Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

# Development of Polymeric Films Based on Gummy Plant Exudates and Natural Plant Fibers

**Gerardo Fonthal**

gfonthal@uniquindio.edu.co

University of Quindío

**Diana Lorena López**

University of Quindío

**Research Article**

**Keywords:** Gummy exudate, Biopolymer, Biodegradable films, Natural plant fibers, Euphorbia species, Mechanical properties

**Posted Date:** November 5th, 2026

**DOI:** https://doi.org/10.21203/rs.3.rs-11026895/v1

**License:** This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

**Additional Declarations:** No competing interests reported.

# Development of Polymeric Films Based on Gummy Plant Exudates and Natural Plant Fibers

**Gerardo Fonthal[1,2,*] and Diana Lorena López[1]**

[1] *Instituto Interdisciplinario de las Ciencias – Universidad del Quindío*

[2] *Programa de Física – Universidad del Quindío*

[*] **Corresponding author:** *gfonthal@uniquindio.edu.co*

*ORCID Gerardo Fonthal:* https://orcid.org/0000-0003-0672-079x

*ORCID Diana Lorena López: https://orcid.org/0009-0000-4671-8518*

**Abstract**

This study addresses the fabrication of biodegradable polymeric films using gummy plant exudates from *Euphorbia cotinifolia* ("liberal rojo") and *Euphorbia laurifolia* ("lechero blanco") as the primary matrix, reinforced with *Musa paradisiaca* (plantain) and *Guadua angustifolia* (guadua bamboo) fibers. A solvent casting technique was employed to evaluate three formulations with varying exudate concentrations, using glycerol as a plasticizer, poly(vinyl alcohol) (PVA) as a crosslinking agent, and Tween 80 as an emulsifier. Formulation 2 (60% v/v exudate) exhibited superior mechanical performance, reaching a tensile strength of 9.52 MPa and an elongation at break of 416.52% in *E. laurifolia* films, significantly outperforming conventional biopolymers. Although natural plant fibers did not improve mechanical resistance due to weak interfacial adhesion with the matrix, they substantially enhanced moisture resistance. Biodegradation assays conducted under ISO 14855 and ASTM D 5988 standards confirmed high biological assimilation and mineralization of the material by soil microorganisms.

**Keywords:** Gummy exudate, Biopolymer, Biodegradable films, Natural plant fibers, *Euphorbia* species, Mechanical properties.

## 1. Introduction

The extensive proliferation of synthetic polymers in the market stems from their indispensability in single-use disposable applications such as bags, food wraps, and packaging materials. However, their post-consumer accumulation generates substantial volumes of persistent solid waste because most synthetic plastics are non-biodegradable and resist natural degradation, posing severe environmental threats. Although global recycling rates have increased, recycling alone does not eliminate plastic pollution in terrestrial fauna, flora, aquatic ecosystems, and human health. Furthermore, conventional synthetic polymers are derived from non-renewable fossil fuel resources, such as petroleum, which face eventual depletion, thereby constraining the long-term availability of petroleum-derived products.

The search for sustainable alternatives to synthetic polymers has driven research into unconventional biological resources. Traditionally, biopolymer development has focused on abundant raw materials including polysaccharides (starch and cellulose), proteins, and lipids extracted via chemical processing or microbial fermentation [1, 2].

An emerging alternative for sustainable biopolymer production lies in gummy exudates naturally synthesized by plants [3]. Currently, natural rubber latex represents one of the most widely utilized plant exudates in the production of tires, inner tubes, and elastomeric insulators due to its exceptional elasticity and mechanical

durability. Within botanical diversity, the Euphorbiaceae family stands out for its high morphological variability, spanning from herbaceous species to economically significant trees. In Colombia, Euphorbiaceae is represented by 78 genera and 390 species, 45 of which are endemic. Notable species include *Euphorbia cotinifolia* (locally known as "liberal rojo") and *Euphorbia laurifolia* ("lechero blanco"). These species are predominantly distributed across tropical regions; specifically, *E. laurifolia* thrives in high-altitude Andean environments between 1000 and 3000 m above sea level, while the broader family can adapt to elevations reaching up to 4000 m [4, 5].

These plants secrete gummy exudates as a specialized defense mechanism against biotic and abiotic stressors. Unlike animal immune systems, plant latex acts as a physical and chemical barrier against biological pathogens and herbivores, exuding rapidly upon mechanical wounding, stem incision, or insect and fungal attack [6]. Synthesized and stored in specialized secretory cells termed laticifers, this exudate consists of a complex mixture of biochemical constituents, displaying maximal exudation yield during dry seasons and adverse environmental conditions [7, 8].

Historically, plant gum exudates have found diverse commercial and traditional applications, ranging from thickening and stabilizing agents in food processing to pharmacological formulations for dermatological and hepatic remedies. More recently, their application has expanded into nanotechnology for controlled drug delivery systems, leveraging their inherent biocompatibility [9]. Nevertheless, utilizing raw plant exudates as primary structural matrices for functional, biodegradable polymeric films remain a highly promising yet under-explored domain [10].

The present work investigates the utilization of *E. cotinifolia* and *E. laurifolia* exudates, key components of Colombian biodiversity, to formulate composite polymeric films reinforced with natural lignocellulosic fibers from *Musa paradisiaca* and *Guadua angustifolia*. This approach aims to address the environmental challenges associated with petroleum-derived plastic waste by providing high-performance bioplastic formulations suitable for biodegradable bag manufacturing and packaging applications.

