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Fire Behavior of Wood–Glass and Jute–Glass Hybrid Laminates Manufactured by Vacuum Infusion

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Abstract: This study explores the fire behavior of wood–glass and jute–glass hybrid laminates, with a focus on the influence of jute and wood veneers as new materials for composite production. Five-layer hybrid laminates were manufactured using the vacuum infusion process (VIP). Combustion and carbonization performances were assessed using a cone calorimeter based on the ISO 5660 method. This study evaluates flammability through key parameters including ignition time, heat release rate, and smoke production. The results indicated that the ignition time was significantly longer (ca. 64 s) for the glass–jute laminate (GJGJG), compared to the wood–glass laminate (WGWGW) (ca. 53 s). The heat release rate of laminates containing organic components was higher than the sample composed only of glass mat (G5) but their rates were all lower than the polyester reference resin. WGWGW, compared to the GJGJG sample, was able to produce a good-quality protective shield and, therefore, postpone the occurrence of the heat release peak. In this way, the fire growth rate index (FIGRA) best performance was accomplished by the WGWGW sample (2.7 ± 0.3 kW/m^2 × s), which was even better than that of the G5 sample. The total-smoke-released value was highest for polyester, 7361 ± 839 m^2/m^2, followed by WGWGW, 2873 ± 188 m^2/m^2, and J5, 2484 ± 216 m^2/m^2. Among the hybrid laminates, the best performance was obtained by GJGJG, 1860 ± 49 m^2/m^2, but compared to the G5 laminates, it was only ~36% higher. The specific extinction area (SEA) is a smoke parameter related to the mass of the samples; the best result was obtained by WGWGW with 697 ± 31 m^2/kg. Finally, the neat polyester and all laminates achieved UL 94HB classification, with firing rates below 40 mm/min.

Keywords: combustion performance; smoke; heat release rate; cone calorimeter

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1. Introduction

The growing demand for environmentally conscious products in the construction industry, driven by public policies and concerns about environmental health, has driven the replacement of conventional materials such as glass with lower-impact options such as plant fibers. Lignocellulosic materials, sourced from renewable plants and trees, inherently offer biodegradability and a lower carbon footprint compared to traditional synthetic fibers.

Lignocellulosic fibers, known for their porous composition and exceptional renewability, stand as a symbolic embodiment of sustainability [1]. As highlighted in a comprehensive review, plant-based materials offer versatility in applications ranging from construction and furniture sectors to emerging domains like adsorption materials and electrode components [1]. In this context, hybrid laminate composites have emerged as a prominent alternative, offering a combination of robust mechanical properties, affordable costs, and compliance with environmental regulations [2].

These laminates, made up of fabrics and/or fiber mats, are mostly made of glass, due to its low cost and excellent mechanical properties [3]. Studies have reported that hybrid laminates can achieve increased tensile strength, bending strength, impact strength, compression-after-impact strength, reduced water absorption, and improved thermal stability compared to their single-component counterparts [4,5]. Hence, in plant-based hybrid laminates, glass layers can mitigate some of the detrimental characteristics of the lignocellulosic ones such as seasonality, limited mechanical properties, high water absorption, suboptimal hydrophobicity, and vulnerability to fracture that make them less desirable for certain applications (e.g., civil construction, furniture, etc.) [6].

Furthermore, recent research has explored various aspects of hybrid laminates, including different stacking sequences, dynamic mechanical properties, Barcol hardness, bearing behavior, fatigue properties, and hydrothermal aging performance [7–9]. These studies have collectively highlighted the potential of hybrid laminates to offer intermediate properties compared to non-hybrid laminates while maintaining a balance between mechanical performance and environmental sustainability [10].

In fact, the use of lignocellulosic materials to manufacture hybrid laminates has emerged over the last few years in the structural composites segment [11]. Dias et al. [12], for example, investigated the influence of hybridization with jute and glass fabrics on the physical and mechanical properties of laminates manufactured by the vacuum infusion process (VIP). Recently, Acosta et al. [13] proposed the use of balsa wood veneers as an alternative material that has a higher-volume production and lower cost (depending on the region) compared to other fibers (e.g., jute, sisal, ramie, etc.), and in a later study [14] the same authors proposed, due to the excellent physical and mechanical properties found in the previous work, the hybridization of pine wood veneers with glass mats and jute fabrics, as an even more economically viable alternative to other types of plant fibers, producing laminates with a physical and mechanical performance notoriously superior even to other types of hybrid laminates using natural fibers [10,12]. Although this is nothing completely new in the literature, these laminates using glass have already been well explored from the point of view of mechanical and physical properties. However, wood is a material considered to be a thermal insulator, and, especially in the case of structural applications, it is extremely important to assess its fire behavior, which is not found in the literature in the studies of laminates produced by the VIP.

Most of the studies focused on studying the behavior of laminates in relation to fire concentrate on exploring laminates produced with commonly used natural mats or fabrics (e.g., jute, cotton, bamboo, ramie, etc.). For example, Zuhudi et al. [15] evaluated the influence of fire on hybrid laminates of polypropylene, bamboo fabrics, and glass (BGPP). The BGPP laminates were manufactured by replacing around 30% of the glass fiber with bamboo fabric, using the compression molding technique. The results of the calorimeter cone tests revealed a superior performance of the hybrid composite, BGPP, compared to the glass–propylene composites, with a significant 19% reduction in the heat release rate and smoke release, as well as a 67% higher ignition time compared to the glass–propylene composite [15]. In addition, Barczewski et al. [16] studied the fire exposure behavior of hybrid epoxy and flax cotton laminates (EP/FF) by adding proportions of 1–10 wt% of micrometric expanded vermiculite (VMT). The addition of VMT quantities of 1 and 2 wt% enabled a 60% reduction in the heat release rate (HRR) and a 20% reduction in the total heat release rate, compared to EP/FF [16].

