Statistical Strategies for Decision-making Regarding the Quality of Particleboards with Glass Wool

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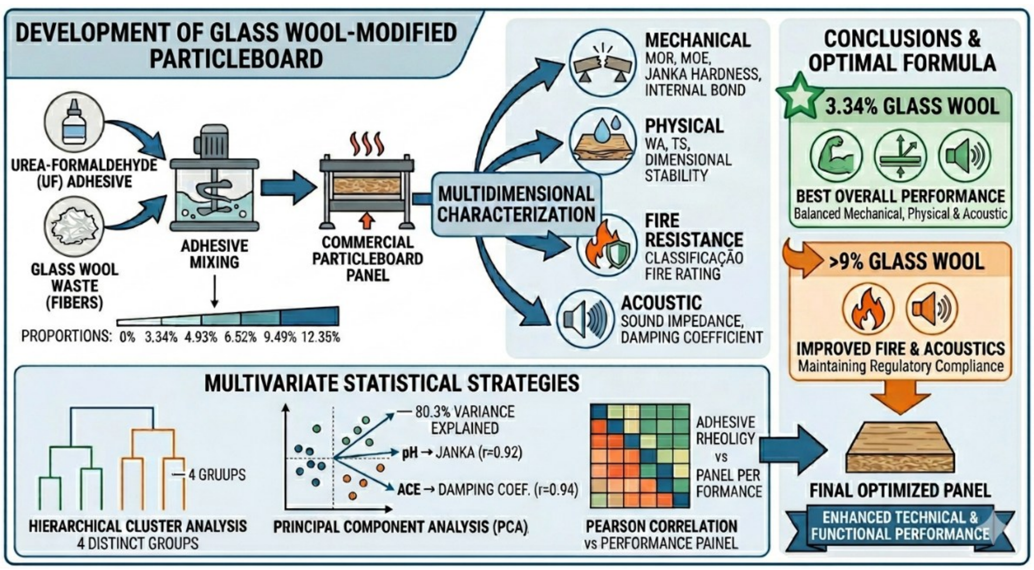
GRAPHICAL ABSTRACT



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This study evaluated multivariate statistical strategies to select critical properties for the performance of particleboards bonded with urea-formaldehyde (UF) adhesive modified with glass wool residues. Panels were produced with six different proportions of glass wool incorporated into the UF adhesive (0%, 3.34%, 4.93%, 6.52%, 9.49%, 12.35%). These panels were characterized by physical, mechanical, fire-retardant, and acoustic properties. Three statistical tools were applied: hierarchical cluster analysis, principal component analysis (PCA), and Pearson correlation. PCA explained 80.3% of the total variance, revealing distinct patterns among treatments, especially at the lowest and highest filler contents. The correlation matrix showed the interdependence between the rheological properties of the adhesive and the final composite performance. Glass wool as a filling material, in the proportion of 3.34% of the adhesive, provided the best performance among the panels, as it promoted balance between mechanical, physical and acoustic properties. Up to the limit of 6.52% glass wool contributed to improving fire resistance without significant changes in mechanical strength but reduced dimensional stability due to changes in adhesive rheology. The combination of multivariate analyses provided a robust approach to identify key attributes and guide the formulation of panels with enhanced technical and functional performance.

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Keywords: Waste; Particleboard; Glass wool; Recycling; Alternative raw material

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INTRODUCTION

In 2024, with a strengthened forestry scenario, Brazil reached the milestone of 10 million hectares of planted forests. This achievement reflects the availability of large-scale renewable raw material and the country's commitment to advancing toward a more sustainable, low-carbon economy (IBÁ 2024).

To supply the flooring and panel industry, 4% of the planted forest area in 2023 was allocated to this segment. Among the highest-quality reconstituted wood panels, MDF has stood out in the market. Sales for MDF grew by 1.5%, totaling 7.1 million m³ (IBÁ 2024). In contrast, particleboards registered a 2.7% drop in domestic sales and continue to be the focus of innovations aimed at improving performance. These improvements involve modified resins or the incorporation of lignocellulosic additives (Mahieu *et al.* 2021; Papadopoulou *et al.* 2024; Mensah *et al.* 2025).

In the construction sector, these panels are part of industrialized building technologies that, while boosting productivity and profits, often impose performance challenges on the materials used (Haas *et al.* 2022). In this context, reconstituted panels gain relevance due to their functional versatility (Santos *et al.* 2021; Fehrmann *et al.* 2022, Cazella *et al.* 2024).

Adequate and sufficient resin application, as well as the control of pressing parameters, are key factors to ensuring the physical-mechanical integrity of the panels (ABNT, 2018). Among the core components of the reconstituted panel sector is urea-formaldehyde resin, which is widely used due to its low cost, fast curing, and high stiffness (Benhamou *et al.* 2022; Wibowo *et al.* 2022; Wang *et al.* 2023). However, its limitations in terms of moisture resistance, formaldehyde emissions, and durability have motivated further studies (Yildirim and Candan 2021; Kelleci *et al.* 2022; Moutousidis *et al.* 2023).

The incorporation of mineral materials such as glass wool and metallic nanoparticles emerges as a promising and effective strategy to alter technological properties of the adhesive, such as pH, viscosity, and gel time, in addition to improving the performance of reconstituted wood panels (Çavdar 2020; Liu *et al.* 2022; Khorramabadi *et al.* 2023, 2024; Gillela *et al.* 2024). Furthermore, the search for new adhesives (García *et al.* 2024; Gonçalves *et al.* 2008), resin enhancers (Sahoo *et al.* 2024), and methodologies that eliminate the need for synthetic adhesives (Guan *et al.* 2022), such as the use of alternatives like liquid glass (Lee and Thole 2018), has gained ground. Evaluating the application of glass wool residues in particleboards represents an innovative approach with significant technical and environmental potential.

Glass wool is produced by melting silicate materials in electric furnaces, followed by extrusion of the molten mass through rotary spinners under compressed air flow. The microfibers formed solidify upon rapid cooling, resulting in discontinuous, amorphous fibers (Tsukamoto *et al.* 2014). These fibers, with a density close to that of glass (≈2500 kg m^{-3}) and diameters between 2 and 20 µm, are classified as solid and isotropic, with structural characteristics depending on the type of binder applied during the production stage (Meftah *et al.* 2019).

