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# Potential Use of Maguey Bagasse as a Filler for Bioplastic Development and Analysis of Its Application as Plastic Mulch

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## Abstract

The generation of agro-industrial residues represents an environmental challenge and an opportunity for their valorization within a circular economy framework. In this study, *Agave salmiana* bagasse residues were evaluated as a reinforcing material for developing bioplastics made from maize starch (polymer matrix). Maguey bagasse was collected, ground and sieved to particle sizes below 200 µm and incorporated into bioplastic formulations at different content levels. Five bioplastic films (M1–M5) were obtained and characterized regarding their physical, chemical, mechanical, thermal, and morphological properties. The evaluated parameters included density, color (CIE Lab*), moisture content, water absorption, FTIR analysis, tensile properties, thermal behavior, and surface morphology via SEM. The results showed significant differences among the bioplastic formulations. The moisture content ranged from 7.15% to 10.57%, while water absorption after 24 h reached values of up to 65% for the formulation with the highest bagasse content. Mechanical and thermal analyses indicated that the incorporation of maguey bagasse influenced the structural performance of the bioplastics, while SEM observations revealed changes in surface morphology associated with fiber incorporation. These findings demonstrate the potential of *A. salmiana* bagasse as a reinforcing agent in starch-based bioplastics, contributing to the development of sustainable materials. The results support their potential as a biodegradable material with exploratory application in an agricultural system.

**Keywords:** *Agave salmiana*; plastic covering; reinforced material; fiber; biodegradable film

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## 1. Introduction

Numerous studies focused on improving environmental sustainability have addressed procedures aimed at contributing to this goal, including the utilization of natural fibers contained in waste materials [1,2]. In most cases, agro-industrial residues are discarded without treatment or valorization. When not properly managed, these residues may generate negative environmental effects, such as emissions produced during their incineration [2–5]. This issue is particularly concerning due to the large quantities generated, which in some cases may reach millions of tons incinerated, depending on the type of waste [2,6]. Agro-industrial residues include bagasse derived from the processing of fruits or vegetables [7], as well as straw from different sources (e.g., rice or wheat) [2,8], in addition to maguey bagasse residues, which are by-products of mezcal or tequila production. Although these agro-industrial residues are mainly composed of natural fibers and are biodegradable, their accumulation without proper management may still generate environmental impacts [5,8–10], hindering the achievement of the United Nations Sustainable Development Goals (UN SDGs) [11].

In countries with significant agri-food production, agro-industrial waste is generated in significant quantities, reaching up to billions of tons per year, which is often managed inadequately, leading to environmental problems associated with its accumulation and disposal [1,5,8]. In Mexico, waste from *Agave* processing, particularly maguey bagasse from mezcal and tequila production, represents a major environmental challenge due to its high organic load, generating large amounts of bagasse with percentages between 30 and 40% of the total processed *Agave* biomass, representing thousands of tons of lignocellulosic residue annually [12,13]. The sustainable management and recovery of this waste are therefore essential to promote circular economy strategies and reduce its negative environmental impacts [10,11].

The utilization of maguey bagasse has been explored across a wide range of applications, including compost production, raw material for biofuel generation, foodstuff [12], construction additives, and as reinforcement in bioplastic development [13]. Chemically, maguey bagasse residues are primarily composed of cellulose, hemicellulose, and lignin, which can influence the properties of materials in which they are incorporated [14].

Maguey bagasse is a lignocellulosic residue mainly composed of cellulose, hemicellulose, and lignin, whose relative proportions depend on the *Agave* species and processing conditions [12,14]. Its high polysaccharide content, rich in hydroxyl functional groups, confers a marked hydrophilic character, which can significantly influence moisture uptake and interfacial interactions when incorporated into starch-based polymer matrices [14,15]. Previous studies have reported that the incorporation of maguey bagasse into starch-based bioplastics affects their physical and mechanical properties due to fiber–matrix interactions, particularly influencing moisture-related properties such as water content and absorption behavior [15].

This research focuses on maguey bagasse residues as components of bioplastics developed from corn starch and other additives [15]. The importance of bioplastic development lies in its potential as an alternative to petroleum-derived plastics, which negatively impact the environment and living organisms due to their low degradability and persistence in air, water, and soil [16–25]. Sajedi et al. [26] described these impacts, including the generation of microplastics and nanoplastics.

Although bioplastics offer advantages due to their biodegradability, various methodologies have been developed to improve their properties, including thermoplastic behavior [27–34]. One approach involves blending natural polymers with synthetic plastics [35,36] or agro-industrial residues, combined with different plasticizers and additives. Among the polymers used for bioplastic development, potato starch and corn starch

are common, the latter being the most widely used [29,36–38]. While positive results have been reported regarding mechanical properties, alternative elements such as citric acid, lignins, and anhydrides have been investigated to further enhance performance [37,38].

Bioplastics can be used for food packaging or utensils such as spoons and plates, each requiring specific properties [39–45]. Research has also focused on the use of bioplastics as agricultural mulches, including formulations combined with fibers, proteins, or lignins. Reported advantages of biodegradable mulches in previous studies include moisture conservation, improved crop yield, and soil temperature regulation, with the added advantage of being biodegradable and biocompostable [45–53]. Nevertheless, its use in soil remains a subject of controversy due to potential environmental implications and long-term effects on soil systems [54]. Shah et al. [53] comparatively described the characteristics of biodegradable plastics versus conventional plastics, focusing on their use as mulch in rice cultivation. In this study, it should be noted that the proposed use as agricultural mulch should be regarded as exploratory, as further optimization of mechanical strength and water resistance is required for its implementation in the field.

The present study evaluates the effect of *A. salmiana* bagasse incorporation on the physical, mechanical, thermal, and morphological properties of corn starch-based bioplastics. It is hypothesized that increasing bagasse content significantly modifies the structural performance and moisture-related behavior of the bioplastics due to fiber–matrix interactions associated with the lignocellulosic nature of the residue. This work is significant because it addresses the limited information available on the use of *A. salmiana* bagasse in starch-based systems and contributes to the valorization of an abundant agro-industrial residue within a circular economy context.

Consequently, this study contributes new knowledge by evaluating *Agave salmiana* bagasse as a reinforcing material in corn starch-based bioplastics plasticized with glycerol. The originality of this work lies in the combined evaluation of the mechanical, thermal, and physical properties of the developed bioplastics, as well as in the valorization of an abundant agro-industrial waste with currently limited applications. These results contribute to the development of sustainable materials and support a circular economy approach for *Agave*-derived residues.

