Fungal Decay, Coating, Burning Properties and Change of Color of Particleboards Manufactured with Woody Biomass, Agricultural Wastes and Tetra Pak Residues

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ABSTRACT

Lignocellulosic residues resulting from agricultural activities and urban centers cause pollution. A possible solution to this problem is to combine these residues with woody plants to produce particleboards. The purpose of this study was to evaluate decay resistance, coating and burning properties and the change of color caused by accelerated weathering of particleboards manufactured with a combination of 3 woody species used for commercial reforestation in tropical areas (Cupressus lusitanica, Gmelina arborea and Tectona grandis), pineapple (Ananas comosus) leaves from the crown and the plant (PL), empty fruit bunch of Elaeis guineensis (EFB) and tetra pak packages (TP). According to the results, the mixtures of T. grandis and EFB were classified as moderately resistant and other mixtures (woody species and PL or TP) were classified as slightly resistant. The finish performance test determined that the mixtures with TP presented the best performance, followed by the mixtures with oil palm components and the mixtures composed of pineapple leaves. Regarding lacquer consumption, no differences were found between the mixtures. The combustion test determined that particleboards with TP and EFB showed the highest resistance to combustion, while pineapple presented the lowest resistances to combustion. In the accelerated weathering exposure test, the mixtures of the three species with TP showed the best performance in accelerated weathering. Contrariwise, the mixtures with pineapple leaves showed the lowest resistance to accelerated weathering. Oil palm particleboards presented lower resistance to weathering than TP, though higher than pineapple leaves’ resistance.

Keywords: Tropical Species; Particleboards; Lignocellulosic Residues; Agricultural Crop

1. Introduction

Tropical regions have environmental factors that favor excellent levels of productivity in agricultural crops [1]. It is estimated that 47,000 hectares have been planted with oil palm and 40,000 hectares with pineapple in Costa Rica [2], with the disadvantage that residues from these crops are not being used. Khalil et al. [3] mention that an oil palm plantation produces about 350 ton of residues/ha/rotation, while Araya [4], found that a pineapple plantation produces around 220 ton/ha per rotation. The limited use of these residues is attributed to a lack of technology for their processing and of commercial products that allow their management [5].

On the other hand, tetra pak packages account for large quantities of waste material worldwide. According to estimations, around 150 trillion packs were produced in 2010 (www.tetrapak.com), to pack and preserve milk, juice, nectars and others [6]. This product decomposes slowly, thus, high technology such as plasma treatment is required to recycle it [7].

Having said this, it is important to find an adequate way to use agricultural residues and tetra pak packages [8]. One possible alternative is to use them to manufacture already established products, such as particleboards. According to estimations, 81.5 million m³ of particleboards were produced in 2004 and their production continues to grow [9].

Lignocellulosic materials are commonly added to products like particleboards. For example, particleboards...
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have been produced using straw and wood from Pinus sylvestris [10], tetra pak packages and Pinus sp. [6]; and bagasse (Saccharum spp) with Eucalyptus grandis [11]. In order to obtain stable and commercially-easy-to-develop particleboards, it is important to consider the interaction between the components of the various types of materials in these mixtures [12]. Good interaction of the materials in the mixture allows obtaining similar mechanical resistance values to those of traditional pure wooden particleboards. Additionally, its water retention and dimension stability are enhanced, and resistance to pathogens such as mold and rot fungi is increased [13,14].

Previous manuscript [15] shows that particleboards manufactured with woody species used in this study (G. arborea, C. lusitanica and T. grandis) combined with tetra pak packages presented the best physical and mechanical properties and particleboards using a mixture of pineapple leaves showed lower values for the properties evaluated.

The objective of this study is therefore to evaluate decay resistance, color change by accelerated weathering exposure, response to application of finishes and combustion properties of particleboards manufactured with combinations of 3 species planted for commercial purposes in tropical areas (Cupressus lusitanica, Gmelina arborea and Tectona grandis), with pineapple leaves from the crown and the plant, fruit and bunch of oil palm and discarded tetra pak packages.