Chemically, glass wool consists primarily of silicon dioxide (SiO_2), sodium oxide (Na_2O), calcium oxide (CaO), aluminum oxide (Al_2O_3), ferric oxide (Fe_2O_3), magnesium oxide (MgO), and boric oxide (B_2O_3), among other components (IARC 1988). This composition exhibits thermal stability, amorphous behavior, and a high surface area, which also contributes to its reactivity in alkaline systems (Yliniemi *et al.* 2020). Such attributes, combined with the importance of the material as a residue, make its incorporation into resin or cement matrices a viable alternative for modifying properties such as density, sound absorption, dynamic stiffness, and matrix-fiber adhesion (Adediran *et al.* 2021; Li *et al.* 2021; Machado *et al.* 2023). When incorporated into the adhesive as a filler material, it is relevant to assess the technological properties of the adhesive and its influence on the quality parameters of the panels produced.

The characterization of panels can be enhanced by methodologies that simultaneously evaluate the interactions among different material properties. The use of multivariate statistical techniques, such as principal component analysis (PCA), hierarchical cluster analysis, and Pearson correlation, enables the interpretation of complex data, the identification of patterns, and the establishment of significant relationships among properties (Fialho *et al.* 2022).

In this context, the present study aims to evaluate the effect of incorporating different levels of glass wool into urea-formaldehyde resin used in the production of particleboards. To this end, multivariate statistical tools were employed to understand correlations among performance variables, identify properties sensitive to the addition of the additive, and characterize behavioral patterns resulting from fiber incorporation.

The study was guided by two fundamental scientific questions: (i) under what conditions does the addition of glass wool positively influence the physical, mechanical, and thermal properties of the panels? (ii) what is the ability of different multivariate statistical approaches to identify patterns, correlations, and critical variables associated with panel performance?

These questions guide the critical analysis of the data and support the proposition of rational strategies to enhance the performance of lignocellulosic composites, focusing on the careful selection of target properties such as fire safety, acoustic insulation, dimensional stability, and mechanical resistance for industrial applications.

EXPERIMENTAL

Raw Material

The raw materials used in the production of medium-density particleboards consisted of *Pinus* spp. wood, glass wool residues, urea-formaldehyde (UF)-based adhesive, and catalyst. The UF adhesive and ammonium sulfate catalyst were purchased from a qualified supplier in the national market. The wood was obtained locally in the form of boards and subsequently crosscut into pieces of approximately 20 × 9 × 2 cm. Particle production was carried out using water-saturated wood, which was cut into flakes, air-dried, milled, and sieved, with particle sizes selected between 2.0 and 4.0 mm. The particles were then oven-dried until they reached 7% moisture and stored hermetically.

The glass wool, originating from urban waste, came from discarded household appliances in the southern region of Espírito Santo, Brazil. The mats were cut into segments of approximately 10 × 10 mm using a guillotine, and the material was manually cleaned to remove metallic particles and other possible impurities. The glass fibers present in the original mattress had a diameter ranging from 5 to 13 µm, with an estimated surface area between 8 and 20 g/m², and a density close to 2.5 g/cm³.

Adhesive preparation and technological characterization

For the adhesive formulations, glass wool was added as a filler to the commercial urea-formaldehyde (UF) adhesive of cascamite type (Redemite, Redelease, Brazil). The glass wool residues were incorporated at different concentrations into the adhesive using a homogenizing device (a homemade blender was used, with a speed of rotation between 3500 and 5000 revolutions per minute), resulting in six treatments (Table 1).

For each adhesive with different filler contents, it was first necessary to determine the solids content, *i.e.*, the amount of resin solids contained in the commercial UF adhesive and in the respective filler concentrations studied.

The technological properties of the adhesives were evaluated in five replications, following previously established criteria (Table 2).

Table 1. Experimental Design According to the Content of Glass Wool Load in the Urea-Formaldehyde Adhesive and in the Particleboard Panels

Treatments	Glass Wool Content in Particleboard (%)	Glass Wool Content in the Urea-Formaldehyde Adhesive (%)
T1	0	0
T2	0.50	3.34
T3	0.75	4.93
T4	1.00	6.52
T5	1.50	9.49
T6	2.00	12.35

Table 2. Analysis of the Technological Properties of Adhesives

Technological Properties	Equipment	Source
pH	Digital pH meter (ALFAKIT, AT-355)	Pereira et al. (2024) Fassarella et al. (2025)
Solid substance (%)	Drying ovel (Solab, SL-101/180)	
Gel time	Test tube	
Viscosity	Digital Viscometer (MARTE, MVD-8)	ASTM D-2556-14 (ASTM, 2018)

The pH was measured in a controlled environment (≈ 25 °C) with a digital pH meter previously calibrated (standard buffer solutions - 4, 7 and 10), recording the value after the electrode stabilized in the sample.

The solids content was obtained by the ratio between dry mass (oven at 103 ± 2 °C for 12 h.) and initial mass of the sample (approximately 2 g of previously homogenized adhesive treatments).

The gel time of pure and filled urea-formaldehyde resin was evaluated considering the solids content and using ammonium sulfate (24%) as a catalyst, in a proportion of 2% based on the solids of the adhesive formed. The determination consisted of homogenizing the sample in a test tube under a water bath (90 °C), timing the interval (in seconds) until the transition from liquid to gel state, indicative of the beginning of curing.

Viscosity was determined according to D-2556-14 standard (ASTM, 2018), using a digital viscometer with a 3-inch stem and a rotation of 30 rpm, expressed in centipoise (cP).

Production of particleboard

The moisture level of the particles was initially determined using an infrared light-based moisture analyzer (LABORGLAS, MOC63u, São Paulo). Based on this value, the quantity of particles required to produce each panel was adjusted, with an additional 5% included to compensate for losses associated with particle moisture.

In all treatments, the same proportion of adhesive was used, corresponding to 12% of the oven-dry mass of the wood particles. The formulations were homogenized manually with the particles, following procedures described in the literature (Dhanapal *et al.* 2024; Fassarella *et al.* 2025), about 10 minutes at room temperature (≈28 ºC). All fractions (wood particles, adhesive and catalyst - ammonia sulfate, glass wool) were calculated based on the dry weight of the composite, for a target density of 700 kg/m³.