Despite the growing research on the fire behavior of laminates, it is important to highlight the scarcity of studies on laminates manufactured by the VIP that mainly use wood, precisely because wood-based laminates manufactured by the VIP are an innovation in laminates in the literature. The VIP involves the use of vacuum pressure to drive resin into a dry fiber lay-up, ensuring complete saturation and optimal distribution of the resin throughout the composite structure. This process has been attracting great attention for its ability to provide a balance of performance, cost efficiency, and environmental sustainability compared to other composite manufacturing methods such as hand lay-up, RTM, and filament winding [17,18]. Its advantages in terms of uniform resin distribution, reduced void content, and environmental benefits make it a preferred choice for producing high-quality composite laminates across various industries [19]. This research aims to address the existing research gap by exploring the fire behavior of wood–glass and jute–glass hybrid laminates, utilizing a cone calorimeter, with a special emphasis on evaluating the effect of natural material-based components.

2. Materials and Methods

2.1. Raw Materials

One mm thick *Pinus elliottii* wood veneers (with an apparent density of 0.59 ± 0.05 g/cm^3, moisture content of $9.97 \pm 1.99\%$, and porosity of $49.25 \pm 2.25\%$) [14] were purchased from EcoFolhas (São Paulo, Brazil). Unidirectional jute fabrics (with an area density of ~239 g/m^2) were sourced from Castanhal Textile Company (Pará, Brazil). Randomly oriented glass mats (with an area density of ~400 g/m^2) were obtained from Owens Corning (Toledo, OH, USA). Pine veneer, jute fabric, and glass mat are denoted as "W", "J", and "G", respectively. An unsaturated isophthalic polyester resin (with a density of 1.19 g/cm^3) and a Butanox 50 initiator (comprising 1.5% by weight relative to the resin) were used as the polymer matrix.

2.2. Composite Manufacturing

The laminates were manufactured using the vacuum infusion process (VIP) at room temperature (~25 °C) by stacking five layers oriented lengthwise, except for the glass mats, which were randomly oriented. Two 250 mm long plastic spiroducts were cut and connected to the inlet and outlet hoses, creating a rectangular injection area of ~250 mm × ~350 mm on a smooth surface. The inlet hose was connected to a 2 L beaker, into which the resin was previously poured. The outlet hose was connected to a pressure vessel, which functioned as a Büchner flask, aligned with a vacuum pump. Wood veneers, unidirectional jute fabrics, and glass mats (dimensions: 250 mm × 350 mm × 1 mm) were stacked between the spiroducts and the injection site. The area was sealed with a vacuum bag and adhesive tape. Subsequently, the vacuum pump was activated and set to a constant pressure of ~92 kPa, ensuring a consistently straight flow. The following laminate stacking sequences were used: GGGGG (G5), JJJJJ (J5), WGWGW, and GJGJG, to investigate fire behavior in relation to hybridization. This stacking configuration was based on a sequence from a previously published paper [14]. The samples reached similar apparent densities, obtained with the measurement of the weights of the samples divided by their volume, calculated with the dimensions measured with a digital caliper. They range from 0.95 ± 0.02 g/cm^3 for the J5 sample to 1.64 ± 0.02 g/cm^3 for the G5 sample. The GJGJG sample has a density of 1.16 g/cm^3 and the WGWGW 1.03 g/cm^3. Figure 1 details the manufacturing process for the composites in this work using vacuum infusion.

2.3. Characterization

The fire behavior of hybrid laminates and pure resin was assessed using a NOSELAB ATS s.r.l. (Bovisio-Masciaco, Italy) cone calorimeter apparatus in accordance with ISO 5660. Compared to the ISO 5660 standard, the sample size was adapted to dimensions of $50 \times 50 \times 2$–4 mm^3. These samples were securely positioned within an aluminum sample holder and exposed to irradiation at 35 kW/m^2 using a horizontal configuration setup.

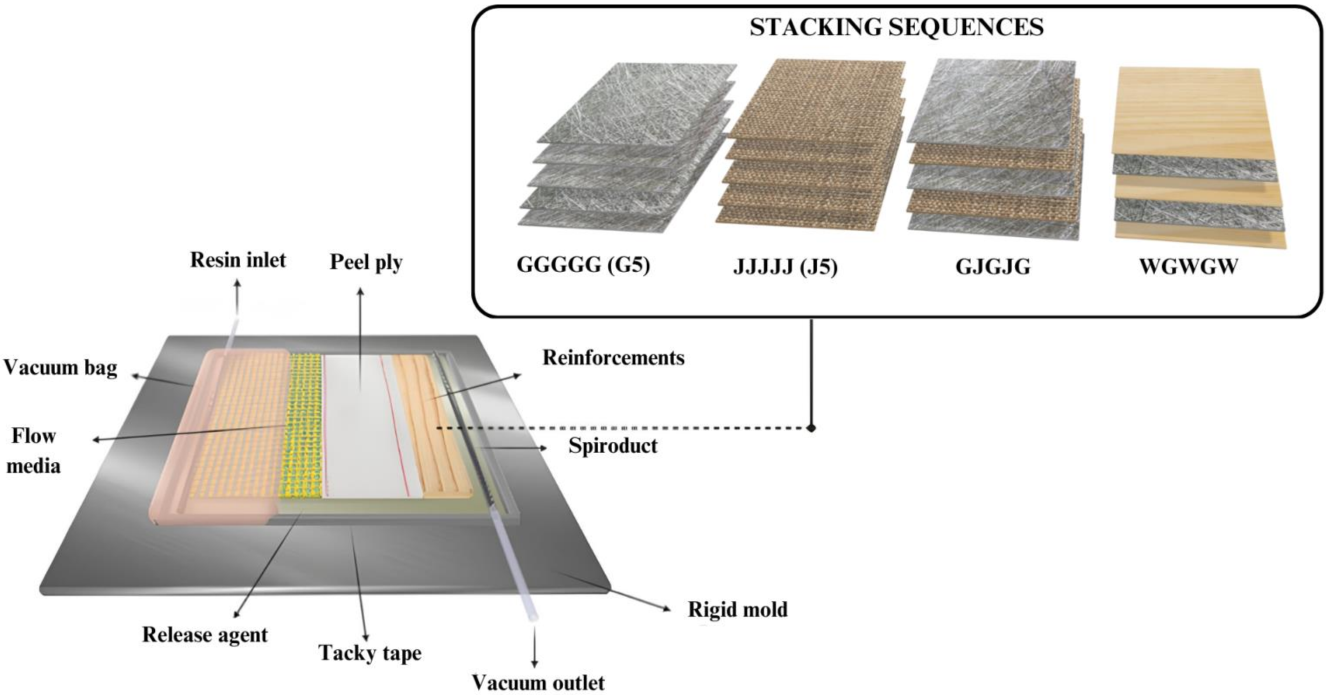

Figure 1. Representation of the VIP for manufacturing the laminates and their different stacking sequences.