2. Material and Methods

2.1. Raw Materials

1) Woody biomass corresponded to Gmelina arborea (GA) from a 9 year old plantation, Tectona grandis (TG) from a 16 year old plantation, and Cupressus lusitanica (CL) from a 22 year old plantation (all of them used for commercial reforestation in tropical countries); 2) Agriculture wastes consisted of pineapple leaves (PL) and residues of oil palm from the extraction of oil empty fruit bunch of oil palm (EFB) and oil palm mesocarp fiber of the fruit (OPMF); PL came from an 18 month old plantation and they were used from the crown (PLC) and from the plant (PLP); and 3) Tetra Pak packages residues (TP) were obtained from recycling centers located at Cartago downtown in Costa Rica. Table 1 presents a summary of the raw materials used in the particleboards fabrication.

2.2. Material Preparation

Pineapple leaves and oil palm residues were dried following the methodology given by Tenorio and Moya [16]. OPMF residues were washed for one hour in hot water stirring continuously, in order to obtain the best performance with adhesives [17]. TP were washed to eliminate residual contents and then they were cut into 1 cm wide strips, using a paper cutter. The three woody species were chipped to size less than 3 mm. Then a Retsch cutting mill was used to reduce the dried chips into particles that resulted of sizes between 0.7 and 6.0 mm. Finally, the particles of each material were placed into a climate-controlled chamber to obtain 6% equilibrium moisture content.

2.3. Particleboard Preparation

Blends of woody biomass and residues (agricultural and TP packages) used for the particleboard preparation are presented in Table 1. They all were prepared using a 50:50 ratio. The adhesive used was urea-formaldehyde (UF) with 62% solids, and the adhesive application corresponded to percentages between 6% - 8% with respect to the total weight of the particleboard. The amount of adhesive applied was taken from previous research [17]. In total, fifteen different blends were prepared and twenty 35 × 35 cm boards were obtained from each mixture. The target particleboard density was of 0.65 g/cm³, with an average thickness of 12.5 mm and 3 layers. The two external layers or faces (2 mm thick) contained fine particles 0.7 to 1.5 mm long while the inner layer (core) contained thicker particles 1.5 to 6.0 mm long. Particleboards were pressed at 25 MPa and 175°C for 10 minutes and after that they were put into a climate-controlled chamber during 24 hours to homogenize their moisture content and to finish their adhesive curing process.

2.4. Fungal Decay Resistance

Two decay resistant specimens (2.5 × 2.5 × 1.2 cm³) were cut from each sheet. The white-rot fungi Trametes versicolor L. Fr. and Gloeophyllum trabeum (Pers.) Murrill, (Brown-rot fungi) were used for testing natural decay resistance following ASTM D-2017 Standard [18].

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The relative resistance of each test block to decay was measured as the percentage loss in relation to initial weight during a 16-week exposure to the fungi. Although ASTM D-2017 specifies that sample dimensions are 2.5 × 2.5 × 0.9 cm, we modified the procedure to use 2.5 cm (width) × 2.5 cm (length) × 1.2 cm (thickness) samples. Resistance rating for fungal decay was established according to ASTM Standard D-2017 [18], which classified fungal decay resistance in non-resistant when weight loss is higher than 45%, slightly resistant for weight loss from 25% to 45%, moderately resistant for 11 to 24 in weight loss and resistant for weight loss from lower than 10% [18].

2.5. Accelerated Weathering Exposure and Wood Color Change of Particleboards

Samples extracted (5.0 cm width × 15.0 cm in length and 1.2 cm in thick) from particleboard sheets were applied an accelerated weathering test, for which a weathering Q-Lab camera was used (QUV/spray model). The ASTM G-152 Standard [19] was applied for this test. The exposure was of five-hour cycles in two phases: firstly, three hours of UV radiation at 60°C and a radiation of 0.63 w/m² (with an UVA mercury bulb and 310 nm wave length), then a second phase of condensation which took two hours and consisted of using evaporated water at 50°C temperature. The total exposure time was 600 hours, except for particleboards with PLC and PLP, because samples supported 350 hrs. Color was measured in intervals of 50 hours with a Hunter Lab mini Skan XE Plus spectrophotometer. Color difference (ΔE*) was determined as the net color variation for each finish in a period of time according to the ASTM D 2244 Standard [20] whose formula is detailed in Equation (1). The change in color was determined between color before and after accelerated weathering exposure.

\[ \Delta E^* = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \]  

(1)

where: \( \Delta E^* \): wood color difference; \( \Delta L \): \( L^* \) before weathering; \( \Delta a \): \( a^* \) before weathering; \( \Delta b \): \( b^* \) before weathering; \( \Delta a^* \) after 600 hours of weathering; \( \Delta b^* \) after 600 hours of weathering.