The particle mat was formed in a laboratory mold without a bottom, with dimensions of 42.5 × 42.5 cm and a removable cover, supported on an aluminum plate. The glued particles were uniformly distributed inside the mold, followed by pre-pressing on the forming cover, compacting and accommodating the particles on the aluminum sheet between two metal spacers with 1.25 cm edges.

The panels were produced using the compression molding method in a hydraulic press (SOLAB, SL12, Piracicaba) with heated plates. Pressing was performed at a temperature of 160 °C, a compression force of 72 tons (3.91 MPa), and a pressing time of 10 minutes.

After pressing and cooling at room temperature, the panels were trimmed to remove the edges and obtain the initial dimension of 40 × 40 cm. Three samples were produced for each treatment, totaling 18 panels, which were stored in a climate-controlled room (65 ± 5% relative humidity – RH and temperature of 25 ± 3 °C) until they reached an equilibrium moisture content of ≈ 12% (minimum 72 h), according to NBR 14810-2 (ABNT 2018).

The physical and mechanical tests proposed in this study and the number of replications for each test are presented in Table 3, along with the dimensions of the specimens according to the respective standards. Further details on sample preparation can be found in Fassarella (2025).

Table 3. Dimensions, Number of Test Specimens and Standards Associated with the Performed Test

Test	Dimensions of Specimens (mm)	Number of Specimens per Treatment	Standard
Apparent density (ρ r-X)	50 × 50	12	NBR 14810-2 (ABNT, 2018)
Water absorption (WA)		11	
Thickness swelling (ST)		9	
Internal bond (IB)		10	
Screw pulling (SP)		9	
Static bending (SB_{MOR})	310 × 50	14	ANSI A208.1 (ANSI, 1999)
Static bending (SB_{MOE})		13	
Janka hardness (JH)	50 × 50	11	
Flammability (Flam)	310 × 50	13	BS EN 11925-2 (ISO, 2020)
Sound impact insulation (SII)#	400 × 400	9	*
Damping coeficiente (DI) #			
Acoustic conversion efficiency (ACE) #			

* Experimental tests without specific standardization; #: Non-destructive testing of the square plate before obtaining the other test specimens.

Statistical analysis

Statistical analyses were conducted individually for each test, eliminating discrepant data based on the interquartile range (IQR) calculated from the 1^{st} and 3^{rd} quartiles, using Excel®. Values outside the minimum and maximum limits were considered outliers and excluded.

The experiments were conducted in a completely randomized design. All tests were initially subjected to regression analysis; since no statistical significance was observed, analysis of variance (ANOVA) followed by the Scott-Knott test ($p < 0.05$) was applied.

Finally, hierarchical cluster analysis, principal component analysis (PCA), and Pearson correlation were performed to synthesize the relationships between variables, identify factors, and verify the strength of associations among parameters. Analyses were performed in R software (R Core Team 2025).

RESULTS AND DISCUSSION

The technological properties of the adhesives and the mechanical and physical properties of the panels are presented in Tables 4, 5, and 6. The data provides an overview of the general behavior of the formulated composites, highlighting the potential effect of mineral additive incorporation on the structure of the materials.

Table 4. Mean Values for the Technological Properties of the Adhesive

Treatment	pH	Solids content (%)	Viscosity (cP)	Gel time (secs)
0%	7.91 (0.06)	62.88 (2.85)	1141.98 (34.33)	83.20 (13.92)
3.34%	8.20 (0.05)	67.42 (0.80)	1288.88 (49.59)	68.20 (9.28)
4.93%	8.15 (0.10)	63.79 (0.72)	1671.96 (55.56)	93.80 (9.91)
6.52%	8.29 (0.05)	68.14 (0.25)	1747.26 (66.77)	67.20 (4.02)
9.49%	8.37 (0.07)	68.64 (0.43)	1960.16 (77.84)	78.40 (11.78)
12.35%	8.59 (0.24)	71.85 (1.99)	7970.72 (993.6)	111.20 (12.64)

Values in parentheses correspond to the standard deviation. Values for 0% glass wool refers to the properties of the urea-formaldehyde adhesive evaluated in the laboratory, prior to its application in the composition of mixtures and application in panels.

A gradual increase in pH was observed with the incorporation of glass wool to the urea-formaldehyde resin in the modified formulations. This behavior is associated with the mineral nature of the filler, whose composition based on silicates and metal oxides can give a slightly alkaline character to the adhesive. Studies indicate that increasing pH raises viscosity and gel time, which may compromise the physical and mechanical properties of the composites (Ghani *et al.* 2018; Kawalerczyk *et al.* 2023). To mitigate these effects, extending pressing time is recommended to ensure proper curing of resins with a more basic character (Ghani *et al.* 2018).

The solids content found was in the common range in urea-formaldehyde adhesives (59 to 66%) (Albuquerque *et al.* 2020). The treatment with 12.35% glass wool presented a higher value, evidencing the direct contribution of the mineral filler to the solid fraction of the formulation.

The increase in the solids content tended to favor the formation of a denser polymeric network, enhancing stiffness and adhesion. However, excessive elevations can intensify the viscosity of the system and compromise the processability during application (Pizzi, 2003). Similar results were reported by Moslemi *et al.* (2020), who observed the influence of the solid fraction on the gelation kinetics of modified UF adhesives, highlighting the role of concentration in the curing process.

The increase in viscosity with the use of additives is associated with the higher solid content and the modification of molecular interactions during adhesive formulation (Achchaq *et al.* 2009; Silva *et al.* 2024). The use of functional fillers, such as microfibrillated cellulose, nanoclays, and silica, demonstrates that moderate concentrations can optimize viscosity and improve the mechanical performance of composites (Lei *et al.* 2008; Veigel *et al.* 2011; Hosseini *et al.* 2020).

Controlled additions, generally below 2%, favor adhesive penetration and curing, while higher contents compromise adhesive flow, resin penetration into wood, and hinder industrial application (Roumeli *et al.* 2012; Salari *et al.* 2013; Kawalerczyk *et al.* 2025). These findings reinforce the importance of balancing formulation and reactivity (Hong and Park 2017), as also evidenced by the multivariate statistical analyses in this study, which identified the rheological parameters of the resin as determinant variables in the final performance of the panels.