To test this hypothesis, the focus of this study is the development of plastics via extrusion to analyze the effect of *A. salmiana* bagasse addition on the physical properties of the obtained bioplastics, with a particular interest in their potential application as agricultural mulch films.

## 2. Materials and Methods

### *2.1. Reagents*

Corn starch (Bestingredients, Monterrey, Mexico), glycerol (Karal, León, Guanajuato, Mexico), glacial acetic acid (Karal, León, Guanajuato, Mexico), maleic anhydride (Sigma-Aldrich, St. Louis, MO, USA), and distilled water were used as raw materials.

### *2.2. Preparation of Plant Material*

Maguey *salmiana* bagasse was obtained from the region of Pinos, Zacatecas, Mexico (22°17′50″ N, 101°34′30″ W). The material was first washed (distilled water), then dried at room temperature (25 ± 2 °C), and milled using an industrial blade processor. Subsequently, it was pulverized using a processor (Osterizer, Juárez, Mexico; 700 W) and manually passed through a series of sieves, with the final fraction passing through a 200 μm mesh to obtain particles smaller than 200 μm.

### 2.3. Preparation and Processing of Bagasse-Based Bioplastics

The components used in the preparation of the bioplastics were corn starch (CS) as the polymeric matrix, glycerol (Gly) and acetic acid (AcOH) as plasticizers, and maleic anhydride (MA). Glycerol and acetic acid were used as plasticizers due to their complementary roles in the processing and final properties of starch-based bioplastics. Glycerol increases the chain mobility and flexibility of the starch matrix, while acetic acid facilitates starch gelatinization and improves intermolecular interactions during processing. The combined use of both plasticizers enhances processability and mechanical performance in starch-based systems.

Maleic anhydride was incorporated as a compatibilizing agent to promote interactions between the hydrophilic starch matrix and the lignocellulosic components of maguey bagasse. Its anhydride groups can interact with the hydroxyl groups present in starch and cellulose, improving interfacial adhesion and fiber dispersion within the composite. Given its low concentration and reactive role during processing, maleic anhydride functions as a coupling modifier to improve compatibility between the matrix and the fibers, rather than as a main structural component of the bioplastic matrix.

*A. salmiana* bagasse (ASB) was incorporated without prior chemical pretreatment to evaluate its reinforcing effect by varying its proportion in combination with the aforementioned components (Table 1). The formulation proportions were expressed as weight percentages (*w*/*w*) to facilitate comparison among bioplastic formulations. The glycerol content was maintained constant based on previous reports indicating that glycerol concentrations in the range of 25–35% (*w*/*w*) are commonly used in starch-based bioplastics to ensure adequate flexibility and processability. This approach allowed the effect of ASB incorporation on the physicochemical and mechanical properties of the films to be evaluated without interference from variations in plasticizer content.

Mixing was performed using a mixer (KitchenAid Artisan) for 15 min. Each mixture was then fed into a co-rotating twin-screw extruder (Micro27, Leistritz, Nuremberg, Germany) with an L/D ratio of 32:1. The screw speed was set at 80 rpm, and the temperature profile was 75, 95, 105, 112, 112, 100, 90, and 80 °C. The extruded filaments were air-cooled and cut into small pieces (<1 cm). Subsequently, they were hot-pressed (130 °C, 111 kN, 3 min) to obtain thin sheets of 3 mm thickness using a hydraulic press (Carver, Autoseries NE, IN, USA). Figure 1 shows macroscopic images of the bioplastics obtained (M1–M5), which were cut using a manual die cutter to obtain the test samples.

**Table 1.** Identification and proportions of the components used in each bioplastic formulation (*w*/*w*%).

| Bioplastics | Corn Starch (CS) | Glycerol (Gly) | Acetic Acid (AcOH) | Maleic Anhydride (MA) | Maguey Bagasse (ASB) |
|---|---|---|---|---|---|
| M1 | 63.73 | 29.41 | 4.90 | 1.96 | 0 |
| M2 | 63.1 | 29.13 | 4.85 | 1.94 | 0.97 |
| M3 | 61.90 | 28.57 | 4.76 | 1.90 | 2.86 |
| M4 | 60.75 | 28.04 | 4.67 | 1.87 | 4.67 |
| M5 | 59.63 | 27.52 | 4.59 | 1.83 | 6.42 |




**Figure 1.** Macroscopic images of the developed bioplastic (M1–M5) showing differences in color and surface appearance as a function of *A. salmiana* bagasse content.

### *2.4. Moisture Content*

Moisture content was determined by weighing 2 g of each plastic sample (4 repetitions). Afterward, the samples were dried for 24 h at 50 °C. After drying, the samples were reweighed, and the moisture content was determined gravimetrically from the difference between the initial and final weights.

### *2.5. Water Absorption Percentage*

Water absorption behavior of bioplastics was studied in contact with water; the percentage of water absorption was estimated gravimetrically, according to the ASTM D570 [55] method with slight modifications [56]. Test specimens (2.5 × 2.0 cm) were cut and conditioned by drying at 50 ± 3 °C for 24 h, and their initial conditioned weight was recorded. They were then placed in glass jars, 20 mL of distilled water was added, and they were left to immerse for different contact times (1, 3, 5, 7, 24, and 48 h) at a temperature of 23 ± 1 °C. At each time interval for weight measurement, the bioplastic specimen was removed from the water with a spatula, placed on an absorbent towel to remove excess water, and then the weight was read and recorded as wet weight. The analyses were performed in triplicate for each sample and for each immersion time. The calculation was performed as follows:

$$Increase\ in\ weight,\ \% = \frac{wet\ weight - conditioned\ weight}{conditioned\ weight} \times 100$$

### *2.6. Determination of Mechanical Properties*

Mechanical properties were determined using a Galdabini QUASAR universal testing machine (Instron Galdabini, Cardano al Campo, Italy) following the ASTM D638 [56] standard method for plastics. Tensile tests were performed at a crosshead speed of 50 mm/min under uniaxial tensile loading conditions at room temperature. Tensile strength at break (maximum stress), elongation at break, and elastic modulus (Young's modulus) were obtained from the corresponding stress–strain curves. Five specimens were analyzed for each bioplastic formulation.

### *2.7. Physical Properties: Mass, Volume, and Density*

To evaluate the physical properties of the bioplastics produced, three fundamental quantities were considered: volume, mass, and density.

Volume was estimated using geometric calculation, multiplying the three main dimensions: length (L), width (W), and thickness (T). The dimensions were obtained by measuring five randomly selected samples for each type of composition in triplicate, using a digital micrometer with an accuracy of 0.001 mm. The volume value for each sample is expressed in $mm^3$, and the arithmetic mean was then obtained to represent the characteristic volume of each sample.