The cone tests were conducted three times for each laminate, and standard deviation values were calculated for the following parameters: ignition time (TTI, s), peak heat release rate (pHRR, kW/m^2), time to peak (TTP, s), total heat release (THR, MJ/m^2), total smoke release (TSR, m^2/m^2), optical transmittance percentage (%), and carbon monoxide (%) and carbon dioxide (%) presence in the exhaust air flow.

The UL 94 test standard is a globally accepted method to assess the flammability of plastic materials. It evaluates how materials react to small flame sources, measuring aspects like flame spread and dripping. Crucial for industries like electronics and construction, this standard ensures product safety by guiding material selection based on fire behavior. Our study, following the UL 94HB test for horizontal burning, provides insights into the burning rate of laminate samples, aiding in understanding their fire performance. Horizontal burning tests on 125 × 13 × 2–4 mm^3 samples were carried out in accordance with UL 94HB in a NOSELAB ATS s.r.l.(Bovisio-Masciaco; Italy) cabin to obtain the burning rate (V). One sample per group was evaluated for this test. Before the flammability and combustion tests, the samples were conditioned in a climate chamber at 23 ± 1 °C and 50% relative humidity for a minimum of 48 h, as suggested by standard ISO 5660.

2.4. Statistical Analysis

One-way analyses of variance (ANOVA) were applied and, whenever the null hypothesis was rejected, Tukey tests were used to compare the means. All statistical analyses were implemented at a significance level of 5%. In all cases where ANOVA was applied, data distribution was used to represent the error instead of the standard deviation, since the statistical difference using ANOVA represents the deviation values.

3. Results and Discussion

The first analysis reported is the cone calorimetry test under a heat flow of 35 kW/m^2 in a horizontal position. The main data obtained from this analysis are reported in Table 1 and then discussed individually.

Table 1. Main data and standard deviations measured of combustion in the cone calorimeter tests.

Sample	TTI (s)	TTP (s)	pHRR (kW/m^2)	THR (MJ/m^2)	TSR (m^2/m^2)	SEA av. (m^2/kg)	MARHE (kW/m^2)	FIGRA ($kW/m^2 \times s$)	Residue (%)
Polyester	58 ± 1	166 ± 3	971 ± 103	116 ± 12	7361 ± 839	1227 ± 8	492 ± 3	5.8 ± 0.5	0.1 ± 0.1
G5	55 ± 15	94 ± 12	322 ± 6	25.1 ± 2.3	1365 ± 191	825 ± 92	141 ± 11	3.5 ± 0.4	62.4 ± 2.3
J5	45 ± 1	105 ± 6	794 ± 45	53.0 ± 7.6	2484 ± 216	825 ± 31	332 ± 23	7.5 ± 0.6	0.5 ± 0.1
GJGJG	64 ± 3	121 ± 8	395 ± 7	40.2 ± 5.1	1860 ± 49	835 ± 90	191 ± 8	3.3 ± 0.2	34.7 ± 1.9
WGWGW	53 ± 3	165 ± 8	453 ± 43	76.5 ± 5.8	2873 ± 188	697 ± 31	270 ± 13	2.7 ± 0.3	1.9 ± 1.1

The times to ignition (TTIs) of the different samples are reported in the first column of Table 1. The TTI is the time required to start burning due to the radiation of heat onto a sample surface in the presence of a spark. The lower the TTI, the more flammable is the material [20]. Considering the TTI necessary for the neat resin used for infusion to ignite (58 ± 1 s), this time was greatly diminished for the J5 sample (45 ± 1 s) and only slightly so for the WGWGW sample (53 ± 3 s). On the other hand, the TTI was postponed for the samples GJGJG (64 ± 3 s) and G5 (55 ± 15 s).

These observations can be attributed to the presence of lignocellulosic material on the face of the WGWGW and J5 laminates. Components like cellulose and hemicellulose in these materials significantly increase their flammability [21]. Conversely, laminates containing glass exhibit longer burn times, particularly on their faces, due to the inorganic nature of glass. Composed of 70–75% silica (SiO_2), sodium carbonate, and calcium carbonate, glass offers greater resistance to fire exposure [12]. The similarity between the reference polyester and G5 can be explained by the high permeability of glass mats during infusion, which can facilitate the flow of resin through fiberglass mats.

Thermal conductivity can also contribute to the first stages of heating and decomposing of the surface of the samples. Wood and jute, for example, have values of conductivity of ~0.1 to ~0.2 W/(m·K) [22], i.e., higher thermal conductivity compared to glass but similar to the infusion resin. Thermal properties pertain to a material's ability to conduct, store, and dissipate energy. Lower thermal conductivity values accelerate carbonization and temperature accumulation on the surface, leading to quicker pyrolysis and carbonization of the material [12,23]. This may be an explanation for the variability of samples with more insulating material on the surface such as G5.

Parameters such as HRR, pHRR, and THR are important to determine, as they give a general indication of the size of the fire and how quickly it spreads [20,24].

The speed with which thermal energy is generated by the combustion of a material is important, especially for structural composites, as it indicates its potential fire risk and combustibility, since materials that release smoke and toxic gases relatively quickly are more dangerous than those that do so more slowly [17]. Figure 2A shows the results obtained in relation to the heat release rate (HRR), while Figure 2B refers to the statistical difference according to the confidence interval. Differences can be seen in the time taken for the different laminates to combust, as well as the pure resin. The polyester resin, used for the matrix of the composites, showed the highest HRR peak value (971 ± 103 kW/m^2), which is related to its chemical composition, which contains a considerable amount (35–40%) of styrene in this particular case, as well as highly volatile ester groups [25]. Combustion lasts a long time, with a progressive increase of the HRR in the first stage and a long combustion of the charred part in the final part of the test, which brings the duration of the flaming phase to over 300 s.