The mechanical performance of particleboards is intrinsically linked to the adhesive formulation and its interaction with lignocellulosic particles (Arias *et al.* 2021; Baharuddin *et al.* 2023). The addition of fillers, such as glass wool, can directly influence structural cohesion and the efficiency of stress transfer within the composite matrix (Lima *et al.* 2020; Costa *et al.* 2024). In this study, when applied in moderate proportions, approximately 3.34%, glass wool provided better mechanical performance and dimensional stability to the panels (Table 5). High concentrations may compromise resin dispersion, leading to interfacial discontinuities and reduced mechanical strength (Baldin *et al.* 2016; Kawalerczyk *et al.* 2025). Therefore, careful adjustment of filler content is essential to optimize crosslinking performance and adhesion of bonded elements, preventing incompatibilities that affect the homogeneity and integrity of the material (Taquetti *et al.* 2023; Silva *et al.* 2024).

Table 5. Mean Values for the Mechanical Properties of the Particleboards Produced with Different Proportions of Glass Wool as Filler

Treatment	SP (N)	JH (MPa)	Static Flexion		IB (MPa)
			MOE (MPa)	MOR (MPa)	
0%	1217 (167.8)	47.76 (14.86)	24731.85 (524.1)	15.33 (2.91)	0.814 (0.12)
3.34%	1404 (72.17)	55.31 (10.21)	26320.62 (306.0)	18.26 (2.21)	0.961 (0.15)
4.93%	1181 (191.2)	52.47 (9.67)	23845.69 (291.0)	16.36 (3.09)	0.745 (0.05)
6.52%	1192 (96.2)	55.21 (152.4)	23567.23 (144.0)	15.44 (2.56)	0.794 (0.13)
9.49%	1145 (58.9)	52.96 (14.95)	23474.92 (228.5)	14.98 (1.95)	0.598 (0.06)
12.35%	1288 (115.1)	63.55 (7.89)	21485.23 (336.3)	14.15 (2.70)	0.804 (0.05)
NBR 14810-2*	1020.0	-	1800.0	11.0	0.40
ANSI A208.1*	1100.0	22.7			

Treatment according to the content of glass wool added to the urea-formaldehyde adhesive. SP: Screw pulling (face); JH: Janka hardness; MOE: Elastic modulus in static bending; MOR: Modulus of rupture in static bending; IB: Internal bond. Values in parentheses correspond to the standard deviation. * Minimum values defined by the Brazilian standard NBR 14810-2 (ABNT, 2018), and American National Standards Institute A208.1 (ANSI, 1999).

The density of particleboards influences properties such as strength, dimensional stability, and adhesion efficiency (Nemli and Demirel 2007; Wong *et al.* 2020; Balea *et al.* 2022). In addition, its distribution, especially in the surface layers, affects fire performance (Harada *et al.* 2006; Najahi *et al.* 2023; Albert and Liew 2024). In the present study, the introduction of glass wool (a dense, friable, and inorganic material) modified the internal structure of the panel, reorganizing elements and filling voids without compromising compaction. However, higher filler contents may have reduced resin coverage on lignocellulosic particles, resulting in lower dimensional stability, as discussed by França *et al*. (2016) and Sozim *et al*. (2019).

Table 6. Mean Values Obtained for the Physical and Acoustic Properties of the Particleboards Produced with Different Proportions of Glass Wool in the Adhesive

Treat*	CR	ρ (r-X) (kg.m^{-3})	WA (%)	TS (%)	Flam (mm^{-2})	SII (dB)	DI (m^{-4}·kg^{-1}·s^{-1})	ACE (m^{-4}·kg^{-1}·s^{-1})
0%	1.37 (0.07)	726.31 (41.58)	56.84 (6.37)	15.8 (0.6)	7503 (315.5)	101.70 (0.64)	0.08772 (0.001)	154.34 (4.61)
3.34%	1.34 (0.04)	729.95 (18.85)	56.63 (2.36)	14.6 (1.05)	9170 (116.4)	102.05 (0.7)	0.08346 (0.000)	165.35 (4.70)
4.93%	1.31 (0.05)	718.33 (28.65)	58.25 (7.68)	15.9 (1.87)	8774 (78.65)	101.85 (0.52)	0.08587 (0.002)	154.85 (8.69)
6.52%	1.30 (0.05)	712.87 (11.19)	60.4 (6.41)	16.5 (1.13)	8022 (161.2)	102.26 (0.71)	0.08587 (0.002)	156.09 (7.34)
9.49%	1.28 (0.04)	725.23 (19.97)	64.87 (4.31)	17.6 (1.97)	6499 (97.14)	101.27 (0.45)	0.08713 (0.002)	151.69 (4.39)
12.35%	1.28 (0.06)	732.06 (42.01)	66.86 (6.39)	18 (0.77)	5570 (161.7)	101.16 (0.97)	0.08825 (0.002)	150.24 (4.47)

* Treatment according to the content of glass wool added to the urea-formaldehyde adhesive. CR: Compression ratio; ρ (r-X): Density apparent – X-ray; WA: Water absorption; TS: Thickness swelling; Flam: Flammability; SII: Sound impact insulation; DI: Damping coefficient; ACE: Acoustic conversion efficiency. Values in parentheses correspond to the standard deviation.

The results indicated that increasing filler content can compromise the glue line due to the release of accumulated internal stresses (Bazzetto *et al*. 2019), while reducing resin content negatively influences moisture resistance (Iwakiri *et al.* 2012; Ayrilmis and Nemli 2017;). On the other hand, the presence of glass wool improved resistance to flammability, which can be attributed to its inorganic silica-rich composition, which acts as a thermal barrier, delaying flame spread (Evangelista *et al*. 2012; Lee and Thole 2018; Lemougna *et al.* 2020). This characteristic, combined with the surface hardness of the panels (Janka), reinforces the role of formulation in enhancing fire resistance (Harada *et al*. 2006; Najahi *et al.* 2023; Albert and Liew 2024), and in this specific case, higher levels (limited to 6.52%) contributed to increased fire resistance.

Overall, the behaviour of acoustic conversion efficiency was only marginally sensitive to variations in filler content, with improvements only when mechanical properties were simultaneously favoured. Acoustic damping effects were of low magnitude, reinforcing the need for integrated approaches between structural performance and vibroacoustic properties.

These data provide a fundamental basis for conducting multivariate statistical analyses, enabling the identification of patterns, correlations, and key variables in the characterization of the particleboards.

Cluster analysis

Hierarchical cluster analysis using Euclidean distance revealed the formation of four distinct clusters among the treatments (Fig. 1). Groups 1, 2, and 3 were composed, respectively, of treatments T2, T6, and T5, while Group 4, with greater multivariate stability, comprised treatments T4, T1, and T3.