## 2. Materials and Methods

### 2.1. Raw Material Collection and Pretreatment

Latex exudates from *Euphorbia cotinifolia* and *Euphorbia laurifolia* were collected in the municipality of Salento, Quindío, Colombia (4º38’11.5’’ N, 75º34’07.3’’ W), located in the central Andean region where these species grow naturally at elevations between 1000 and 3000 m above sea level. The plant materials used in this study were obtained from cultivated specimens on private property at 1900 m a.s.l.. Collection was carried out with the authorization of the landowner. Collected latex samples were preserved at 4 °C to prevent biochemical degradation.

Lignocellulosic fibers extracted from *Musa paradisiaca* (plantain stem) and *Guadua angustifolia* (guadua bamboo) were subjected to an alkaline surface treatment using a 2% w/v NaOH solution for 4 h to partially remove lignin and hemicellulose fractions, which otherwise hinder interfacial bonding with the polymer matrix [11, 12]. Following alkali treatment, the fibers were thoroughly washed with a 50% v/v acetic acid solution followed by distilled water until neutral pH was restored. The fibers were subsequently dried in a forced-air oven at 30 °C for 8 h to eliminate residual moisture. Both fiber types were milled and sieved through a 0.5 mm mesh; additionally, a fraction of *G. angustifolia* fibers was sieved through a fine 0.1 mm mesh.

### 2.2. Film Formulation and Additive Selection Rationale

To develop functional polymeric films, the natural plant exudate was blended with targeted functional additives. Preliminary screening trials were performed by varying additive ratios to identify optimal processing conditions and film integrity.

**Glycerol (Plasticizer):** Added to disrupt intermolecular hydrogen bonding between matrix polymer chains, reducing material brittleness while increasing chain mobility, flexibility, and elongation [13].

**Poly(vinyl alcohol) (PVA - Crosslinking/Matrix Agent):** A biocompatible, water-soluble synthetic polymer utilized to form a coherent semi-interpenetrating molecular network, imparting structural stability, cohesion, and elasticity to the natural latex matrix [14].

**Tween 80 (Emulsifier/Surfactant):** An amphiphilic non-ionic surfactant incorporated to reduce interfacial tension, stabilize the oil-in-water emulsion of immiscible components, prevent phase separation, and ensure microstructural homogeneity during casting [15].

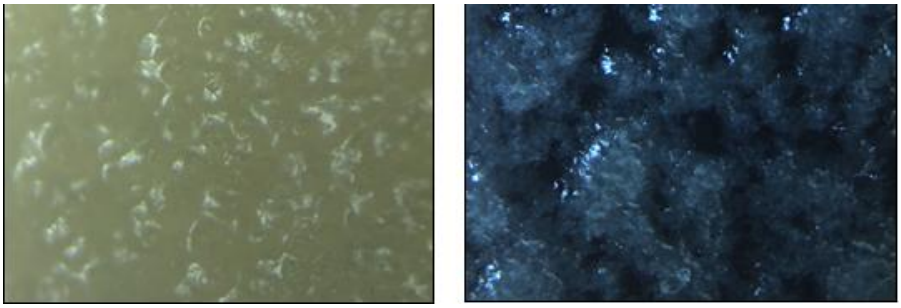
The detailed composition of the tested formulations is presented in Table 1.

**Table 1.** Formulations evaluated for biopolymer film fabrication (volume percentages).

| Formulation | Exudate (% v/v) | PVA (% v/v) | Glicerol (% v/v) | Tween 80 (% v/v) |
|---|---|---|---|---|
| **1** | 70 | 15 | 10 | 5 |
| **2** | 60 | 25 | 10 | 5 |
| **3** | 50 | 35 | 10 | 5 |

Component blending was carried out using a heated magnetic stirrer (Scilogex MS7-H550-Pro) at 600 rpm and 35 °C for 1 h under controlled room conditions ($T = 23$ °C, relative humidity = 60%, ambient atmospheric pressure).

Polymeric films were prepared via the solvent casting technique by pouring 25 g of homogenous precursor solution into glass Petri dishes. Unreinforced films were prepared across all three formulations. Fiber-reinforced films were produced exclusively using Formulation 2 as the matrix. Milled fibers of *G. angustifolia* and *M. paradisiaca* (0.5 mm size) were incorporated at mass fractions of 1%, 5%, and 10% w/w relative to total solution mass; fine *G. angustifolia* fibers (0.1 mm size) were tested at a 1% w/w loading. Cast solutions were dried in a forced-convection oven (Binder FD 115) at a constant temperature of 35 °C for 15 h. After this time had elapsed, the films were taken out of the stove, weighed, measured for thickness across five randomized locations using a digital micrometer (Mitutoyo Digimatic), and microstructurally analyzed using a stereomicroscope (Nikon SMZ800 NI-150). Optical micrographs confirmed that Formulation 2 yielded the most structurally uniform films (Figure 1).