To determine the amount of material, five samples were randomly selected for each type of composition and weighed individually in triplicate using an electronic balance with an accuracy of 0.001 g. The average value of the measurements represented the characteristic mass of each group of bioplastics.

The density of each sample was calculated as the ratio between the mass (g) and the volume ($mm^3$) determined previously. This parameter allowed for a direct relationship to be established between the compaction of the material and its composition, providing a relevant indicator of the efficiency of the forming process and the mechanical performance of the bioplastics.

### *2.8. Shear Strength*

Although shear strength is a mechanical property, this test was evaluated separately from tensile properties due to the different loading mode and experimental configuration involved. The shear strength test was performed using a Warner–Bratzler blade [57] mounted on a KRN 3.0 electromechanical device developed by AORTech® laboratories under intellectual property protection (MX/u/2018/000512). This equipment was designed to accurately measure the force required to fracture samples using a rectangular cutting shear, allowing comparable values to be obtained between different treatments. For each analysis, five pieces were randomly selected from each experimental group, allowing for a representative evaluation of the differences in mechanical resistance induced by the inclusion of different percentages of applied materials. The Warner–Bratzler blade is commonly used in food texture analysis, as its application in thin polymeric sheets facilitates the evaluation of resistance to localized shear and fracture, providing comparative information on structural integrity and cohesion among formulations.

### *2.9. Colorimetry Analysis*

Color measurements were performed using a CM-700d/600g colorimeter, previously calibrated against a white standard reference. Five measurements were taken for each sample and color coordinates were recorded in the CIE L*a*b* color space, where L* represents lightness, a* the red–green axis, and b* the yellow–blue axis. Measurements were conducted under the instrument's standard factory configuration.

### *2.10. Thermogravimetric Analysis*

The thermal stability of the bioplastics obtained was determined using thermogravimetric analysis by measuring the amount and rate of weight change as a function of temperature in a controlled atmosphere (inert gas). A TGA Q500 V6.3 Build 189 (TA Instruments, New Castle, DE, USA) was used to perform the analysis. For this purpose, between 15 and 20 mg of each material were weighed, placed on the instrument's oven tray and analyzed at a controlled heating rate and temperature (10 °C/min and a range of 30 to 500 °C, respectively), using an inert nitrogen atmosphere.

### *2.11. SEM*

Scanning electron microscopy (SEM) analysis was performed using a JEOL JSM 6010-LA (Akishima, Japan). The experimental conditions included backscattered electrons, an accelerating voltage of 20 kV, a pressure of 60,000 Pa, and working distances of $10^{-9}$ mm. Micrographs at various magnifications were obtained to assess both surface and cross-sectional morphology, as presented in the corresponding figures.

### *2.12. Fourier Transform Infrared Spectroscopy (FTIR)*

FTIR spectra were recorded using a Fourier transform infrared spectrophotometer (Thermo Fisher, Nicolet, Waltham, MA, USA) with 16 scans, a spectral resolution of 4 $cm^{-1}$, and a wavenumber range from 4000 to 400 $cm^{-1}$.

### *2.13. Statistical Analysis*

An analysis of variance (ANOVA) was performed to determine statistically significant differences between the means, since they met the statistical postulates required to perform the parametric analysis. Compliance with these postulates facilitates a reliable comparison of the response variables among the obtained plastics.

All experiments were performed in quadruplicate to ensure repeatability and robustness of the results. The analyzed parameters included moisture content, water absorption, solubility, and mechanical properties of the bioplastic films.

Statistical analysis was conducted using one-way analysis of variance (one-way ANOVA) to evaluate differences among the different bioplastic formulations. Prior to analysis, the data were verified to meet the assumptions of parametric tests, including normality, homoscedasticity, and independence of observations.

A significance level of $\alpha = 0.05$ was applied. Values are expressed as mean $\pm$ standard deviation. When statistically significant differences were detected, least significant difference (LSD) post hoc tests were used to compare the mean values among formulations composed of corn starch with glycerine (G), acetic acid (AA), maleic anhydride (MA), and *salmiana* maguey bagasse (B). Statistical assumptions were verified prior to analysis. Parametric data were analyzed using one-way ANOVA followed by Fisher's LSD test ($\alpha = 0.05$), while moisture content was analyzed using the Kruskal–Wallis test.

## 3. Results

### *3.1. Determination of Moisture Percentage*

The Kruskal–Wallis analysis indicated a significant difference ($p = 0.008$) between the medians of the moisture content variable for the different proportions of bioplastic mixtures (M1, M2, M3, M4, and M5) regarding the moisture content (%) variable, with a 95% confidence level. The Mann–Whitney test of medians shows significant differences between the different bioplastic samples, with different treatments indicated by different letters. The results show that the bioplastic mixture M5 exhibited the highest mean moisture content of 8.60 ($\pm$Q1 = 8.70, Q2 = 8.40), followed by M4 of 7.44 ($\pm$Q1 = 7.56, Q2 = 7.39). The median values of M3, M2, and M1 were 7.30 ($\pm$Q1 = 7.38, Q2 = 7.03), 6.1 ($\pm$Q1 = 6.62, Q2 = 5.57), and 7.9 ($\pm$Q1 = 6.25, Q2 = 8.06), respectively (Figure 2). (Q1 and Q2 denote the maximum and minimum quartiles, respectively.)

### *3.2. Determination of the Percentage of Water Absorption in Bioplastics by Mixture Type*

The one-way analysis of variance indicated highly significant differences ($p < 0.001$) among the means of the different proportions of bioplastic mixtures M1 to M5, as shown in Figure 3, with a 95% confidence level. From the obtained results, it can be highlighted that the water absorption percentages of the bioplastics corresponding to materials M3 to

M5 present the highest mean percentages with values of 63.19 (±Q1 = 64.47, Q2 = 61.89), 65.18 (±Q1 = 65.40, Q2 = 64.96), and 65.27 (±Q1 = 66.17, Q2 = 63.98), respectively. On the other hand, the lowest values observed correspond to the bioplastics of the mixtures M1 and M2, with absorption percentages of 57.93 (±Q1 = 58.61, Q2 = 57.20) and 57.93 (±Q1 = 58.03, Q2 = 57.81), respectively. (Q1 and Q2 denote the maximum and minimum values, respectively.)