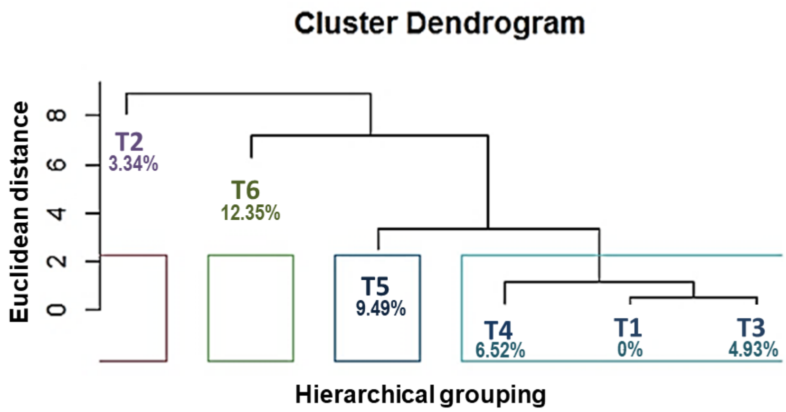

Fig. 1. Dendrogram of the hierarchical cluster analysis of the treatments applied according to the content of glass wool added to the urea-formaldehyde adhesive (UF). Euclidean distance indicates dissimilarity; lower branches indicate greater similarity.

Treatment T2, with a lower filler content and greater Euclidean distance from the other groups, suggests that the adhesive formulation used in this case promoted a behavior that influenced the joint response of several parameters.

Similarly, treatments T6 (12.35%) and T5 (9.49%) formed separate branches, reflecting greater dissimilarity, which was likely due to the high concentration of additives. Elevated levels of inorganic fibers, such as glass wool, can impair the interaction among lignocellulosic particles, reduce internal bonding, and increase panel heterogeneity (Ülker and Burdurlu 2015; Sato *et al.* 2024).

Excessive filler levels in adhesives can increase viscosity, hinder homogeneous dispersion over wood particles, and compromise proper compaction. This not only reduces bonding uniformity but also weakens the structural integrity of the linkage, lowers workability, and may induce mechanical weaknesses and durability deficiencies in the composite (Dashti *et al.* 2012; Khanjanzadeh *et al.* 2019; Chen *et al.* 2022).

Although such effects interfere with the kinetics and efficiency of the curing process, thus justifying the isolation of treatment T6 in the hierarchical clustering, it is noteworthy that the panels still surpassed the minimum requirements of applicable standards, highlighting the structural resilience of the material.

The joint clustering of treatments T4, T1, and T3 indicates a zone of higher homogeneity, possibly related to the incorporation of moderate glass wool contents (between 0% and 6.52%), which may have favored a more uniform fiber dispersion within the lignocellulosic matrix of particleboards (Pintiaux *et al.* 2015).

According to Srivabut *et al.* (2018), the incorporation of mineral fillers such as nanoclay, talc, and calcium carbonate into lignocellulosic fiber composites can significantly enhance mechanical and physical properties, particularly when applied at optimal levels that improve dispersion within the polymeric matrix and interfacial interaction. These results corroborate the effects observed in treatment T2, in which the moderate glass wool incorporation into both the panel structure and the urea-formaldehyde adhesive likely contributed to improvements in the physical and mechanical properties of the material (Baharoğlu *et al.* 2013; Cosereanu and Cerbu 2019).

This compatibility may have contributed to a more balanced performance in physical-mechanical properties. Similar outcomes were reported by Lu *et al*. (2016), who emphasized the role of chemical compatibility between fibers and wood particles in dimensional stability and internal bond strength of particleboards.

Principal components analysis (PCA)

The principal components analysis (PCA) revealed multivariate patterns among the physical-mechanical, chemical, and acoustic properties of the particleboards produced with varying levels of glass wool incorporated into urea-formaldehyde adhesive. The first two principal components accounted for 80.3% of the total variance, with Principal Component 1 (PC1) explaining 59% and Principal Component 2 (PC2) explaining 21.3% (Fig. 2).

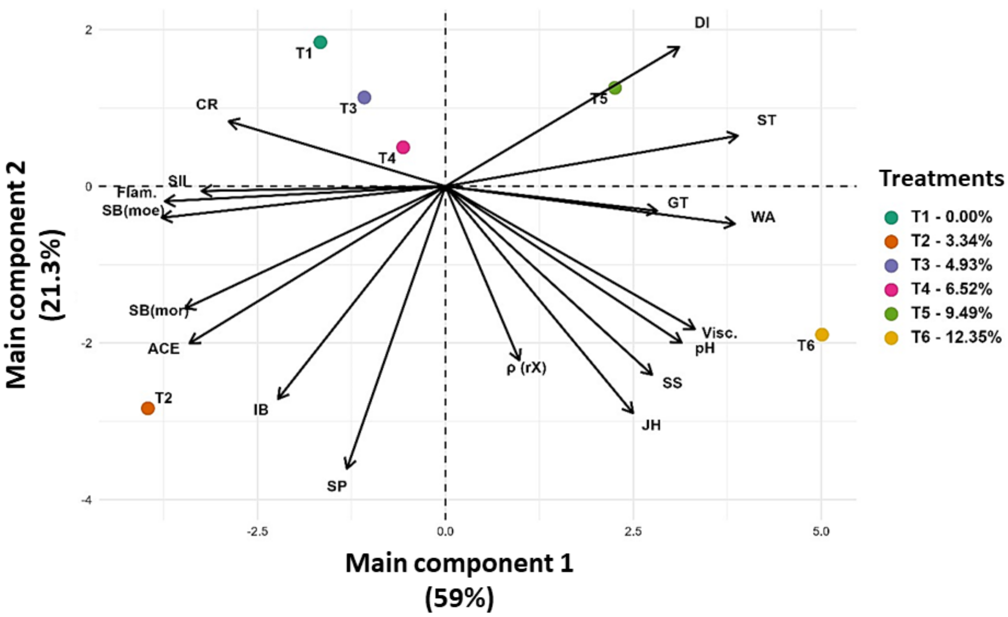

Fig. 2. Principal components analysis (PCA) of the properties of particleboard panels. T: Treatment according to the content of glass wool added to the urea-formaldehyde adhesive. GT: Gel time. Visc: Viscosity; SC: Solid content; ρ(r-X): apparent density; CR: Compression ratio; WA: Water absorption; ST: Swelling in thickness; SB(MOE): Elastic modulus in static bending; SB(MOR): Modulus of rupture in static bending; IB: Internal bond; JH: Janka hardness; SP: Screw pulling (face); Flam: Flammability; DI: Damping coefficient; ACE: Acoustic conversion efficiency; SII: Sound impact insulation.