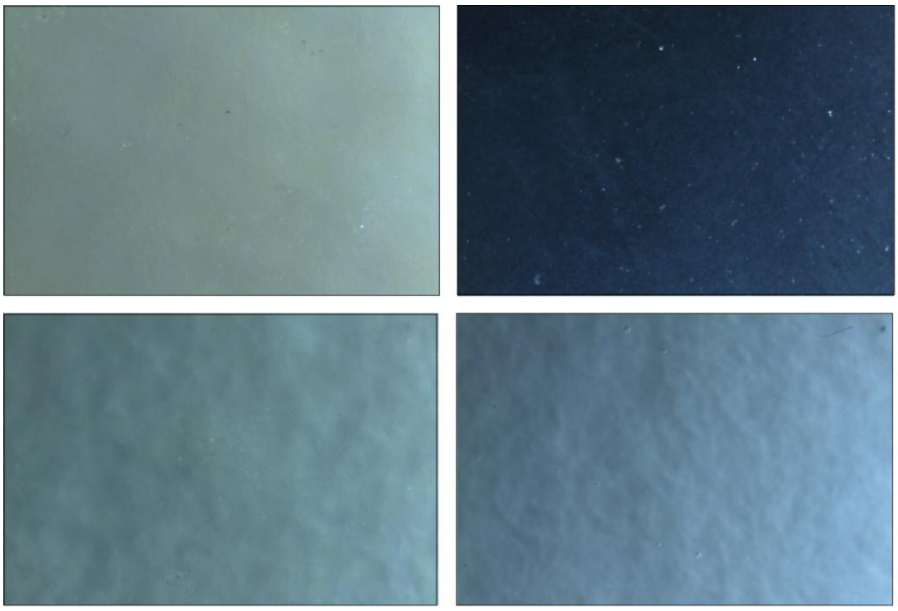


**Fig1** *Micrographs at 5X magnification showing film surface morphology for Formulations 1, 2, and 3 derived from E. cotinifolia (left) and E. laurifolia (right)*

Ultrathin films with a controlled thickness of ~0.2 mm were additionally cast via spin coating for Formulation 2 (Figure 2).



**Fig2** *Thin films (~0.2 mm thickness) produced via spin coating using Formulation 2 derived from E. cotinifolia (right) and E. laurifolia (left)*

**2.3. Mechanical Testing and Long-Term Stability**

Tensile properties were evaluated according to ASTM D882-02 standard using a texture analyzer (Stable Micro Systems TA.XT Plus) operated at a crosshead speed of 1 mm/s. Rectangular film strips ($40 \times 20$ mm) were tested to determine tensile strength (MPa) and elongation (%). Long-term environmental stability was assessed via periodic visual and physical inspection under standard room storage ($23 \pm 2$ °C, 50–60% RH); remarkably, the manufactured films maintained their physical integrity, color, and flexibility without observable deterioration after more than 4 years of room-temperature aging.

**2.4. Rheological Characterization**

Flow properties of film-forming polymer emulsions were measured on a rotational rheometer (Anton Paar MCR 301) equipped with a concentric cylinder geometry (CC27/T200/SS, 1 mm gap) and parallel plate configuration (25 mm diameter upper plate). Shear rate sweeps were fitted to the Ostwald-de Waele (power-law) model to evaluate non-Newtonian pseudoplastic flow behavior.

**2.5. Thermal Analysis (DSC / TGA)**

Differential Scanning Calorimetry (DSC) was conducted using a NETZSCH DSC 214 Polyma analyzer. Sealed aluminum pans containing 7 mg sample masses were heated under nitrogen atmosphere (20 mL/min flow rate) at a heating rate of 10 °C/min over temperature ranges of -50 °C to 200 °C and 20 °C to 500 °C to establish glass transition ($T_g$) and phase transitions. Thermogravimetric Analysis (TGA) was performed simultaneously on the same system from 20 °C to 500 °C at 10 °C/min under nitrogen to track thermal degradation stages and mass loss.

**2.6. Biodegradability Assays**

Environmental degradation performance was evaluated through two standardized testing procedures:

**ISO 14855 Standard (Controlled Composting Biodegradability):** Measures ultimate aerobic biodegradation under controlled composting conditions. Film specimens ($25 \times 25$ mm) were subjected to two distinct moisture regimes: Treatment 1 (85% relative moisture) and Treatment 2 (5% relative moisture) over a 6-month exposure period, recording gravimetric mass loss and microbial colonization.

**ASTM D 5988 Standard (Soil Biodegradability via Respirometry):** Quantifies carbon mineralization into $CO_2$ generated by soil microbial respiration during polymer assimilation [16]. Samples placed in sealed respirometric biometric flasks were monitored for cumulative $CO_2$ production under controlled moisture and temperature regimes.

**2.7. Resistance to Liquid Chemical Reagents**

Chemical durability was evaluated following Colombian Technical Standard NTC 1027 (equivalent to standard methods for testing chemical resistance of plastics). Film specimens ($25 \times 25$ mm, neat and fiber-reinforced) were weighed initially ($W_0$) and immersed in 50 mL of two solvents representing extreme polarities: distilled water (highly polar) and chloroform (non-polar) for 24 h at 25 °C. After exposure, specimens were removed, dried in an oven at 50 °C for 2 h, and re-weighed ($W_f$) to compute relative mass change.

**3. Results and Discussion**

**3.1. Mechanical Performance and Comparative Benchmark**

The mechanical properties of the developed biopolymer formulations are illustrated in Figure 3 (tensile strength) and Figure 4 (elongation at break).