2.6. Coating Performance

Samples extracted (5.0 cm width × 15.0 cm length and 1.2 cm thickness) from the particleboard sheets were applied lacquer finish (from nitrocellulose resins and nitrated plasticizers). Sealant was previously applied to the samples. The base of this sealant was of concentrated methyl methacrylate, diluted in a 1:3 ratio with thinner. Evaluation took into consideration finish consumption (finish grams/m²) on the surface of the particleboards. The samples were initially weighed and four layers of nitrocellulose sealant and two layers of nitrocellulose lacquer (composed of nitrocellulose resins and plasticizers) were applied using an ordinary paintbrush. Both the sealant and the lacquer were applied according to recommendations given by the manufacturer. Once the last layer was dry, the sample was weighed and the film thickness (FT) was measured in µm using a Positector (200 series) coating meter, which measures FT following the ASTM D-6123 Standard [21]. Consumption of coating was determined based on the difference between the weight before and after coating application and expressed according to the sample area. Three types of consumption were determined: the first, Sealant Consumption (SEA), which corresponds to the amount of dry sealant left on the particleboard’s surface after four applications of this finish; the second type of consumption corresponds to Lacquer Consumption (LAC), applied on two occasions to the surface with sealant; and the third parameter evaluated corresponds to the Total Consumption (TC), that is, the sum of SEA and LAC.

2.7. Burning Test

Two samples (2.0 cm width × 15.0 cm length and 1.2 cm thickness) of each of the formulations were evaluated in a high temperature chamber proposed by Castro and Costa [22] to evaluate the combustion properties. In the chamber, the test tubes were placed on a base on a scale in a compartment to reach 500°C. Weight measurement was performed in periods of one minute until sample combustion was complete. Next, the consumed mass percentage (Equation (2)) and the mass derivative (Equation (3)) on the basis of lapse of time, were estimated. Lastly, these two values were graphed in relation with time.

\[ MP = \left( \frac{W_x - W_{0\text{min}}}{W_{0\text{min}}} \right) \times 100 \]  

(2)

\[ \frac{dm}{dt} = \frac{(W_{x+s} - W_{x+1})}{(t_{x+1} - t_x)} \]  

(3)

where: \( MP \): Mass Percentage; \( W_x \): specific mass at a time of combustion; \( W_{0\text{min}} \): mass before combustion; \( dm/dt \): mass derivative; \( W_{x+s} \): a second over of combustion \( W_x \); \( t_{x+1} \): time in \( W_{x+1} \); \( t_x \): it is the time in \( W_x \).

2.8. Statistical Analysis

One-way ANOVA was applied to the results obtained in the decay resistance and finish application tests to find whether there were any significant property differences among the particleboard mixtures of each species. The tests of each of the properties that showed significant
differences with the ANOVA, were applied the Tukey test with a significance level of $P < 0.05$. The average value of each property was introduced in the model. For all these analyses, the SAS 8.1 statistics program for Windows (SAS Institute Inc., Cary, N.C.) was used. With the results obtained in the accelerated weathering exposure and wood color change test, the values of $\Delta E^*$ were compared to the value reported by Cui et al. [23], who determined that if values of $\Delta E^*$ equal or higher than twelve are obtained, a total change in color is obtained after a period of weathering exposure.

3. Results

3.1. Fungal Decay Resistance

Table 2 presents the weight loss percentages (WL) of the particleboards exposed to *T. versicolor* and *G. trabeum*. In CL and TG particleboards exposed to *T. versicolor*, the mixtures with oil palm components (EFB and OPMF) showed significantly higher WL values, whereas pineapple leaves mixtures (PLC and PLP) and TP had the lowest significant values of WL. No differences were found for WL values in the mixtures of GA particleboards. With regard to CL particleboards exposed to *G. trabeum*, no differences were found in WL between mixtures with pineapple and oil palm components, while the CL-TP mixture presented the statistically lowest WL value. GA particleboards presented no statistical differences among mixtures of pineapple leaves, OPMF and TP, except for the GA-EFB mixture, being the only one that presented the lowest WL. Finally, TG particleboards presented no differences in the WL values of the five mixtures evaluated (Table 2).