In Fig. 2, treatments are represented by color-coded points according to increasing glass wool content. PC1 was strongly associated with variables such as thickness swelling (TS), water absorption (WA), viscosity (Visc), solid content (SC), pH, gel time (GT), damping coefficient (Dl), acoustic properties (ACE), and mechanical properties SB(MOE)) and SB(MOR)).

PC2 was related to apparent density (ρ r-X), compression ratio (CR), screw withdrawal resistance (SP), Janka hardness (JH), and internal bond (IB), thus reflecting the structural and strength-related characteristics of the panels.

The correlation coefficients of the variables with PC1 and PC2, which together explained most of the variance in the dataset, are presented in Table 7. These coefficients allow the identification of variables most sensitive to glass wool incorporation into urea-formaldehyde adhesive and support the selection of key attributes for determining particleboard performance.

Table 7. Correlation of the Evaluated Variables with the First Two Principal Components (PC1 and PC2) Obtained in the Principal Component Analysis (PCA)

Variables	CP1	CP2
CR	-0.7708	0.0901
ρ r-X	0.2403	-0.5821
WA	0.9606	-0.1222
ST	0.9733	0.1559
SP	-0.3371	-0.908
JH	0.6159	-0.722
$SB_{(MOE)}$	-0.9441	-0.0928
$SB_{(MOR)}$	-0.8694	-0.3743
IB	-0.5642	-0.6851
pH	0.7801	-0.4924
SC	0.6803	-0.5958
Visc	0.8241	-0.4723
GT	0.7039	-0.1026
Flam	-0.9331	-0.0284
SII	-0.8117	0.0075
DI	0.7809	0.4192
ACE	-0.8563	-0.4866

* CR: compression ratio; ρ(r-X): Apparent density; WA: Water absorption; ST: Swelling in thickness; SP: Screw pulling (face); JH: Janka hardness; SB(MOE): Elastic modulus in static bending; SB(MOR): Modulus of rupture in static bending; IB: Internal bound; pH: Hydrogen potential; SC: Solids content; Visc: Viscosity; GT: Gel time; Flam: Flammability; SII: Sound impact insulation; DI: Damping coefficient; ACE: Acoustic conversion efficiency

The use of principal component analysis (PCA) in this study made it possible to identify complex interrelationships among the properties. The presented correlation matrix allows for understanding the degree of contribution of each property to the factorial directions that explain most of the variance observed in the data (Fialho *et al.* 2022). This multivariate approach not only highlights the properties most sensitive to the addition of glass wool but also identifies those with greater discriminating power among treatments, providing objective support for selecting key variables in the overall performance of particleboards.

PCA revealed a strong correlation of adhesive technological variables with the first principal component (PC1), such as viscosity (0.8241), pH (0.7801), and gel time (0.7039), indicating that the addition of glass wool significantly modified the behavior of the commercial resin.

The chemical changes in the adhesive system directly influenced the quality of the produced panels. Among the particleboard properties, high negative correlations were observed on PC1 for modulus of elasticity (–0.9441), modulus of rupture (–0.8694), screw withdrawal resistance (–0.908), flammability (–0.9331), and acoustic conversion efficiency (–0.8563), along with positive correlations with water absorption (0.9606) and thickness swelling (0.9733). These data indicate that modifying the adhesive formulation with glass wool incorporation plays a decisive role in the physical, mechanical, and thermal performance of particleboards, representing a potential strategy to optimize specific properties through rheological and chemical adjustments of the adhesive matrix.

This multivariate technique proved highly efficient by reducing an extensive set of variables into two principal components, which together represented 80.3% of the total variance of the experimental data—a percentage considered high and consistent with investigations involving lignocellulosic composites (Fehrmann *et al.* 2023).

Located in the lower-left quadrant, treatment T2 showed a strong association with the vectors modulus of rupture (SB(MOR)), acoustic conversion efficiency (ACE), and internal bond (IB), indicating satisfactory performance both in mechanical and acoustic terms.

This spatial configuration suggests that, despite the low glass wool content in the adhesive (3.34%), the treatment achieved a remarkable balance between structural stiffness and sound functionality. These results are consistent with the literature emphasizing the positive effects of moderate inorganic fiber incorporation in wood-based panels (Park *et al.* 2020; Yildirim and Candan 2021), indicating effective interaction between the lignocellulosic material and the modified adhesive.

T6 Treatment, located in isolation at the far right of PC1, showed high correlation with pH, viscosity, and solid content, evidencing the predominance of rheological factors. This behavior indicates that the high glass wool concentration (12.35%) significantly influenced adhesive characteristics, improving parameters such as gel time and colloidal stability. Although filler content reduced the uniformity of dispersion and adhesive penetration into wood particles, due to the lower amount of UF resin available in the bond (Hong and Park 2017), all panels met the minimum values required by the NBR 14-810-2 (2018) standard.

According to Calovi and Rossi (2023) and Iglesias *et al.* (2021), high levels of fibrous fillers promote increased adhesive viscosity and impair the wetting efficiency of lignocellulosic surfaces. Such limitations in anchorage capacity may justify the separation of T6 from variables associated with mechanical performance and dimensional stability.

Positioned in the upper-right quadrant, treatment T5 was close to the vectors ST, WA, and Dl, characterized by a profile strongly influenced by dimensional stability and specific acoustic attributes. These results suggest that the intermediate glass wool concentration (9.49%) favors a balance between acoustic performance and moisture absorption behavior, although increased ST may represent a limitation in terms of stability (Li *et al.* 2012; Sakamoto *et al.* 2024).

T1, T3, and T4 Treatments exhibited closer distribution to each other, indicating greater uniformity from the multivariate perspective. Treatments T3 and T4, with moderate glass wool levels (4.93% and 6.52%, respectively), behaved similarly to the commercial panel (T1), suggesting that controlled fiber incorporation does not compromise structural integrity nor cause significant variations in physical-chemical and mechanical properties (Benthien *et al.* 2019; Engehausen *et al.* 2024).