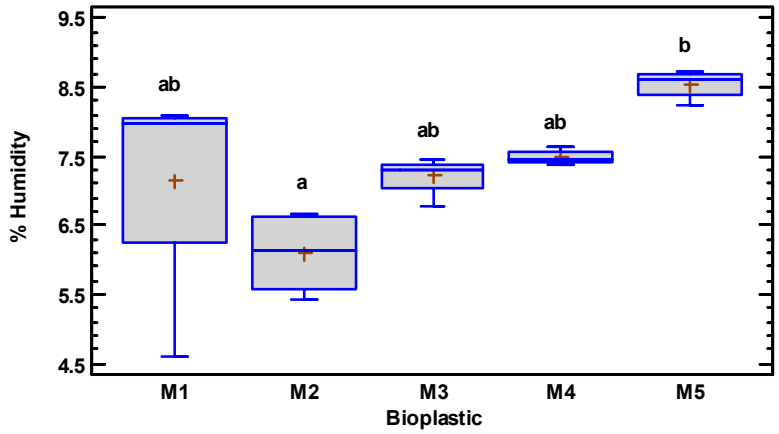



**Figure 2.** Moisture content (%) values of the bioplastics obtained from mixtures M1 to M5. Different letters represent differences in treatment ($p < 0.05$). Error bars represent standard deviation from replicate measurement (range is $n = 3$ or $n = 4$, depending on experiment). The symbol (+) represents the median value.

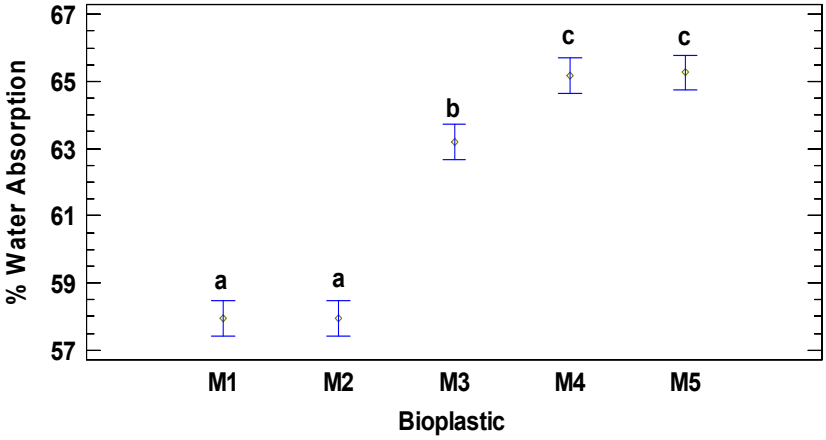



**Figure 3.** Water absorption percentages (%) of bioplastics at 24 h from mixtures M1 to M5. Different letters indicate statistically significant differences among samples ($p < 0.05$). Error bars represent standard deviation from replicate measurement (range is $n = 3$ or $n = 4$, depending on experiment).

### *3.3. Determination of the Water Absorption Percentage as a Function of Time*

Regarding the analysis of variance, highly significant differences ($p < 0.001$) were observed among the mean values for different proportions of bioplastic mixtures with respect to water absorption percentage at different times (1, 3, 5, 7, 24, and 48 h) with a 95% confidence level. As shown in Figure 4, the lowest mean absorption rate was observed after 1 h of contact between the biopolymers and water, reaching 61.37% (±Q1 = 69.38, Q2 = 37.64). The highest values were obtained after 24 and 48 h, with 73.46% (±Q1 = 78.44, Q2 = 57.21) and 73.19% (±Q1 = 78.66, Q2 = 56.84), respectively. Overall, the absorption rates increased over time. (Q1 and Q2 denote the maximum and minimum values, respectively).

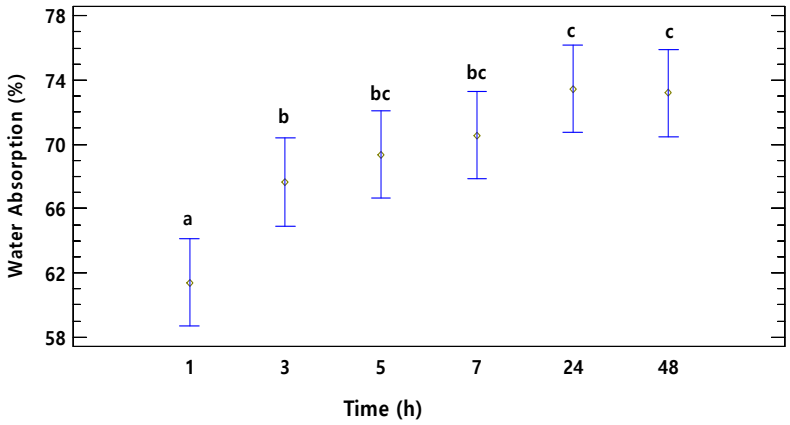



**Figure 4.** Water absorption behavior of bioplastics at different immersion times (1, 3, 5, 7, 24, and 48 h). Values represent mean water absorption. Error bars indicate standard deviation ($n$ = 3). Different letters indicate statistically significant differences among immersion times ($p < 0.05$).

### *3.4. Color Tests*

Table 2 shows the L*, equivalent to lightness; a*, equivalent to the green–red axis; and b*, equivalent to the blue–yellow axis, parameters of the CIE LAB System [55]. According to the results obtained, the highest lightness value (L) corresponds to plastic M1, which contains no bagasse (0%). This same trend is observed in the b* and a* values of the same bioplastic (Table 2). On the other hand, it is observed that these L values tend to decrease as the amount of bagasse increases. The lowest value obtained was for bioplastic M5, which contains the highest bagasse content (6.42%).

**Table 2.** Results of indicators from the color tests of bioplastics M1, M2, M3, M4, and M5. Values are expressed as mean ± standard deviation ($n$ = 3).

| Bioplastics | L* | a* | b* |
|---|---|---|---|
| M1 | 38.7 ± 0.9 | 5.0 ± 0.3 | 12.6 ± 0.6 |
| M2 | 32.2 ± 1.1 | 3.8 ± 0.2 | 8.5 ± 0.4 |
| M3 | 24.5 ± 0.8 | 1.5 ± 0.1 | 3.8 ± 0.3 |
| M4 | 24.0 ± 0.7 | 1.2 ± 0.1 | 1.6 ± 0.2 |
| M5 | 23.8 ± 0.6 | 1.1 ± 0.1 | 1.1 ± 0.1 |

### *3.5. Density Tests*

Regarding the density results, the analysis of variance revealed highly significant differences among the means obtained with a 95% confidence level. The treatment showed that for bioplastics M1 and M2, mean values between 1 (±Q1 = 0.94, Q2 = 1.09) and 0.99 (±Q1 = 0.92, Q2 = 1.06) were obtained. On the other hand, the values obtained for M3, M4, and M5 were 0.89 (±Q1 = 0.79, Q2 = 0.96), 0.90 (±Q1 = 0.76, Q2 = 1.15), and 0.88 (±Q1 = 0.80, Q2 = 0.99), respectively (Figure 5) (Q1 and Q2 denote the maximum and minimum values, respectively). Several studies have highlighted the importance of obtaining low-density values for practical purposes regarding material handling [55]. The results obtained regarding variations in density may be related to differences in moisture content and thermal mass-loss behavior in thermogravimetric analysis, considering that the presence of hydrophilic groups and fiber content has effects on both water retention and compactness in the matrix structure. This variability is also associated with differences in internal structure and compaction promoted by the incorporation of lignocellulosic bagasse within the polymeric matrix structure. (Q1 and Q2 denote the maximum and minimum values, respectively).