The G5 sample presents an extremely reduced HRR trend compared to the polyester resin. Indeed, the peak was reduced to 322 ± 6 kW/m^2. This fact is certainly due to the glass part, which, not being combustible, limits the release of energy during the combustion of the specimen. The residue appears to be around 60% of the original weight entirely attributable to the glass mat, as can also be seen from the photograph in Figure 3. The combustion time was almost halved with respect to the neat resin (161 s), and the peak of heat release appeared earlier (TTP 94 ± 12 s vs. 166 ± 3 s). The opposite formulation sample, the J5 one, composed of resin and organic material, presented a behavior similar to the neat resin, with an even sharper peak at 794 ± 45 kW/m^2 and a TTP of 105 ± 6 s. The entire combustion process appeared to be the fastest of the samples examined, with an average combustion phase of around 115 s. The two samples containing the hybrid layers between the glass and organic substances presented similar behavior to each other, with the presence of a first small peak in the first stages of combustion (20–30 s from starting of flame), probably due to the resin's presence. Subsequently, in both cases, there was a protective layer formation phase, which could be made of glass or carbonized organic material or their combination. During this period, the HRR curve essentially remained constant or decreased significantly. This phase lasted for a shorter time for the GJGJG sample, which then presented the HRR peak of 395 ± 7 kW/m^2 at 121 ± 8 s, while it lasted longer for the WGWGW sample and caused a higher-in-intensity peak of 453 ± 43 kW/m^2, postponed until 165 ± 8 s. Probably, the WGWGW compared to the GJGJG sample is able to produce a good-quality protective shield and, therefore, postpone the occurrence of the peak. However, by having a larger quantity of organic content than the GJGJG, it produces a slightly higher peak.

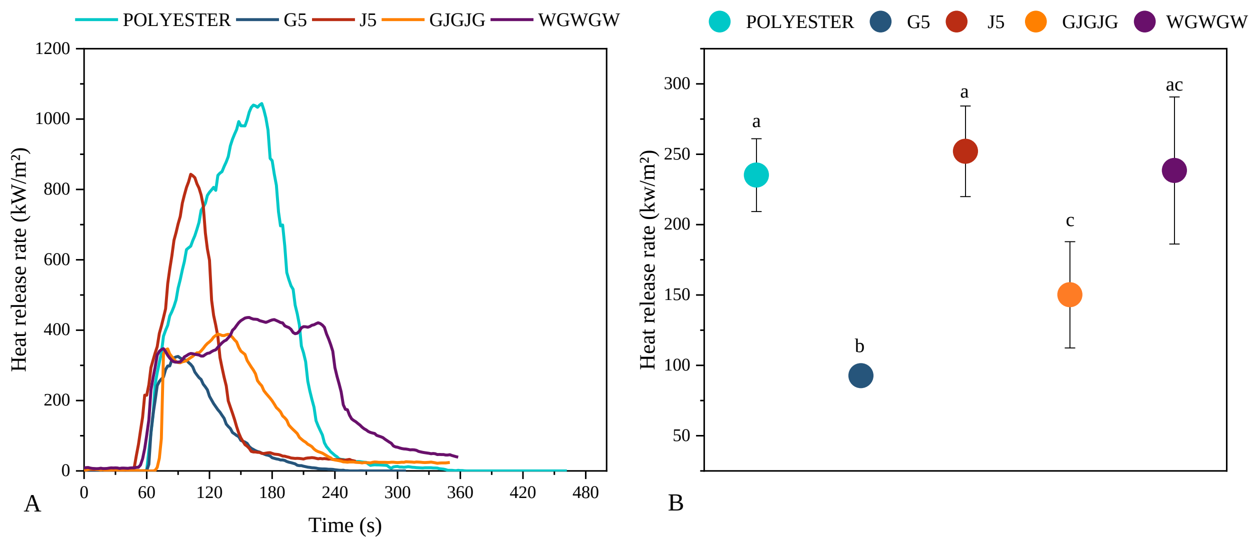

Figure 2. Heat release rate as a function of time for each group analyzed (**A**) and the average values of the heat release rate and confidence interval of 95% (**B**). Different letters above the errors in each group represent a statistical difference.

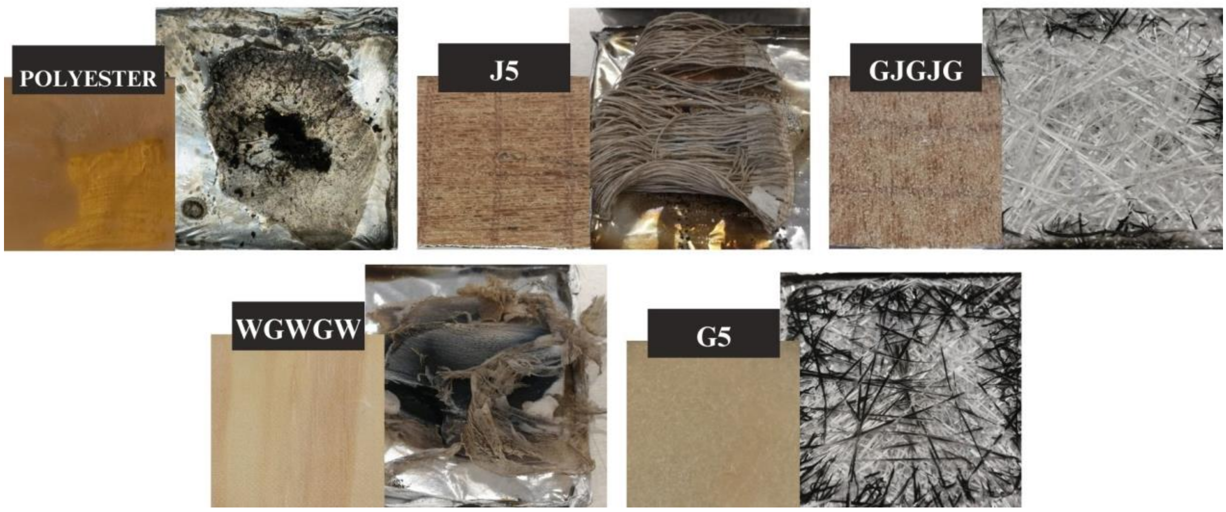

Figure 3. Appearance of the samples before and after the cone calorimeter tests.