In the factorial plane, the vectors corresponding to gel time (GT) and water absorption (WA) showed similar orientation, suggesting a positive correlation between these variables, that is, higher GT values may be associated with increased water absorption. However, the GT vector had a lower magnitude, indicating a relatively smaller contribution to overall data variability compared with panel water absorption.

Similarly, the proximity of the vectors for pH, viscosity, and solid content reveals a trend of co-evolution of these variables depending on adhesive formulation (Gultom *et al.* 2013). Interestingly, the proximity of distinct properties such as flammability (Flam), modulus of elasticity (SB(MOE)) and acoustic impedance (SII) suggests potential correlations among them.

Conversely, vectors oriented in opposite directions indicate relevant inverse relationships. The damping coefficient (Dl) vector was oriented opposite to the acoustic conversion efficiency (ACE) and modulus of rupture (SB(MOR)) vectors, suggesting that higher levels of viscoelastic energy dissipation may compromise both acoustic performance and rupture strength (Krushynska *et al.* 2021; Kumar *et al.* 2025).

Likewise, the opposition between the modulus of elasticity (MOE) and thickness swelling index (ST) vectors highlights a possible antagonism between structural stiffness and dimensional stability, possibly due to limitations in adhesive formulation regarding its interaction with the particulate matrix (Gultom *et al.* 2013; Iswanto *et al.* 2023).

The results reinforce the hypothesis that incorporating glass wool into urea-formaldehyde adhesive simultaneously and interdependently influences multiple particleboard properties. When properly adjusted, parameters such as viscosity, pH, and gel time can contribute to panel performance optimization, promoting better adhesion between adhesive and particles and resulting in joint advances in mechanical, acoustic, and dimensional stability properties (Gultom *et al.* 2008; Gonçalves *et al.* 2017; Iswanto *et al.* 2023).

In this context, PCA has been shown to be a robust statistical tool, capable of identifying latent multivariate patterns and providing an integrated interpretation of treatment effects, effectively complementing traditional analyses.

Pearson correlation

The Pearson correlation was applied to quantify the intensity of linear relationships among the physical-mechanical, rheological, and acoustic properties of the modified particleboards (Fig. 3).

	pH	*SC*	*Visc*	*GT*	ρ (r-X)	CR	*WA*	*ST*	*SB (MOE)*	*SB (MOR)*	*IB*	*JH*	*SP*	*Flam*	*SII*	*DI*	*ACE*
pH	1																
SC	0.95**	1															
Visc	0.79^{ns}	0.74^{ns}	1														
GT	0.42^{ns}	0.25^{ns}	0.80^{ns}	1													
ρ (r-X)	0.24^{ns}	0.33^{ns}	0.48^{ns}	0.41^{ns}	1												
CR	-0.88*	-0.74^{ns}	-0.55^{ns}	-0.35^{ns}	0.08^{ns}	1											
WA	0.88*	0.82*	0.77^{ns}	0.53^{ns}	0.25^{ns}	0.87*	1										
ST	0.73^{ns}	0.64^{ns}	0.69^{ns}	0.55^{ns}	0.09^{ns}	-0.79^{ns}	0.95**	1									
SB (MOE)	-0.71^{ns}	-0.57^{ns}	-0.79^{ns}	-0.73^{ns}	0.005^{ns}	-0.74^{ns}	-0.86*	-0.92**	1								
SB (MOR)	-0.43^{ns}	-0.36^{ns}	-0.59^{ns}	-0.57^{ns}	0.002^{ns}	0.49^{ns}	-0.75^{ns}	-0.91*	0.88*	1							
IB	-0.22^{ns}	-0.06^{ns}	-0.01^{ns}	-0.18^{ns}	0.27^{ns}	-0.60^{ns}	-0.55^{ns}	-0.69^{ns}	0.52^{ns}	0.62^{ns}	1						
JH	0.92*	0.89*	0.86*	0.48^{ns}	0.33^{ns}	-0.66^{ns}	0.68^{ns}	0.49^{ns}	-0.59^{ns}	-0.26^{ns}	0.15^{ns}	1					
SP	0.09^{ns}	0.24^{ns}	0.19^{ns}	-0.06^{ns}	0.60^{ns}	0.33^{ns}	-0.25^{ns}	-0.49^{ns}	0.43^{ns}	0.59^{ns}	0.88*	0.39^{ns}	1				
Flam	-0.62^{ns}	-0.61^{ns}	-0.75^{ns}	-0.61^{ns}	-0.4^{ns}	-0.55^{ns}	-0.88*	-0.92*	0.82*	0.89*	0.49^{ns}	-0.46^{ns}	0.27^{ns}	1			
SII	-0.50^{ns}	-0.42^{ns}	-0.65^{ns}	-0.71^{ns}	-0.63^{ns}	0.48^{ns}	-0.76^{ns}	-0.75^{ns}	0.62^{ns}	0.65^{ns}	0.51^{ns}	-0.34^{ns}	0.17^{ns}	0.86*	1		
DI	0.23^{ns}	0.16^{ns}	0.54^{ns}	0.66^{ns}	0.16^{ns}	0.27^{ns}	0.61^{ns}	0.78^{ns}	-0.77^{ns}	-0.95**	-0.55^{ns}	0.09^{ns}	-0.53^{ns}	-0.86*	-0.73^{ns}	1	
ACE	-0.37^{ns}	-0.22^{ns}	-0.53^{ns}	-0.66^{ns}	0.03^{ns}	0.53^{ns}	-0.72^{ns}	-0.88*	0.87*	0.95*	0.75^{ns}	-0.17^{ns}	0.69^{ns}	0.82*	0.71^{ns}	-0.94**	1

Legend: Weak correlation ($0 > r \leq 0.3$); Moderate correlation ($0.3 > r \leq 0.6$); Strong correlation ($0.6 > r \leq 0.9$); Very strong correlation ($0.9 > r < 1$)

Fig. 3. Observed values for Pearson correlation. **: significant correlations at 1%; *: significant correlations at 5%; ns: non-significant correlations (p > 0,05); r: Pearson correlation coefficient; * pH: Hydrogen potential; SC: Solids content; Visc: Viscosity; GT: Gel time; ρ (r-X): Apparent density; CR: Compression ratio; WA: Water absorption; ST: Swelling in thickness; SB(MOE): Modulus of elastic modulus in static bending; SB(MOR): Modulus of rupture in static bending; IB: Internal bound; JH: Janka hardness; SP: Screw pulling (face); Flam: Flammability; SII: Sound impact insulation; DI: Damping coefficient; ACE: Acoustic conversion efficiency.