Formulation 2 based on *E. laurifolia* latex demonstrated optimal mechanical balance, reaching a tensile strength of 9.52 MPa and an elongation at break of 416.52%. When benchmarked against conventional bio-based films reported in the literature, *Euphorbia* exudate films demonstrate superior mechanical performance. For instance, hydroxypropylated cassava starch films exhibit a tensile strength of 4.6 MPa and an elongation of only 24% [17]. Even advanced biocomposites combining thermoplastic starch, poly($\epsilon$-caprolactone) (PCL), and soy protein isolate achieve 7.6 MPa strength but exhibit a minimal strain at break of 2.4% [18–20]. The *Euphorbia* latex matrix retains a deformation capacity up to ~20 times greater than typical bioplastic formulations reported in previous studies. This high extensibility is attributed to the intrinsic molecular cohesiveness and elastic rubber-like terpenoid/polyisoprene architecture naturally present in *Euphorbia* latex, establishing these exudates as excellent matrices for flexible packaging films.

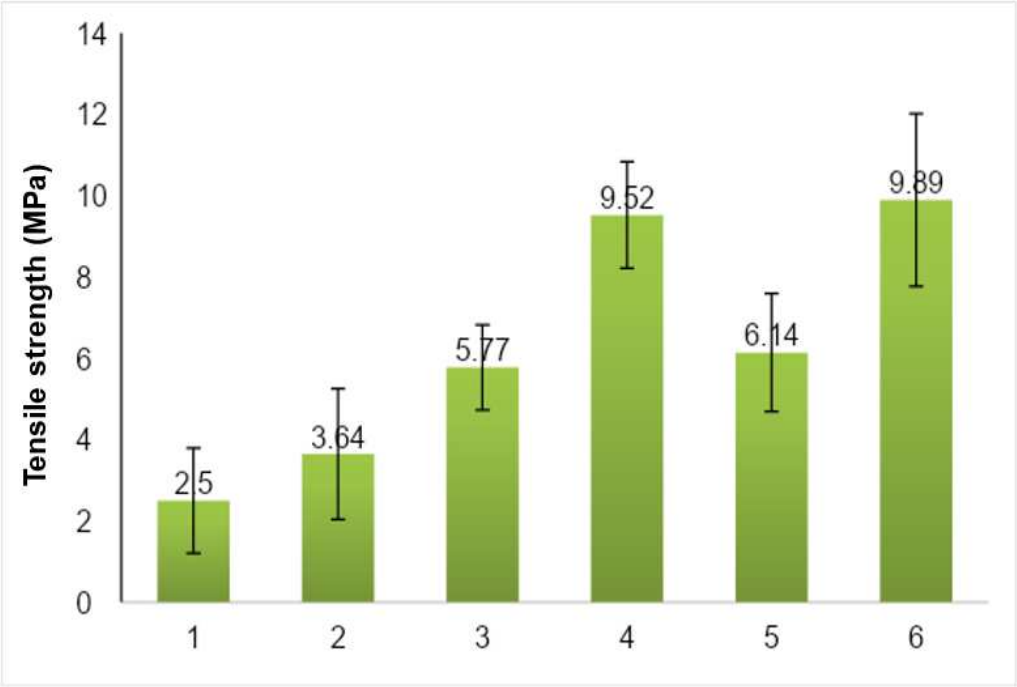



**Fig3** *Tensile strength of biopolymer films. Formulations 1 (bars 1 and 2), 2 (bars 3 and 4), and 3 (bars 5 and 6). Odd numbers represent E. cotinifolia ("liberal rojo") and even numbers represent E. laurifolia ("lechero blanco")*

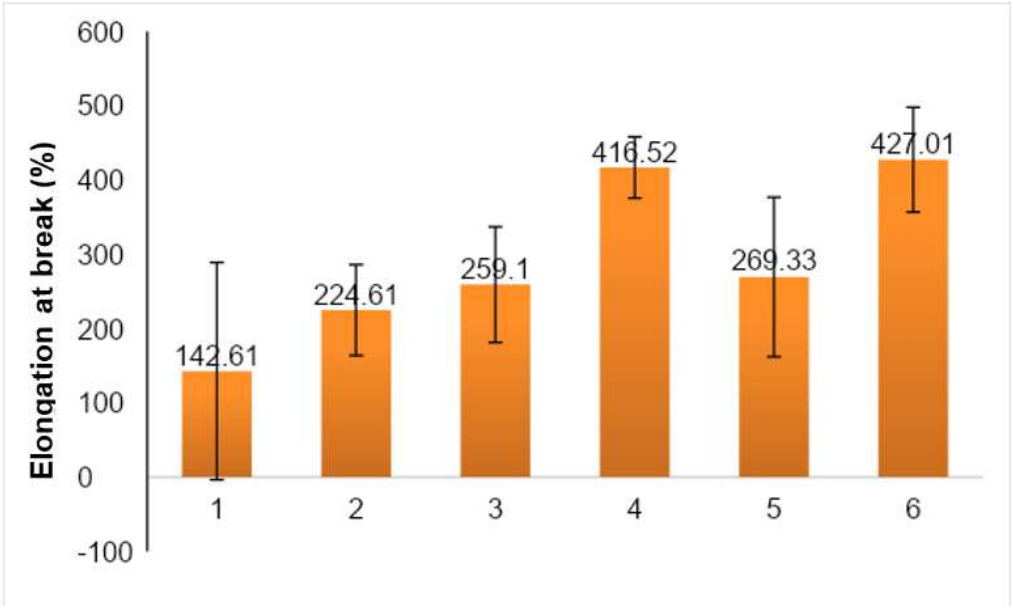



**Fig4** *Elongation at break of biopolymer films. Formulations 1 (bars 1 and 2), 2 (bars 3 and 4), and 3 (bars 5 and 6). Odd numbers represent E. cotinifolia ("liberal rojo") and even numbers represent E. laurifolia ("lechero blanco")*

**3.2. Rheological Behavior**

Shear rate sweeps for film-forming precursor emulsions corresponding to Formulation 2 (Figure 5) revealed characteristic non-Newtonian pseudoplastic (shear-thinning) flow, where apparent viscosity decreased progressively with increasing shear rate.