3.2. Accelerated Weathering Exposure and Wood Color Change of Particleboards

Variations in $\Delta E^*$ are presented in Figure 1, which shows that: 1) $\Delta E^*$ increases with time of exposure to UV light in all particleboards; 2) after 350 hours of exposing the mixtures with pineapple components (PLC and PLP) to light, it was not possible to continue with the trial, since UV radiation degraded the external layer of the particleboards; 3) the mixtures of the three species with pineapple components (PLC and PLP) and oil palm components (EFB and OPMF) presented the greatest changes from the beginning of the exposure up to 200 hours; after that period, variations in color were not of the same magnitude; 4) the particleboards manufactured with TP presented the lowest $\Delta E^*$ values during the whole period of exposure. Particleboards containing oil palm components (EFB and OPMF) were the least affected, the most affected being therefore those with pineapple leaves components (PLC and PLP).

Table 2. Weight loss of particleboards manufactured of *Cupressus lusitanica*, *Gmelina arborea* and *Tectona grandis* mixed with pineapple leaves, fiber from oil palm fruit and tetra pak package exposed to fungi *Trametes versicolor* and *Gloeophyllum trabeum*.

| Species            | Treatments | *Trametes versicolor* | *Gloeophyllum trabeum* |
|--------------------|------------|-----------------------|------------------------|
|                    |            | Weight loss (%) | Resistance rating | Weight loss (%) | Resistance rating |
| *Cupressus lusitanica* | PLC        | 41.1<sup>DE</sup> | Sr         | 30.9<sup>AB</sup> | Sr          |
|                    | PLP        | 39.8<sup>DE</sup> | Sr         | 32.9<sup>AB</sup> | Sr          |
|                    | EFB        | 50.2<sup>ABCD</sup> | Sr         | 30.9<sup>AB</sup> | Sr          |
|                    | OPMF       | 54.6<sup>ABCD</sup> | Sr         | 33.7<sup>A</sup> | Sr          |
|                    | TP         | 36.6<sup>C</sup> | Sr         | 18.8<sup>C</sup> | Sr          |
|                    | PLC        | 41.8<sup>DE</sup> | Sr         | 31.2<sup>AB</sup> | Sr          |
|                    | PLP        | 42.2<sup>DE</sup> | Sr         | 27.4<sup>ABC</sup> | Sr          |
| *Gmelina arborea*  | EFB        | 50.8<sup>ABCD</sup> | Sr         | 13.6<sup>C</sup> | Sr          |
|                    | OPMF       | 48.1<sup>ABCD</sup> | Sr         | 30.7<sup>ABC</sup> | Sr          |
|                    | TP         | 54.6<sup>DE</sup> | Sr         | 28.2<sup>AB</sup> | Sr          |
|                    | PLC        | 48.3<sup>ABCD</sup> | Sr         | 27.9<sup>ABC</sup> | Sr          |
|                    | PLP        | 46.8<sup>BCDE</sup> | Sr         | 32.1<sup>ABC</sup> | Sr          |
| *Tectona grandis*  | EFB        | 59.3<sup>A</sup> | Mr         | 31.1<sup>AB</sup> | Sr          |
|                    | OPMF       | 57.7<sup>A</sup> | Mr         | 31.4<sup>AB</sup> | Sr          |
|                    | TP         | 47.5<sup>BCD</sup> | Sr         | 22.9<sup>B</sup> | Sr          |

*According to ASTM Standard D-2017 (ASTM, 20012c), Sr: Slightly resistant, Mr: Moderately resistant. Averages with equal letters do not present significant differences. Determined at $P$-value > 0.01.
3.3. Coating Performance

Table 3 shows average SEA, LAC, TC and FT consumption for the particleboards studied. In particleboards with CL and TG, the mixtures with pineapple (PLC and PLP) were found to present the statistically highest values of SEA, while mixtures with TP presented the statistically lowest SEA values.