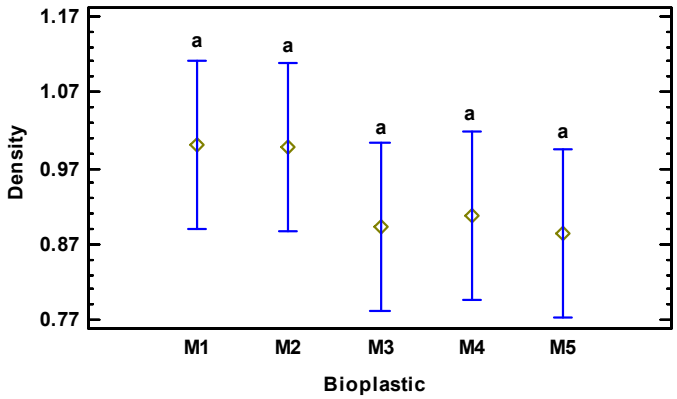



**Figure 5.** Density values (mg/mm$^3$) of bioplastics M1, M2, M3, M4 and M5 obtained from the mixtures. Values are expressed as mean ± standard deviation. The same letter a indicates no statistically significant differences among the samples ($p > 0.05$). Error bars represent standard deviation from replicate measurement (range is $n = 3$ or $n = 4$, depending on experiment).

### *3.6. Shear Strength Tests*

Through one-way analysis of variance, highly significant differences ($p < 0.001$) were observed among the mean shear strength values for each of the developed bioplastics (M1, M2, M3, M4, and M5), with a 95% confidence level. The multiple mean comparison using the LSD test indicated that different letters represented different treatments ($p < 0.05$). As shown in Figure 6, the lowest mean shear strength value corresponded to bioplastic M1, with a value of 8.25, which does not contain bagasse. The highest value was for bioplastic M5, which contains the largest amount of bagasse (6.42% g), with a mean value of 16.48 (±Q1 = 17.66, Q2 = 15.04). The mean values obtained for bioplastics M2, M3, and M4 have values of 13.46 (±Q1 = 13.28, Q2 = 13.68), 11.71 (±Q1 = 12.03, Q2 = 11.39), and 12.3 (±Q1 = 13.60, Q2 = 10.67), respectively, as shown in Figure 6. (Q1 and Q2 denote the maximum and minimum values, respectively.)

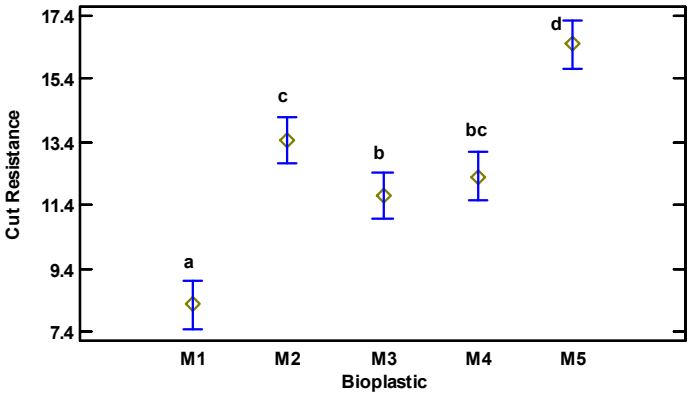



**Figure 6.** Shear strength test values of bioplastics obtained from mixtures M1, M2, M3, M4, and M5. Different letters represent differences in treatment ($p < 0.05$). Error bars represent standard deviation from replicate measurement (range is $n = 3$ or $n = 4$, depending on experiment).

### *3.7. Mechanical Testing: Tensile and Deformation Tests*

To analyze the effect of bagasse content, this test was performed on bioplastics from mixtures M1 to M5. The results obtained from the analysis of variance indicated highly significant differences ($p < 0.001$) among the means of the different proportions of bioplastic mixtures regarding tensile strength (MPa) and deformation (%) at a 95% confidence level. Likewise, the multiple mean comparison using the LSD test indicated that different letters represented significant differences between the different proportions of bioplastic mixtures.

The results regarding tensile strength show that bioplastic M1 has the lowest tensile strength mean with a value of 0.28 MPa, in contrast to the highest value obtained for bioplastics M4 and M5 (0.51 and 0.55 MPa, respectively), as shown in Figure 7.

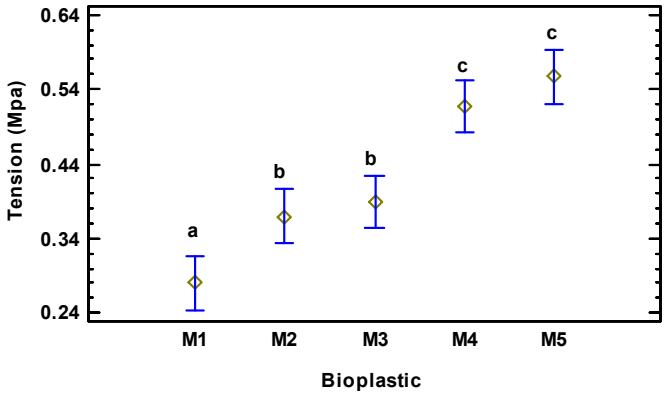



**Figure 7.** Tensile strength values of bioplastics obtained from mixtures M1 to M5. Different letters represent differences in treatment ($p < 0.05$). Q1 and Q2 denote the maximum and minimum values, respectively. Error bars represent standard deviation from replicate measurement (range is $n = 3$ or $n = 4$, depending on experiment).