Finally, it is important to note that the WGWGW hybrid laminate, predominantly composed of wood veneers, especially in its surface layer, exhibited a heat release time that ranged on average from 53 s to 255 s. This range is significantly higher compared to the other laminates, showing fire resistance and delayed carbonization. These results highlight the effectiveness of hybrid laminates in improving their properties when exposed to heat, especially those wherein the hybridization chosen was with wood and glass [24,26]. To further highlight this fact, a parameter widely used in the flame retardancy literature named FIGRA (fire growth rate index) is reported in Table 1. This value is obtained by dividing the pHRR by the time at which this peak is obtained, i.e., the TTP. It is therefore evident that the smaller this parameter is, the better is the behavior. The best performance result is attributed to the WGWGW sample (2.7 ± 0.3 kW/m^2 × s), which is even better than the G5 sample (3.5 ± 0.4 kW/m^2 × s).

MARHE (kW/m^2), the maximum average rate of heat emission, is a parameter similar to the HRR that is used in large-scale tests as a single burning item (SBI). Basically, it can be observed that the ratios between the analyzed samples remain the same compared to the pHRR value reported. The best performance was obtained by the G5 sample, with 141 ± 11 kW/m^2, and the worst by the neat polyester resin, 492 ± 3 kW/m^2.

The J5 and polyester samples showed a greater deviation in HRR compared to other laminates, likely due to their higher void content, as reported by Acosta et al. [14]. Void spaces within the material can act as pockets for the accumulation of combustible gases, promoting faster and more intense combustion when exposed to heat [27]. Additionally, the presence of voids can alter the heat transfer mechanisms within the material, leading to localized hotspots and uneven combustion. This can result in fluctuations and deviations in the HRR measurements. The voids may also affect the thermal stability and decomposition pathways of the material. The increased void content can facilitate the escape of volatile components and combustion products, influencing the combustion kinetics and heat release characteristics during the test [28].

Figure 4A shows the curves for the total heat release (THR) of the laminates, while Figure 4B shows the statistical differences according to the confidence interval of 95%. It can be seen that the WGWGW hybrid laminate showed statistically higher values (76.5 ± 5.8 MJ/m^2) than the GJGJG (40.2 ± 5.1 MJ/m^2), corroborating the theory that the material present on the surface of the hybrid laminate has a significant influence on heat release. This is evidenced by the presence of glass (an inorganic non-combustible material), which showed lower average values [29]. Finally, the G5 mono-component laminate had statistically lower average values than pure resin (~−78%, 25.1 ± 2.3 MJ/m^2), since pure resin has low fire resistance and tends to release a considerable amount of heat in a short period of time [25]. It is important to emphasize that, despite the resin having low fire resistance, an improvement in combustion performance was observed for all laminates. Even WGWGW, which is an interesting alternative, combining fire resistance with low raw material costs for composites, as well as wood being an environmentally friendly material, reached a reduction of 34% with respect to the neat resin [21,30].

Figure 5A shows the total smoke release (TSR) curve in relation to time for the different laminates produced, as well as for the pure resin. One of the problems associated with fires is the smoke produced. Smoke means the mixture of pyrolysis products and air near the site of the fire and represents a potential hazard because it interacts with light to obscure vision and probably contains harmful and toxic substances [31]. This makes it interesting to determine the amount of smoke production. In general, for the materials under study, the value of smoke formed was highest for polyester, 7361 ± 839 m^2/m^2, followed by WGWGW, 2873 ± 188 m^2/m^2, and J5, 2484 ± 216 m^2/m^2. Among the hybrid laminates, the best performance was obtained by GJGJG, 1860 ± 49 m^2/m^2; compared to the G5 laminates, it was only ~36% higher. The amount of total smoke released during the burning of materials such as wood and jute, which have organic compounds in their composition, also includes the release of carbonized particles, organic vapors, and gases, and is expected to be greater than glass mat, as it has no smoke release [20].

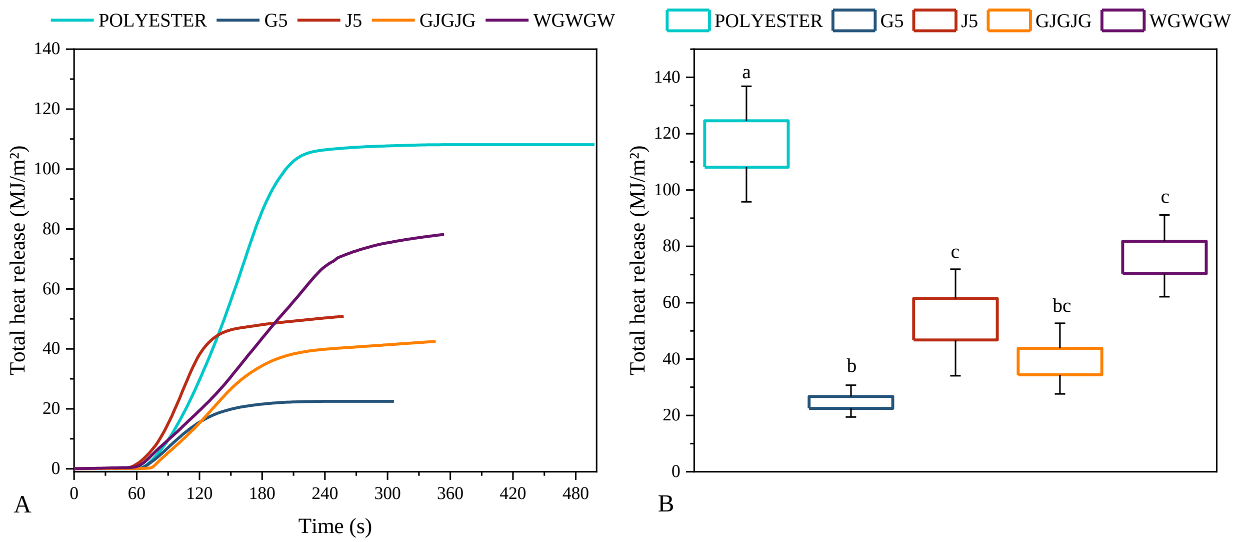

Figure 4. Total heat release (THR) as a function of time for each group analyzed (**A**) and average maximum values for THR (**B**). Different letters above the errors in each group represent a statistical difference.