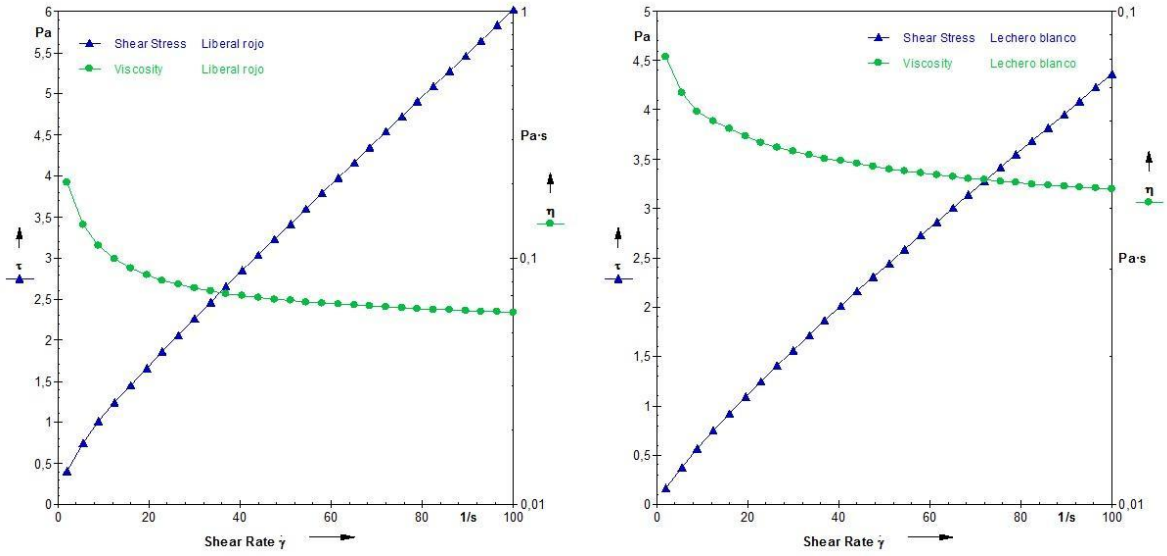



**Fig5** *Rheograms showing shear stress (triangles) and apparent viscosity (circles) versus shear rate for Formulation 2 emulsions derived from E. cotinifolia (left) and E. laurifolia (right)*

Table 2 presents the rheological parameters derived by fitting the flow curves to the Ostwald-de Waele power-law model ($\tau = K\dot{\gamma}^n$) [21].

**Table 2.** Power-law rheological parameters for Formulation 2 film-forming solutions.

| Sample | ηap,100 (Pa·s) | Flow index (n) | Consistency index (K, Pa·s$^n$) | $R^2$ |
|---|---|---|---|---|
| *E. laurifolia* ("lechero blanco") | 0.0437 | 0.84315 | 0.08911 | 0.99995 |
| *E. cotinifolia* ("liberal rojo") | 0.0602 | 0.71037 | 0.21637 | 0.9954 |

A flow behavior index ($n < 1.0$) across all formulations confirms pseudoplasticity. This shear-thinning response is processing-advantageous: under high shear rates during agitation and casting, solution viscosity drops, facilitating smooth spreading and mold filling; once resting on the substrate, viscosity recovers, preventing sagging and promoting uniform film thickness. *E. cotinifolia* displayed a higher consistency index ($K = 0.21637$ Pa·s$^n$) and higher apparent viscosity at 100 s$^{-1}$($\eta_{ap,100} = 0.0602$ Pa·s) compared to *E. laurifolia*, favoring dimensional stability during casting.

### 3.3. Thermal Behavior (DSC and TGA)

Thermal degradation profiles and phase transition behavior obtained via TGA and DSC are presented in Figure 6.

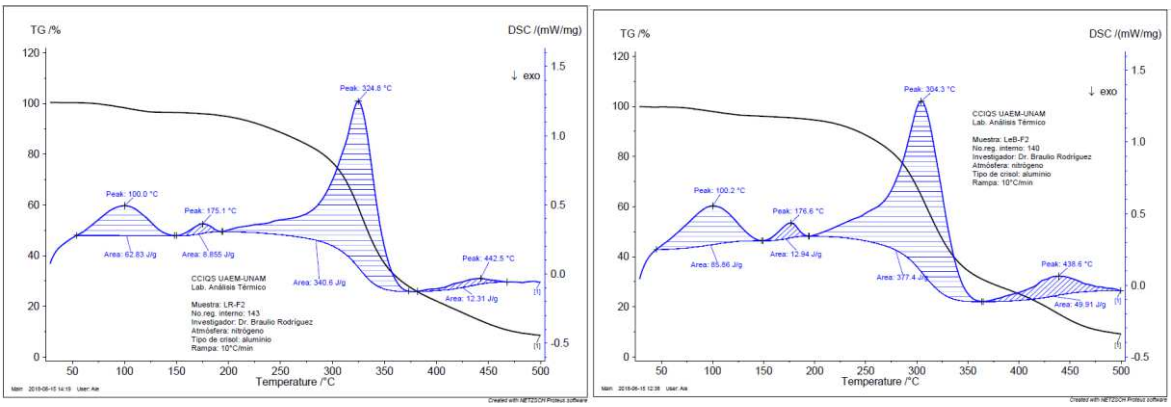



**Fig6** *TGA weight loss curves and DSC thermograms for E. cotinifolia (left) and E. laurifolia (right) films from 20 °C to 500 °C*