The results regarding the deformation variable show that the M1 bioplastic mixture presented the highest deformation mean with a value of 67.32% (±Q1 = 68.68, Q2 = 65.97), followed by the values of mixtures M2, M3, and M4, which correspond to values of 47.81% (±Q1 = 53.48, Q2 = 43.47), 47.93% (±Q1 = 51.37, Q2 = 42.13), and 46.58% (±Q1 = 47.11, Q2 = 45.97), respectively. The lowest value observed was bioplastic M5 (42.72% ± Q1 = 56.73, Q2 = 31.04). In this case, as shown, bagasse affects the reduction in deformation, since mixture M1 differs from the other bioplastics (M2–M5) in that it does not contain bagasse, as seen in Figure 8. (Q1 and Q2 denote the maximum and minimum values, respectively).

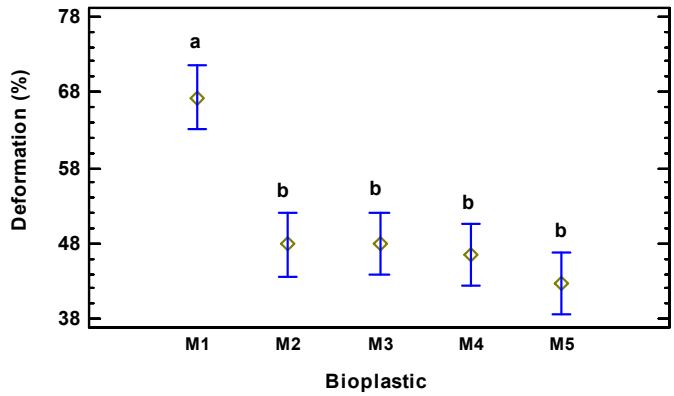



**Figure 8.** Deformation values of the bioplastics obtained from mixtures M1 to M5. Different letters represent differences in treatment ($p < 0.05$). Error bars represent standard deviation from replicate measurement (range is $n = 3$ or $n = 4$, depending on experiment).

### *3.8. Thermal Analysis*

The thermal behavior of the bioplastics (Figure 9 and Table 3) was evaluated using a TGA Q500 V6.3 Build 189 instrument, which allows for continuous monitoring of mass variation during heating. The analysis was carried out by applying a temperature ramp from 30 °C to 500 °C at a rate of 10 °C/min, corresponding to a total duration of approximately 47 min. Data acquisition was performed using Suite Advantage software

(version 5.0), which processes the balance data and generates real-time visualizations, including chronological measurement tables and drying kinetics curves. Through this analysis, it was possible to identify the different stages of mass loss associated with moisture release and thermal degradation of both the polymeric matrix and the lignocellulosic components. Upon completion of the analysis, a report was automatically generated in CSV format, including the processing parameters and graphical results. This approach improves the reliability of thermogravimetric analysis by minimizing human error and enhancing data traceability.

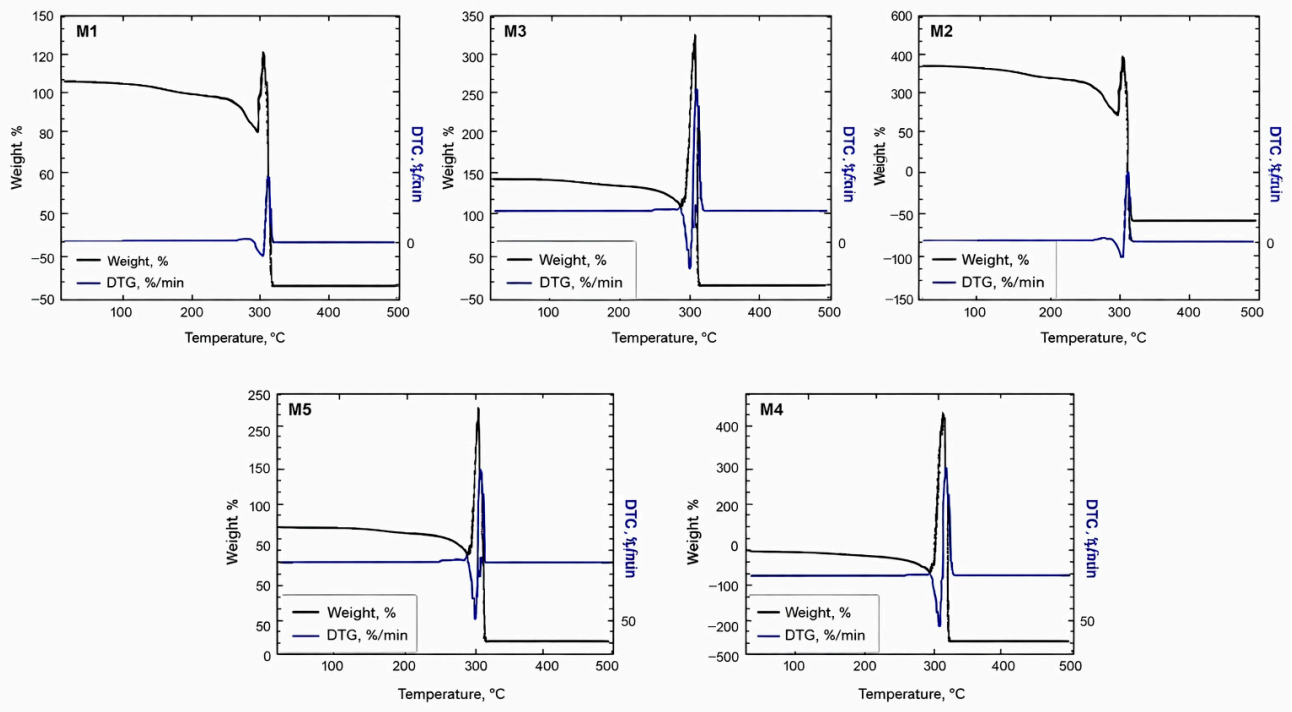



**Figure 9.** Thermal analysis of bioplastics M1, M2, M3, M4, and M5 in the range of 30 to 500 °C.

**Table 3.** The changes observed in the TGA analysis.

| Observed Changes | Change Interval (°C) | | Loss Weight, % | | | | |
|---|---|---|---|---|---|---|---|
| | Ti | Tf | M1 | M2 | M3 | M4 | M5 |
| 1 | 30 | 155 | 2.5 | 3.7 | 6.6 | 5.3 | 6.0 |
| 2 | 155 | 255 | 14.1 | 10.7 | 6.7 | 6.2 | 7.8 |
| 3 | 255 | 300 | 24.2 | 32.0 | 24.7 | 25.4 | 24.4 |
| 4 | 300 | 500 | 59.2 | 53.6 | 62.1 | 63.1 | 61.8 |

### *3.9. SEM Images*

Figure 10 shows SEM images of bioplastics M1, M2, and M5, whose differences are based on the proportion of bagasse in the bioplastics, with 0, 0.97, and 6.42%, respectively. These images facilitate observation of their surface and cross-sectional morphology. For bioplastic M1, which does not contain bagasse, a rougher appearance with lower uniformity can be distinguished compared to M2 and M5, which have the lowest and highest amounts of bagasse, respectively.