For GA particleboards, GA-PLP mixture presented the statistically highest values of SEA, while GA-TP mixture had the lowest consumption. Regarding LAC, no statistical differences were found between the five mixtures studied. In relation with TC, particleboards manufactured with CL combined with PLC, and those with a combination of GA and PLP showed significantly higher values compared to the rest of the mixtures. Mixtures containing TP present significantly lower finish consumption. Lastly, in the FT evaluation no significant differences were found among the species and mixtures of lignocellulosic materials studied.

3.4. Burning Test

Figure 2 presents the mass percentage (MP) curves and the mass derivative with respect to time for the various kinds of particleboards, where combustion properties appear to be different for each kind of mixture. For CL particleboards (Figure 2(a)), combustion times varied from 25 to 34 minutes; for which CL-TP and CL-EBF mixtures lasted the longest, confirmed by the fact that $-\frac{dm}{dt}$ does not present values as high as those of the other particleboards (Figure 2(d)).

Meanwhile, the mixtures with pineapple leaves or OPMF presented the highest values of $-\frac{dm}{dt}$ in short periods of time. For GA particleboards (Figure 2(b)) the combustion periods ranged from 24 to 34 minutes. The mixtures with pineapple components (PLC and PLP) and OPMF presented the highest combustion masses during the first minutes (five to eight minutes) (Figure 2(f)), therefore resulting in the highest mass loss (Figure 2(c)). Contrariwise, the mixtures of this species with TP and...
Table 3. Consumption of sealant, lacquer, total and film thickness of particleboards of Cupressus lusitanica, Gmelina arborea and Tectona grandis combined with pineapple leaves, fiber from oil palm fruit and tetra pak package.

| Species           | Treatment | SEA (g/m²) | LAC (g/m²) | TC (g/m²) | FT (mm) |
|-------------------|-----------|------------|------------|-----------|---------|
| Cupressus lusitanica | PLC       | 1391abc    | 403a       | 1795abc   | 2.4abc  |
|                   | PLP       | 837bcd     | 363b       | 1236bcde  | 1.8abc  |
|                   | EFB       | 570bcde    | 338b       | 909bcd    | 2.1abc  |
|                   | OPMF      | 641bcde    | 454b       | 1098bcd   | 2.0abc  |
|                   | TP        | 507c       | 295b       | 802c      | 2.2abc  |
|                   | PLC       | 540bcde    | 337b       | 879bcd    | 2.0abc  |
|                   | PLP       | 1300abc    | 478b       | 1778abc   | 2.6abc  |
|                   | EFB       | 668bcd     | 389b       | 1006bcde  | 2.0abc  |
|                   | OPMF      | 705bcde    | 309a       | 1015cd    | 1.5abc  |
|                   | TP        | 457c       | 335b       | 792c      | 1.5abc  |
|                   | PLC       | 1272bcde   | 349b       | 1621bc    | 2.4abc  |
|                   | PLP       | 1048bcde   | 348b       | 1395abcd  | 2.5abc  |
| Gmelina arborea    | EFB       | 852bcde    | 372b       | 1224bcd   | 1.5abc  |
|                   | OPMF      | 602bcde    | 364a       | 966bcde   | 2.3abc  |
|                   | TP        | 407c       | 309a       | 716c      | 2.7abc  |

Legend: Averages with equal letters do not present significant differences. Determined at P-value > 0.01. SEA: Consumption of sealant; LAC: Consumption of lacquer; TC: Total consumption and FT: Film thickness.