Low-temperature DSC analysis (-50 °C to 200 °C), which are not shown in this article, identified a glass transition temperature ($T_g$) of -18.8 °C for neat *E. laurifolia* matrix. Incorporation of *G. angustifolia* (guadua) fibers shifted $T_g$ upward to 11 °C, whereas *M. paradisiaca* (plantain) fibers shifted $T_g$ to 0.9 °C. For neat *E. cotinifolia*, $T_g$ was subtle, but addition of guadua and plantain fibers established distinct glass transitions at -0.8 °C and -19.7 °C, respectively. The observed elevation in $T_g$ upon fiber incorporation stems from restricted polymer chain mobility caused by physical entanglement with lignocellulosic fibers and interfacial hydrogen bonding between fiber hydroxyls and matrix plasticizers [22].

TGA mass-loss curves (Figure 6) display three main degradation stages. An initial endothermic weight loss of ~4.2% centered around 100 °C, corresponding to free and bound water evaporation.The primary mass-loss step (~64.31%) occurring between 200 °C and 350 °C, attributed to thermal volatilization of glycerol plasticizer and decomposition of low-molecular-weight exudate components [23]. Endothermic melting peaks observed at ~170 °C across all formulations, corresponding to the crystalline melting point of PVA [24]. Incorporation of plant fibers did not significantly alter the primary thermal stability thresholds of the matrix network.

### 3.4. Biodegradability Performance

#### 3.4.1. ISO 14855 Composting Biodegradation

During the 6-month exposure period under controlled composting, unreinforced films biodegraded faster than fiber-reinforced films. *E. laurifolia* neat films exhibited an average mass loss of 98% under Treatment 1 (85% relative moisture) and 77% under Treatment 2 (5% relative moisture). *E. cotinifolia* neat films lost 90% and 72% under Treatments 1 and 2, respectively. High moisture levels in Treatment 1 accelerated fungal hyphal growth and enzymatic hydrolysis. Conversely, natural fibers acted as physical water barriers, retarding moisture penetration into the polymer core and moderating overall degradation rate.

#### 3.4.2. ASTM D 5988 Soil Respirometric Biodegradation

Microbial $CO_2$ production measured over incubation time is plotted in Figure 7.

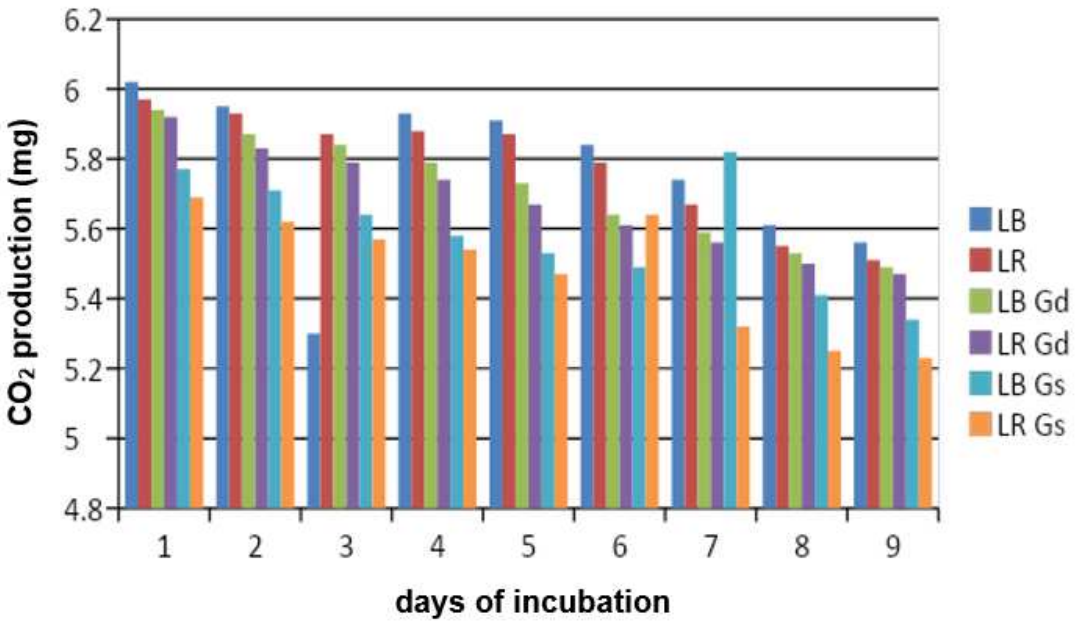



**Fig7** *Daily CO2 evolution (mg) during soil incubation for neat and reinforced films derived from E. laurifolia (LB) and E. cotinifolia (LR). The added fibers are: Guadua angustifolia (Gd) and Musa paradisiaca (Gs)*

Continuous evolution of $CO_2$ confirms that soil microorganisms metabolically assimilated the biopolymer carbon backbone under aerobic conditions, driving organic carbon mineralization into inorganic $CO_2$ [25]. Unreinforced films produced higher daily $CO_2$ volumes, reflecting rapid enzymatic cleavage of the uninhibited plant latex/PVA network. Inclusion of *G. angustifolia* (Gd) or *M. paradisiaca* (Gs) fibers decreased overall $CO_2$ release. This reduction is linked to lower matrix accessibility for microbial enzymes, reduced water absorption, and hydrophobic barrier effects imparted by alkali-treated fibers. These findings align with ISO 14855 composting data, establishing that while all formulations are fully biodegradable, lignocellulosic fiber reinforcement effectively tunes and extend material degradation kinetics.

