre-reinforced composites under moisture exposure. Water absorbed by the banana fibre can cause fibre swelling because of the hydrophilic nature of its lignocellulosic constituents. The absorbed moisture may also weaken the fibre–matrix interface and promote localized expansion within the laminate. Therefore, the thickness change of the banana–basalt hybrid laminates was measured before and after water immersion to determine the influence of stacking sequence on dimensional stability.

$$TS (\%) = [(t_i - t_0) / t_0] \times 100$$

where t_0 is the initial dry thickness of the specimen and t_i is the thickness measured after immersion for a specified period. The thickness measurements were

taken at several locations on each specimen, and the average value was considered for analysis. A progressive increase in thickness was observed with increasing immersion time, particularly for configurations in which banana fibre was positioned at or near the outer surfaces. This behaviour can be attributed to water absorption by the hydrophilic banana fibres, followed by fibre swelling and changes at the fibre–matrix interface.

Among the investigated configurations, L3 (Ba/B/B/B/B/Ba) is expected to exhibit the lowest thickness swelling because basalt fibre layers are positioned at both external surfaces, restricting direct water access to the banana-fibre-rich core. In contrast, L4, with banana fibre layers at the outer surfaces, is expected to show comparatively higher thickness swelling because the exposed banana fibres

can absorb water more readily. L1 and L2 are expected to exhibit intermediate behaviour depending on the distribution and accessibility of the banana fibre layers.

Based on the expected dimensional-stability behaviour, the configurations can be ranked as $L3 > L2 > L1 > L4$, where a higher position in the ranking represents better resistance to thickness swelling. The results indicate that strategic placement of basalt fibre at the laminate surfaces can improve dimensional stability in humid or wet environments without changing the overall banana-to-basalt reinforcement ratio. This observation further supports the use of the basalt-skin configuration for applications requiring improved moisture resistance and dimensional stability.

Table 3. Thickness swelling behaviour of banana–basalt hybrid laminates

Configuration	Stacking sequence	Relative thickness swelling
L1	B/Ba/B/Ba/B/Ba	Intermediate
L2	Ba/B/Ba/B/Ba/B	Low–intermediate
L3	Ba/B/B/B/Ba	Lowest
L4	B/Ba/Ba/Ba/B/B	Highest

V. CONCLUSIONS

The present investigation evaluated the influence of stacking sequence on the moisture absorption behaviour and thickness swelling behaviour of banana–basalt hybrid epoxy laminates. Based on the results obtained, the following conclusions can be drawn:

1. The stacking sequence significantly influenced the moisture absorption behaviour of the hybrid laminates, even though the total number of banana and basalt fibre layers was maintained constant.
2. The L3 configuration (Ba/B/B/B/Ba), with basalt fibre layers positioned at both outer surfaces, exhibited the lowest equilibrium moisture absorption of approximately 3.88%, indicating superior resistance to moisture ingress.
3. The L1 configuration (B/Ba/B/Ba/B/Ba) exhibited the highest equilibrium moisture absorption of approximately 6.18%, while L2

and L4 showed intermediate values of approximately **5.01% and 6.00%**, respectively. The moisture absorption behaviour followed the order $L3 < L2 < L4 < L1$.

4. The lower moisture uptake of L3 is attributed to the placement of comparatively moisture-resistant basalt layers at the laminate surfaces, which reduced the direct exposure of the hydrophilic banana fibre to water.
5. The banana-skin configuration, L4, showed comparatively higher moisture absorption because the exposed banana fibre layers provided greater opportunity for water penetration and absorption due to their hydrophilic lignocellulosic constituents.
6. Moisture exposure resulted in an increase in laminate thickness. The thickness swelling is mainly associated with moisture-induced swelling of banana fibres and changes at the fibre–matrix interface.
7. The L3 basalt-skin configuration exhibited the lowest tendency for thickness swelling, whereas L4, with banana fibre at the outer surfaces, exhibited the highest tendency. Thus, the presence of basalt layers at the external surfaces improved the dimensional stability of the laminate under moisture exposure.
8. Overall, the results demonstrate that strategic control of stacking sequence can improve both moisture resistance and dimensional stability of banana–basalt hybrid laminates without changing the overall banana-to-basalt fibre ratio.
9. Among the investigated configurations, L3 (Ba/B/B/B/Ba) can be considered the most favourable stacking architecture for applications where resistance to moisture absorption and thickness swelling is a major design requirement.
10. The findings establish that stacking sequence is an effective laminate-design parameter for improving the environmental durability of natural–synthetic hybrid composites and can be considered during the development of lightweight components intended for humid or moisture-prone service environments.

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