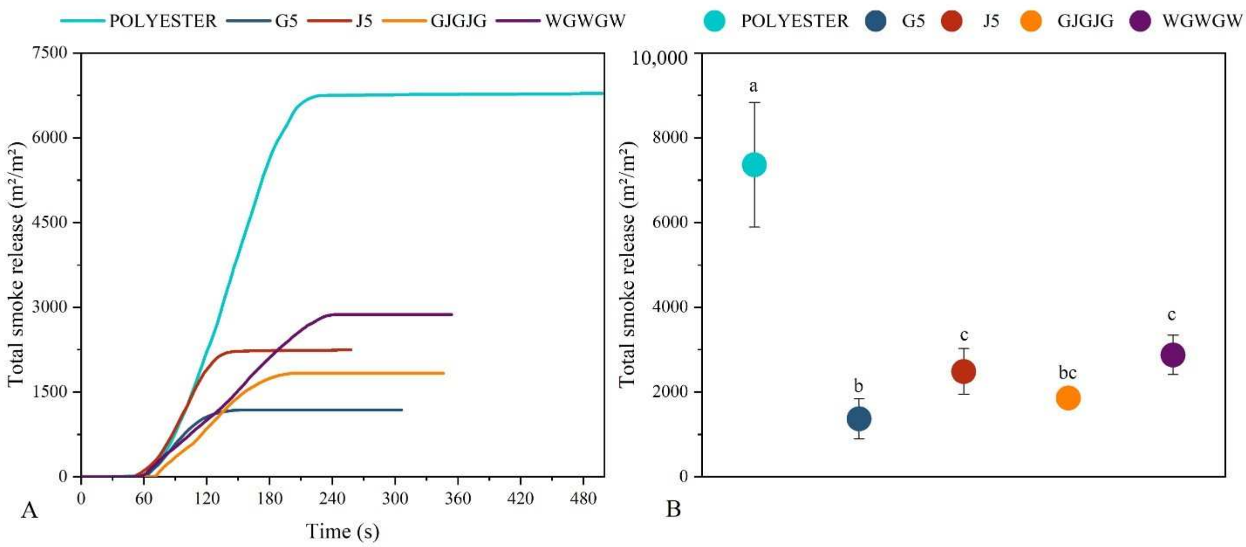

Figure 5. Total smoke release as a function of time for each group analyzed (**A**) and average values for total smoke release at the end of the test (**B**). Different letters above the errors in each group represent a statistical difference.

Figure 6 shows the results of the percentage of reduction in transmittance of the laser in the exhaust air flow. This information is used by the instrument to process all data regarding smoke production.

The specific extinction area (SEA, m^2/kg) is the ratio of smoke production to specimen mass loss averaged over the test duration. This parameter is interesting, compared to the others reported on the smoke produced, because is related to the mass of the sample and not to its exposed surface. Using this measure, it is possible to compare samples that have significantly different masses, like those in this study. According to this process, the polyester resin has the highest SEA value of 1227 ± 8 m^2/kg. On the contrary, the samples G5, J5, and GJGJG are fully comparable, with values around 825 m^2/kg, and the best result was obtained by WGWGW, with 697 ± 31 m^2/kg. This is mainly due to the fact that the WGWGW sample was the heaviest of the laminates.

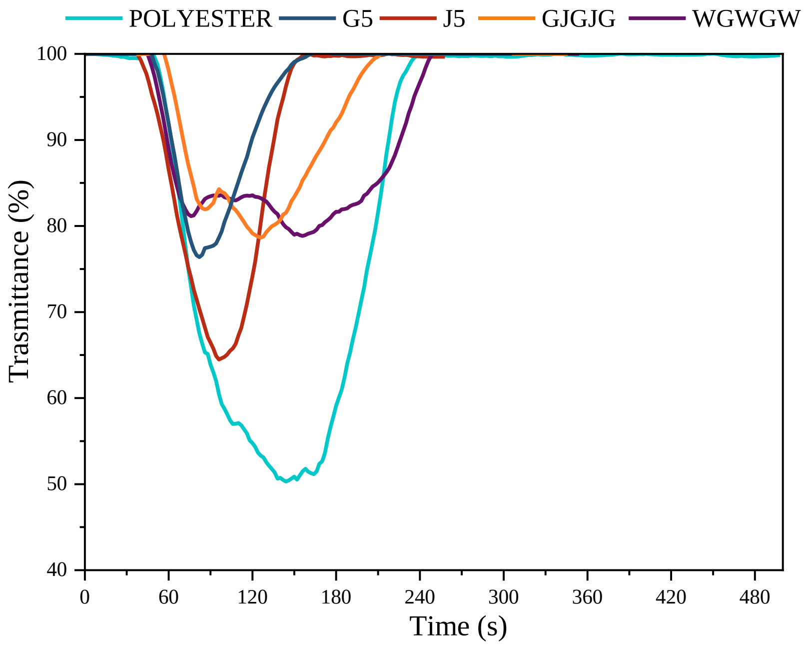

Figure 6. Percentage of reduction in transmittance of the laser in the exhaust air flow as a function of time for each group analyzed.