### 3.5. Chemical Resistance to Liquids (NTC 1027)

Alkaline treatment altered fiber surface chemistry, reducing overall fiber hydrophilicity, as mentioned above. When immersed in distilled water for 24 h, fiber-reinforced films lost only 22% of their mass, whereas unreinforced films lost 60% due to dissolution of uncross linked PVA and glycerol leaching. Conversely, immersion in chloroform (non-polar) resulted in no physical deformation or optical change but induced moderate mass loss, approximately 14% for reinforced films, 9% for unreinforced films. This behavior reflects solvent-matrix thermodynamic affinity. Water readily solvates hydrophilic hydroxyl groups present in PVA, glycerol, and exudate polysaccharides, promoting mass extraction. In contrast, non-polar chloroform does not swell the polar PVA matrix but selectively extracts low-molecular-weight lipophilic terpenoid compounds naturally present in the *Euphorbia* latex matrix or fiber-matrix interfacial boundary, consistent with swelling behaviors reported for crosslinked PVA systems [26].

## 4. Conclusions

This investigation successfully demonstrated the viability of solvent casting to manufacture biodegradable polymeric films using natural latex exudates from *Euphorbia cotinifolia* and *Euphorbia laurifolia, with thicknesses close to 0.2 mm*. The resulting films exhibited excellent mechanical properties, with Formulation 2

reaching a tensile strength of 9.52 MPa and an elongation at break of 416.52%, outperforming traditional starch, PCL, and protein-based bioplastics. While natural lignocellulosic fibers did not increase tensile strength due to limited interfacial adhesion, they significantly enhanced water resistance and dimensional stability in aqueous environments. Overall, *Euphorbia* plant exudates represent a promising, eco-friendly, and fully biodegradable raw material for developing sustainable flexible packaging and low-cost bioplastic bags.

**Acknowledgements** The authors acknowledge the funding of project 832 by the University of Quindío.

**Author contributions statement** GF proposed the research, wrote the article, and reviewed the final version. DLL carried out the experimental part and wrote the analysis of the results, as well as reviewing the final version of the article.

**Ethics approval and consent to participate:** The plant materials used in this study were obtained from cultivated specimens of *Euphorbia cotinifolia* and *Euphorbia laurifolia* located on private property in Salento, Quindío, Colombia. Collection was carried out with the authorization of the landowner. No sampling was conducted in protected areas, and no wild populations or threatened species were involved. Therefore, no specific permit for the collection of wild plant specimens was required. All plant sampling procedures complied with applicable local and national regulations in Colombia.

**Consent for publication:** Not applicable.

**Competing interests:** The authors declare no competing interests.

**Data availability statement** Data set measured, used and/or analyzed during the present study is available from the corresponding author on reasonable request

**References**

[1] K. Olonisakin, A. K. Mohant, M. Thimmanagar y M. Manjusri (2025) Recent advances in biodegradable polymer blends and their biocomposites: a comprehensive review. *Green Chem.,* https://doi.org/10.1039/d5gc01294e.

[2] A. Dirpan, A. F. Ainani y M. Djalal (2023) A Review on Biopolymer-Based Biodegradable Film for Food Packaging: Trends over the Last Decade and Future Research. *Polymers, https://doi.org/10.3390/polym15132781*

[3] A. Nehra, D. Biswas, V. Siracusa y S. Roy (2023) Natural Gum-Based Functional Bioactive Films and Coatings: A Review *International Journal of Molecular Sciences. ,* https://doi.org/10.3390/ijms24010485

[4] T. Lewinsohn (1991) The geographical distribution of plant latex *Chemoecology.* https://doi.org/10.1007/BF01240668

[5] L. Salomé-Abarca, D. Gođevac, M. Kim, S. H. Geum, S. C. Park, Y. P. Jang, J. J. Van Den Hondel, R. Verpoorte, G. L. Klinkhamer y Y. Hae (2021) Latex Metabolome of Euphorbia Species: Geographical and Inter-Species Variation and its Proposed Role in Plant Defense against Herbivores and Pathogens. *J Chem Ecol.,* https://doi.org/10.1007/s10886-021-01274-x

[6] G. Krstić, B. Anđelković, Y. Choi, V. Vajs, T. Stević, V. Tešević y D. Gođevac (2016) Metabolic changes in Euphorbia palusrtis latex after fungal infection. *Phytochemistry,* 10.1016/j.phytochem.2016.08.005

[7] J. Hagel, E. Yeung y P. Facchini (2008) Got milk? The secret life of laticifers. *Trends Plant Sci., https://doi.org/10.1016/j.tplants.2008.09.005*.