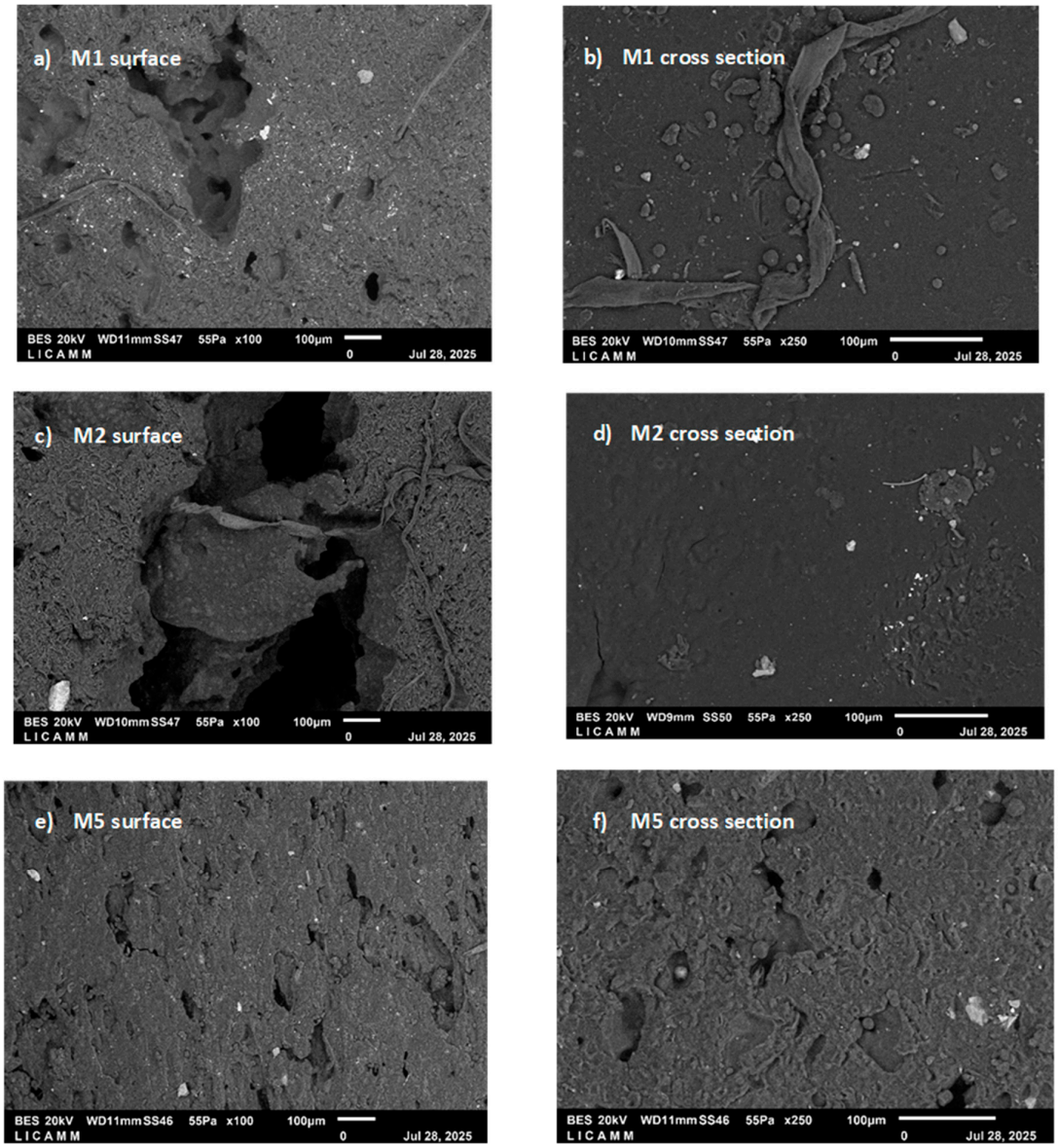



**Figure 10.** Representative SEM images of selected bioplastic formulations: M1 (without bagasse): (**a**) Surface (×100) and (**b**) cross-section (×250); M2 (0.97% bagasse): (**c**) Surface (×100) and (**d**) cross-section (×250); and M5 (6.42% bagasse): (**e**) Surface (×100) and (**f**) cross-section (×250).

### *3.10. FTIR*

Figure 11 shows the FTIR spectra of the obtained bioplastics (M1–M5), where a strong characteristic peak can be highlighted in the range of 1000 to 1030 $cm^{-1}$, present in all bioplastics and probably attributed to C–O bonds of the plasticizer or the starch polymeric matrix. Likewise, a broad and predominant band can be observed in all bioplastics around 3300 $cm^{-1}$, which could be related to hydroxyl groups associated with corn starch and glycerol. The presence and intensity of these bands are consistent with the lignocellulosic nature of the incorporated bagasse and suggest hydrogen bond interactions between starch, glycerol, and the fibrous components. This behavior indicates adequate compatibility between the components and supports the observed trends in moisture content and mechanical behavior discussed in previous sections, confirming the relevance of FTIR analysis for evaluating interactions within the bioplastic matrix.

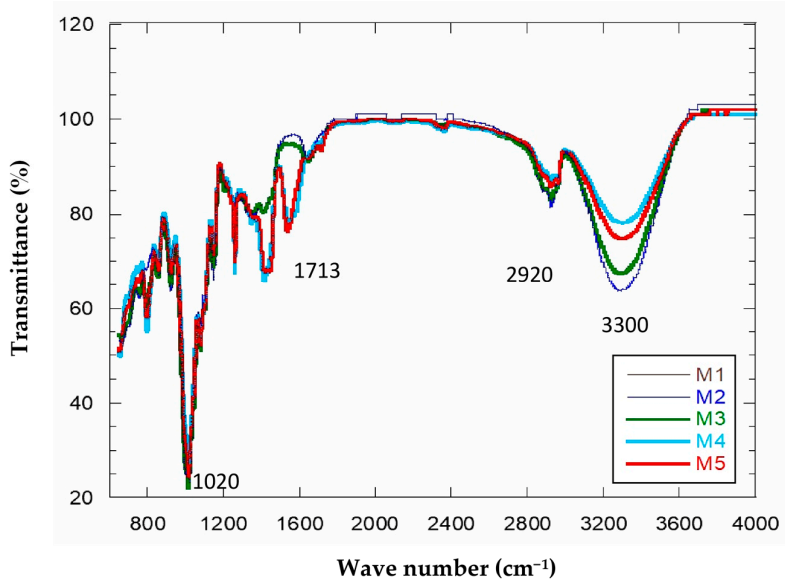



**Figure 11.** FTIR image of bioplastics M1, M2, M3, M4, and M5.

According to the spectra shown in Figure 11, no new distinctive FTIR bands associated with esterification reactions are observed; this may be due to the overlap of bands between the starch, glycerol and lignocellulosic components. It is therefore interpreted that the role of maleic anhydride is to improve interfacial compatibility rather than to form covalent bonds that are clearly detectable under the conditions evaluated.