Burning materials can result in the emission of gases that are harmful to the environment and human health. Initially, during incomplete combustion, carbon monoxide (CO) and soot are released. Later, these gases are oxidized to form carbon dioxide (CO_2) and water, representing the complete combustion of the material [32]. Figure 7A,B show the results of the measurements of the percentages in the instrument's exhaust air of carbon monoxide (CO) and carbon dioxide (CO_2) during the combustion of the different laminates. The results show that the wood–glass and jute–glass composites showed more than a 50% reduction in the CO and CO_2 maximum peaks of emissions compared to polyester resin. The best performance was obtained by the G5 sample.

The lower CO and CO_2 values observed for the G5 hybrid laminate in Figure 7 can be attributed to the inherent properties of glass fibers. Glass fibers are non-combustible and can act as an effective barrier to heat transfer, thereby reducing the rate of combustion and the subsequent emission of gases like carbon monoxide (CO) and carbon dioxide (CO_2) [33]. Therefore, the inert nature of glass fibers ensures minimal contribution to gas emissions during the combustion process, which explains the lower values of CO and CO_2 observed for the G5 laminate compared to other hybrid laminates containing natural fibers.

In addition, another two-component laminate, GJGJG, despite having glass sheets on the faces, showed higher CO/CO_2 emissions than the single-component laminate, G5. This is probably related to the configuration of the laminate, since jute fabric is used between the glass mats [13].

Figure 7B shows a significant discrepancy in the largest error bar defined by the 95% confidence interval for the carbon monoxide values between neat polyester and the hybrid laminates incorporating jute, wood, and glass. A possible mechanism to explain the observed discrepancy could be related to the enhanced char formation and insulation properties conferred by the natural fibers and wood veneers [34]. During combustion, the jute and wood components may contribute to the formation of a more robust and heat-resistant char layer, which could potentially reduce the rate of carbon monoxide emission. Additionally, the presence of glass fibers might further modify the combustion process by providing structural integrity and promoting a more controlled release of gases. Further investigations are warranted to elucidate these differences and provide a comprehensive understanding of the observed discrepancies in the combustion performance of the tested materials.

Figure 8 shows the firing rate results for the different laminates. The firing rate values obtained were 27.5, 17.3, 13.5, 16.8, and 12.7 mm/min, respectively, for polyester, G5, J5, GJGJG, and WGWGW.

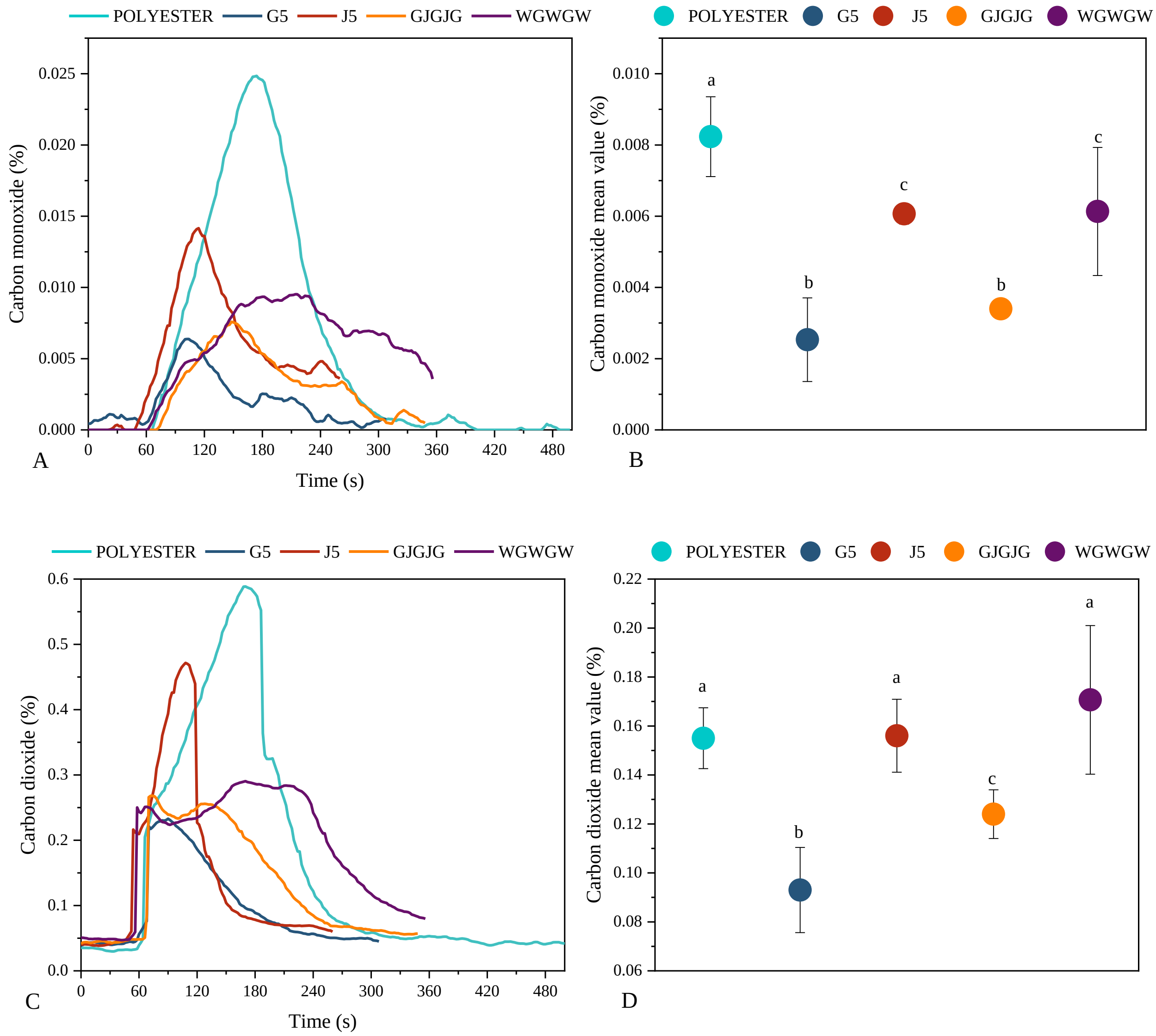

Figure 7. Carbon monoxide and carbon dioxide as functions of time for each group analyzed (**A**,**C**) and average values for carbon monoxide and carbon dioxide (**B**,**D**). Different letters above the errors in each group indicate a statistical difference.