[8] K. Konno (2011) Plant latex and other exudates as plant defense systems: roles of various defense chemicals and proteins contained therein. *Phytochemistry,* 10.1016/j.phytochem.2011.02.016

[9] W. Hussain, S. Batool, S. Baha, B. Shahida, S. Bangash, A. Ali, Hussain, H. Hussain, I. Ali, M. Ali y R. W. Bussmann (2020) Ethnopharmacological survey of herbal remedies used in the treatment of hepatitis. *Ethnobotany Research & Applications,* https://ethnobotanyjournal.org/index.php/era/article/view/2237

[10] P. Thirukumaran, S. P. Asrafali y J. Lee (2025) Recent Advances in Functional Biopolymer Films with Antimicrobial and Antioxidant Properties for Enhanced Food Packaging. *Polymers,* DOI:10.3390/polym17091257

[11] J. Gómez (2009) Diseño de un material compuesto con fibra natural para sustituir la utilización de la fibra de vidrio. *Tesis en Ingeniería. Universidad EAFIT. Medellín, http://hdl.handle.net/10784/297*

[12] C. Rovera, D. Carullo, T. B. Bellesia, D. Büyüktaş, M. Ghaani, E. Caneva y S. Farris (2022) Extraction of high-quality grade cellulose and cellulose nanocrystals from different lignocellulosic agri-food wastes. *Frontiers in Sustainable Food Systems,* https://doi.org/10.3389/fsufs.2022.1087867

[13] A. D. Yermagambetova, S. M. Tazhibayeva, B. B. Tyussyupova, K. B. Musabekov y L. Pastorino (2024) «ffect of plasticizers on the rheological properties of xanthan gum–starch biodegradable films. *Heliyon,* DOI: 10.1016/j.heliyon.2024.e34550

[14] A. Zakrzewska, S. S. Zargarian, C. Rinoldi, A. Gradys, D. Jarząbek, M. Zanoni, C. Gualandi, M. Lanzi y F. Pierini (2023) Electrospun Poly(vinyl alcohol)-Based Conductive Semi-interpenetrating Polymer Network Fibrous Hydrogel: A Toolbox for Optimal Cross-Linking. *ACS Materials,* https://doi.org/10.1021/acsmaterialsau.3c00025

[15] S. Udomrati, N. Cheetangdee, S. Gohtani, V. Surojanametakul y S. Klongdee 2020) Emulsion stabilization mechanism of combination of esterified maltodextrin and Tween 80 in oil-in-water emulsions. *Food Science and Biotechnology,* https://doi.org/10.1007/s10068-019-00681-x

[16] J. R. A. Pires, V. G. L. Souza, P. Fuciños, L. Pastrana y A. L. Fernando (2022) Standard methods for testing biodegradability of bio-based polymers: A comparative study. *Environmental Science and Pollution Research,* **https://doi.org/10.3390/polym14071359**

[17] J. Cortés, A. Fernández, S. Mosquera y S. Velasco (2014) Evaluación de propiedades mecánicas, ópticas y de barrera en películas activas de almidón de yuca. *Biotecnología en el Sector Agropecuario y Agroindustrial, 12(1)*pp. 88-97,

[18] P. Mariani, K. Allganer, F. Oliveira, E. Cardoso y L.H. Innocentini-Mei (2009) Effect of soy protein isolate on the thermal, mechanical land morphological properties of poly (ε -caprolactone) and corn starch blends. *Polymer Testing,* doi:10.1016/j.polymertesting.2009.07.004

[19] M. Enríquez, R. Velasco y V. Ortiz (2012) Composición y procesamiento de películas biodegradables basadas en almidón. *Biotecnología en el Sector Agropecuario y Agroindustrial, 10(1)* pp. 182-192

[20] M. Pereda , M. Moreira , S. Roura , N. Marcovich y M. Aranguren (2014) Bio-películas para el envasado de alimentos: proteínas y carbohidratos. *Ciencia e Investigación. https://api.semanticscholar.org/CorpusID:135183908*

[21] J. F. Steffe (1996) Rheological Methods in Food Process Engineering. 2nd ed., Freeman Press, East Lansing, MI

[22] A. Curvelo, A. Carvalho y J. A. M. Agnelli (2001) Thermoplastic starch-cellulosic fibers composites: preliminary results. *Carbohydrate Polymers,* https://doi.org/10.1016/S0144-8617(00)00314-3

[23] M. Taghi y N. Sabouri (2013) Thermal Degradation Behavior of Polyvinyl Alcohol/Starch/Carboxymethyl Cellulose/ Clay Nanocomposites. *Universal Journal of Chemistry,* DOI: 10.13189/ujc.2013.010202

[24] A. Valencia, C. Rivera y E. Murillo (2013) Estudio de las propiedades de mezclas de alcohol polivinílico-almidón de yuca-sorbitol obtenidas por casting. *Revista Colombiana de Materiales,* DOI:10.17533/udea.rcm.15089

[25] J. R. Pires, V. G. L. Souza, P. Fuciños, L. Pastrana y A. L. Fernando (2022) Methodologies to Assess the Biodegradability of Bio-Based Polymers—Current Knowledge and Existing Gaps. *Polymers,* ***https://doi.org/10.3390/polym14071359***

[26] K. Kamemaru, S. Usui, Y. Hirashima y A. Suzuki (2018) Irreversible Swelling Behavior and Reversible Hysteresis in Chemically Crosslinked Poly(vinyl alcohol) Gels. *Gels, DOI: 10.3390/gels4020045*

**Acknowledgements** This work was funded by Universidad del Quindío project: internal code 832

**Author contributions statement** GF proposed the research, wrote the article, and reviewed the final version. DLL carried out the experimental part and wrote the analysis of the results, as well as reviewing the final version of the article.

**Competing and financial interests** The authors declare no competing or financial interest.

**Data availability statement** Data set measured, used and/or analyzed during the present study is available from the corresponding author on reasonable request