For interpretation of the coefficients, the classification proposed by Navarro and Foxcroft (2025) and Weisburd *et al.* (2020) was adopted, considering strong correlations within the range $0.60 < r \leq 0.90$ and very strong within $0.90 > r < 1$.

The resulting matrix revealed a high degree of interdependence among the analyzed variables, with than 49.26% of the correlations classified as strong or very strong, and about 29.41% as moderate. This indicates statistical consistency of the data and coherence in the response patterns of the panels.

Among the main results, a very strong correlation was observed between pH and solid content (r = 0.95**), as well as a strong correlation between viscosity and solid content (r = 0.80). These findings suggest that urea-formaldehyde adhesive formulations with higher alkalinity and solid content tend to exhibit higher viscosity. This behavior is consistent with the literature, which highlights the sensitivity of viscosity to solid concentration in colloidal systems with particulate additives (Akpabio 2012; Bacigalupe *et al.* 2020).

Conversely, viscosity showed a strong negative correlation with the modulus of elasticity (SB(MOE)) (r = –0.79), indicating that more viscous formulations may hinder adequate adhesive penetration into the lignocellulosic particles, reducing internal cohesion and structural stiffness of the panels, as also reported by Cesprini *et al.* (2022).

A very strong correlation was also observed between pH and Janka hardness (JH) (r = 0.92), indicating that more alkaline conditions favor more efficient resin curing and greater resistance to penetration. This effect is particularly relevant in formulations with higher glass wool content, in which alkalinity contributes to more complete polycondensation reactions and formation of a stronger adhesive matrix (Wang *et al.* 2016).

Regarding dimensional stability, a very strong negative correlation was found between flammability (Flam) and thickness swelling (ST) (r = –0.92**), suggesting that lower moisture absorption is associated with higher fire resistance. This behavior may be linked to greater porosity in the panels, which facilitates water penetration and contributes to swelling. Nevertheless, despite this less compact structure, the presence of silica derived from glass wool acts as a thermal barrier, delaying flame propagation and explaining the observed reduction in flammability (Costa *et al.* 2020) as well as enhancing fire resistance (Çavdar 2020; Najahi *et al.* 2023). This trend aligns with several studies emphasizing the role of material composition and structure in determining both fire resistance and dimensional stability (Maminski *et al.* 2011; Kweon *et al.* 2012; Yoo and Kim 2014; Jeon *et al.* 2017).

Acoustic conversion efficiency (ACE) showed a very strong negative correlation with the damping coefficient (Dl) (r = –0.94**) and a strong positive correlation with acoustic impedance (SII) (r = 0.71), indicating that stiffer structures with lower viscoelastic dissipation provide better sound transmission (He *et al.* 2018).

The modulus of rupture (SB(MOR)) correlated strongly with the acoustic conversion efficiency (ACE) (r = 0.95) and negatively with the damping coefficient (Dl) (r = -0,73ns), suggesting that both acoustic and mechanical performance are influenced by viscoelastic mechanisms, especially those related to internal cohesion, stiffness, and uniformity of the lignocellulosic matrix (Taghiyari *et al.* 2017; Bertolini *et al.* 2019).

Properties such as screw withdrawal (SP) and internal bond (IB) exhibited weak correlations with rheological variables, including pH, viscosity, and solid content, indicating that their variation may be more closely related to structural aspects such as particle orientation, localized density, and mixture uniformity (Arabi *et al.* 2012; Engehausen *et al.* 2024). However, IB showed meaningful correlations with SB(MOR) (r = 0.62ns) and ACE (r = 0.87), reinforcing its importance in the functional response of the panels.

Overall, these results demonstrate that the rheological properties of the adhesive play a crucial role in defining the structural and functional characteristics of the panels. Adjustments in formulation parameters—particularly pH, viscosity, and solid content—can directly affect mechanical stiffness, acoustic performance, and dimensional stability (Ramesh *et al.* 2022; Jalowy *et al.* 2025). Within this context, the Pearson correlation matrix complements principal component analysis (PCA) by enabling the identification of directed associations between specific variables, thereby supporting the development of consistent models for the integrated performance of particleboards.

In an integrated framework, the combination of Pearson correlation, PCA, and hierarchical clustering made it possible to identify critical properties and similarity patterns across treatments. This joint approach enhances interpretive robustness and contributes to the optimized formulation of panels with functional additives. Such an approach supports targeted variable selection, increasing efficiency in the development of sustainable materials with improved mechanical, physical, and functional performance.

CONCLUSIONS

1. The application of multivariate statistical techniques allowed the effects of glass wool addition to urea-formaldehyde adhesive in wood particleboards to be understood. The study demonstrated that incorporating glass wool residue into urea-formaldehyde (UF) resin significantly alters adhesive rheological properties (viscosity, pH, and solid content).
2. PCA revealed that 80.3% of the total variance was explained by the first two principal components, establishing strong correlations between adhesive rheological properties and the final performance of the panels. Hierarchical clustering analysis identified four distinct groups, and the Pearson correlation matrix revealed expressive associations between adhesive rheological properties and the physical-mechanical and acoustic performance of the panels, including very strong correlations between pH and Janka hardness ($r = 0.92$) and between ACE and the damping coefficient ($r = –0.94$).
3. The strong correlations detected for MOE, MOR, WA, TS, Flam, and ACE with multiple parameters reinforce their role as critical indicators for quality control, dimensional stability, mechanical resistance, and fire performance. Thus, these variables make the greatest contribution to treatment differentiation.
4. The adhesive with 3.34% glass wool content enhanced the mechanical, physical, and acoustic performance of the panels, while higher addition levels (>9%) improved fire resistance and reduced sound impedance without compromising compliance with normative requirements for other parameters.
5. The results indicate that modification of the adhesive with glass wool contributes to the optimization of the physical, mechanical, fire-retardant, and acoustic properties of particleboards. Therefore, this study validates glass wool as a functional additive of technological interest, offering scientific evidence to support the design of products with improved performance efficiency, safety, and environmental relevance.

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