In accordance with the UL 94 standard [35], to fulfil the UL 94HB test criteria, the material must be classified as one of the following:

(a) The fire must not exceed a burning rate of 44 mm/min for materials with thicknesses of 3.0–13 mm;
(b) The fire must not exceed a burning rate of 75 mm/min for materials with thicknesses of less than 3.0 mm;
(c) The fire must stop before the 100 mm reference mark.

In this way, all laminates are aligned with the standard used by the UL standard item, which refers to UL 94HB, and can be used for environmental applications where exposure to fire is a concern, such as in construction and other industries.

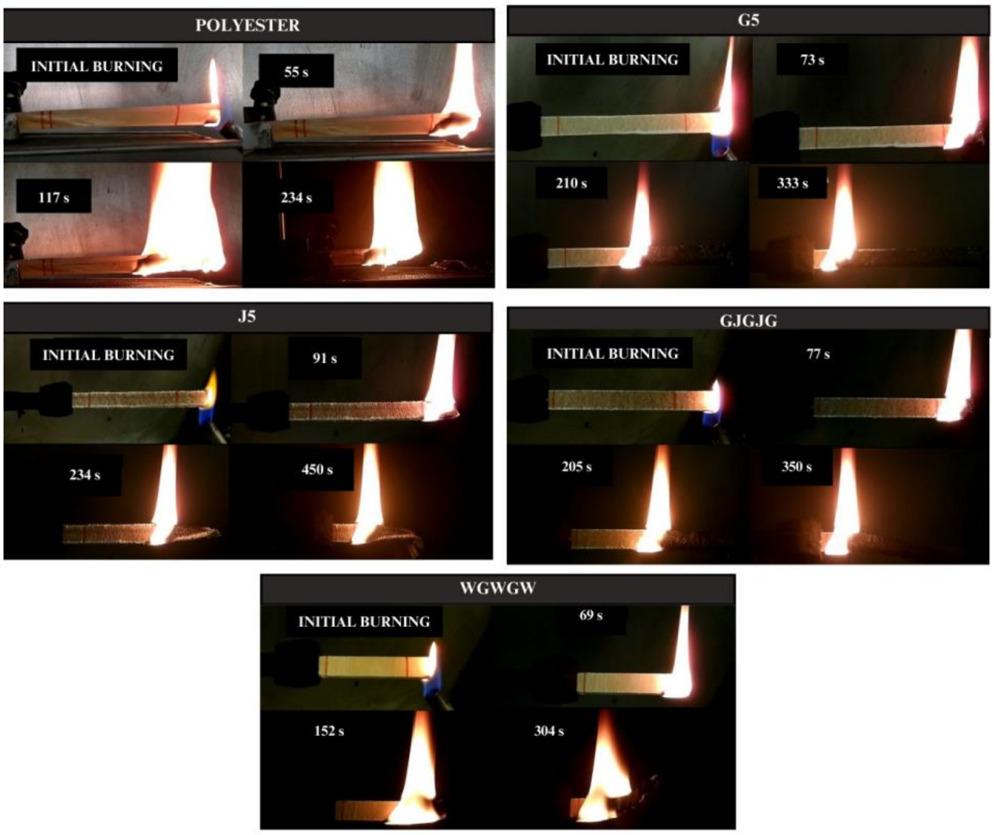

Figure 8. Appearance of the samples during the horizontal firing test in accordance with UL 94.

4. Conclusions

This comprehensive study provided insights into the fire behavior of various hybrid laminates, emphasizing the roles of materials like wood, jute, and glass in influencing combustion characteristics. Laminates containing lignocellulosic materials, particularly WGWGW and J5, exhibited good flammability, attributed to components like cellulose and hemicellulose. In contrast, those with glass showed enhanced fire resistance, with longer burn times, thanks to their inorganic nature and thermal stability.

The heat release rate (HRR) was highest for polyester resin, likely due to its volatile esters and styrene content. However, the WGWGW laminate, enriched with glass, displayed improved fire resistance and delayed carbonization, highlighting the pivotal role of glass in influencing combustion kinetics. Moreover, laminates with wood and jute released a great quantity of smoke due to their organic composition, but in any case, it was less than the neat resin. In contrast, the incorporation of glass in hybrid laminates significantly reduced smoke production, suggesting its potential to mitigate environmental hazards during fires.

In terms of harmful gas emissions, hybrid laminates generally exhibited reduced CO/CO_2 emissions compared to pure polyester and J5 laminates. This reduction can be attributed to glass fibers acting as barriers, limiting heat conduction and reducing oxygen exposure during combustion.

All laminates met the UL 94HB test criteria, confirming their suitability for fire-sensitive environmental applications. These findings hold significant implications for the field of composite materials and fire safety. Glass incorporation can markedly enhance laminate fire resistance, making them adaptable for fire-sensitive applications in construction and industries prioritizing fire safety. By understanding laminate combustion characteristics, industries can adopt measures to mitigate environmental hazards linked with fires. Laminates with reduced smoke and harmful gas emissions, especially those containing glass, can foster safer and more sustainable environments.

Looking ahead, optimizing laminate configurations for superior fire resistance without compromising mechanical and functional properties is a promising avenue for future research. Exploring interactions between wood, jute, and glass can further refine our understanding and contribute to the evolution of innovative, fire-resistant composite materials. Evaluating the burning characteristics of the material under fire conditions stands out as a crucial area for future study. In conclusion, while glass fiber laminates generally exhibited superior fire performance, wood–glass and jute–glass hybrid laminates, with their distinct advantages and positive influence on combustion performance, offer viable alternatives. Thus, selecting the most suitable material hinges on specific application requirements. Future studies with expanded sample sizes, different burning conditions, and rigorous statistical analyses are warranted to corroborate these findings and offer definitive material selection guidelines for specific applications.

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