Figure 2. Behavior of MP and the mass of the derivative function of time in particleboards of Cupressus lusitanica, Gmelina arborea and Tectona grandis particleboards combined with pineapple leaves, fiber from oil palm fruit and tetra pak packages during the combustion test.
time reduction, and mass consumption in time occurred at OPMF, TG-PLP and TG-TP mixtures showed fast MP (mainly because it absorbs 85% to 90% of UV light) and the board, thus generating depolymerization of lignin processes [26,27], produced by long periods of exposure on the particleboard surface [28], which probably affected depolymerization also generates macroscopic cracks on the particleboard surface disintegration processes. Lignin cellulose, which both produce changes in color as well as augmentation the presence of volatile substances; moreover, variability increases in the particleboard mixture, in- easier to burn. Pineapple leaves particleboards, instead, were more resistant because their surfaces are the most homogeneous, with less rugosity than particleboards manufactured with pineapple leaves or oil palm fruit parts [15]. Low rugosity surfaces (homogeneous surfaces) are easier to coat and consume less finish [29,30]. Sealant application on the particleboard surface results in homogeneous surfaces (covering empty spaces, defects or irregularities), and allows a homogeneous lacquer coating and consumption by the various kinds of particleboards. Moreover, uniformity of the FT parameter [15] shows how uniform the two kinds of finishes were. Combustion results (Figure 2) showed that particleboards with lignocellulosic materials from EFB and TP (except for the TG-TP mixture) presented higher combustion resistance, while particleboards of the three species with pineapple residues and OPMF (in addition to the TG-TP mixture) presented the lowest combustion resistance. The latter particleboards present less thermal stability in the presence of flame, therefore increased risk of combustion than particleboards of the first group (particleboards manufactured with EFB and TP). TP-composed particleboards resist combustion better due to the presence of aluminum and polyethylene in their composition. Korkmaz et al. [7] mention that polyethylene requires over 180°C for its total combustion, and aluminum acts as heat reflector, which delays the process. Pineapple leaves particleboards, instead, were easier to burn. Pineapple leaves particleboards, instead, were easier to burn. Pineapple leaves particleboards, instead, were easier to burn. Pineapple leaves particleboards, instead, were easier to burn. Pineapple leaves particleboards, instead, were easier to burn. Pineapple leaves particleboards, instead, were easier to burn. pine
OMMF) and from the three woody species, resulting in diverse mixtures and increasing the presence of volatile substances and mixture instability. Regarding oil palm, close relationship with chemical composition of the three species was found, therefore more stable mixtures are obtained [15]. Variations between OPMF and EFB were possibly due to the previous treatment given to OPMF.

5. Conclusions

TG-EBF and TG-OPMF mixtures were classified as moderately resistant, while the rest of the mixtures as slightly resistant to T. versicolor. In addition, with G. trabeum all particleboards of the three woody species were classified as slightly resistant.

In the accelerated weathering exposure test, all mixtures intensified their change of color ($\Delta E^*$) the longer they were exposed to UV light. However, the mixtures of the three species with TP showed the best performance in accelerated weathering, since $\Delta E^*$ did not exceed twelve, which is the value indicating total change in the color of the surface. Contrariwise, the mixtures with pineapple leaves showed the lowest resistance to accelerated weathering, the surface of the particleboard starting to disintegrate after 350 hours of exposure. Oil palm particleboards, on the other hand, presented lower resistance to weathering than TP, though higher than pineapple leaves’ resistance.

The finish performance test determined that the mixtures with TP (of all three species) presented the best performance, since the surface showed few irregularities, followed by the mixtures with oil palm components and finally by the mixtures composed of pineapple leaves. Regarding lacquer consumption, no differences were found between the mixtures of the three species, which was attributed to the fact that the sealant homogenized the surface.

Finally, the combustion test determined that particleboards with TP and EFB showed the highest resistance to combustion, while pineapple and OPMF mixtures presented the lowest resistances to combustion. Such behavior is attributed to TP polyethylene and aluminum delaying combustion. Pineapple particleboards, on the other hand, presented the highest combustion capacity due to the heterogeneity of the mixtures, with higher content of extractives and volatile substances. Oil palm particleboards showed higher homogeneity. OPMF and EFB were attributed to a previous treatment applied to OPMF.

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List of Abbreviations

| Abbreviation | Description |
|--------------|-------------|
| PL:          | pineapple leaves |
| PLC:         | pineapple leaves from the crown |
| PLP:         | pineapple leaves from the plant |
| EFB:         | empty fruit bunch of oil palm |
| OPMF:        | oil palm mesocarp fiber of the fruit |
| UF:          | adhesive of urea-formaldehyde |
| TP:          | tetra pack packages |
| CL:          | wood of *Cupressus lusitanica* |
| TG:          | wood of *Tectona grandis* |
| GA:          | wood of *Gmelina arborea* |
| UF:          | adhesive of urea-formaldehyde |

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