## 4. Discussion

The results of each analyzed variable provide information on the interactions among the polymeric matrix and plasticizers and, as an important objective of this research, on the contribution of maguey bagasse reused for bioplastics production. When bioplastics are proposed as biodegradable mulch, moisture content is of great importance, as it defines physical properties related to durability or decomposition, since higher moisture values facilitate the proliferation of fungi or bacteria [58,59]. Research related to rice starch-based biopolymers incorporating vegetal bagasse residues shows a decrease in moisture values [60]. It has also been reported that lignin-rich residues tend to exhibit lower moisture contents [52,61].

Studies on sugarcane bagasse-based bioplastics using cellulose and sorbitol report moisture contents of approximately 8.1%, with values increasing as the proportion of bagasse relative to cellulose increases [62]. A similar trend was observed in this study as the maguey bagasse content increased, reaching a maximum moisture value of 10.57%. However, the comparatively higher moisture content observed for film M5 can be attributed to the hydrophilic nature of glycerol and starch combined with the initial incorporation of bagasse, which promotes water retention at low fiber contents.

The bioplastics that exhibited the highest water absorption were M4 and M5, which contain the highest amounts of bagasse (4.67% and 6.42% ASB, respectively) compared to the other bioplastics. Several authors attribute this behavior, in this particular case, to interactions with hydroxyl groups from bagasse [34,42]. On the other hand, in the water absorption test at different times, a gradual increase in absorption over time was observed, since the initial absorption at 1 h was 61.37%, compared to 73.19% at 48 h. Amusat et al. reported that reinforcing bioplastics with mulch improves water retention capacity, thus improving moisture conservation in soil [49].

Regarding mechanical properties, increases in tensile strength values were observed as the bagasse content increased, while deformation tended to decrease with higher bagasse percentages. This behavior can be explained by the fact that glycerol and the starch polymeric matrix generally exhibit high deformability; however, when maguey bagasse is incorporated, lignocellulosic fibers promote intermolecular interactions through hydrogen bonding among glycerol, starch, and bagasse hemicellulose [34,42,63–67], resulting in a stiffer composite structure. The results of incorporating maguey bagasse into starch-based systems, which showed a similar trend in terms of increased stiffness and reduced deformation, are consistent with the authors' previous work [15]. It is worth noting that the shear strength values were verified through repeated measurements to ensure their reproducibility, particularly in the case of formulation M2. The updated results showed a more consistent trend across the formulations, thereby supporting the contribution of bagasse as a reinforcing agent due to the lignocellulosic fibers within the polymer matrix, which improve tensile strength through fiber–matrix interactions. This effect has also been observed in other studies [15].

It is important to note that the bagasse used in this study was incorporated without chemical pretreatment; it was only washed, dried, and milled. This approach was intentionally adopted to evaluate the interaction between the residue and the starch matrix under minimally processed and more sustainable conditions, avoiding aggressive alkaline treatments commonly applied to modify fiber surfaces. Consequently, the mechanical performance observed should be interpreted as representative of preliminary environmentally friendly formulations, which is consistent with the lower mechanical performance of starch-based bioplastics [63–69].

Although the tensile strength values obtained are lower than those of commercial polyethylene mulch films, which typically present tensile strengths in the range of several MPa, the developed materials exhibited measurable elongation and deformation capacity, indicating that they are not excessively rigid. These materials should therefore be considered preliminary experimental formulations, and further optimization of formulation and processing conditions, together with field-scale evaluation, would be necessary to confirm their suitability for agricultural mulching applications. The high water absorption values observed are related to the hydrophilic nature of starch, glycerol and lignocellulosic fibers [62]. While this behavior may limit structural stability under prolonged exposure to water, it also reflects the inherent interaction of the material with moisture. The proposed application as mulch should therefore be interpreted as a potential and exploratory use, requiring further optimization to balance water resistance and mechanical performance under real field conditions [69–71].

Low-density values are a key point indicating ease of handling, transportation, or installation, particularly referring to bioplastic films used as mulch. Harussani et al. observed plasticizer effects that tend to decrease density values by increasing plasticizer content in corn starch, reporting density values of 1.4 $g/cm^3$ for bioplastics with 60% sorbitol compared to 1.39 $g/cm^3$ with 60% glycerol [70].

In this case, the color of the bioplastics is determined by the effect of the components. For bioplastics developed with maguey bagasse, their brown coloration is naturally attributed to the bagasse, with the advantage of not containing or requiring synthetic colorants. This behavior is consistent with previous studies on biopolymer composites containing lignocellulosic fillers. This behavior has been reported in similar studies [67], wherein the incorporation of lignin into PHA-based materials led to decreased transparency and darker coloration due to light scattering and the intrinsic color of the filler. Their use as mulch influences radiation levels, promotes weed suppression, and increases soil temperature when applied to crops. While conventional or synthetic plastics offer a wide

range of colors, their disadvantage lies in microplastic generation and long biodegradation periods. The lightness results obtained in this research are lower than those reported by Navia et al. [58] for plastics developed with cassava flour at 180 °C without applied pressure (0 psi). In contrast, Francisco-Ponce et al. obtained lightness values of L = 28.61 and L = 28.84 for bioplastics developed from starch gelatin with added mango and coffee residues, respectively, used for spoon production [71].

The behavior of the thermal analysis will depend on the composition of the bioplastic material developed, as described below. The initial thermal stage (30 to 155 °C) demonstrated a mass loss rate of 0.02–0.053 °C/min, where the evaporation of water and volatile compounds was (2.5–6.6%). The second stage (155–255 °C range) showed mass loss rates of 0.062–0.14 °C/min, which is attributable to the beginning of the material decomposition process, causing the loss of some components, showing plasticizers and *Agave* with mass loss between 6.2% (observed in M4) and 14.1% (for M1). Adnan et al. [72] performed thermal analysis of polyvinyl alcohol on cassava and potato starch plastic film, heating from 20 to 200 °C, and observed a decrease in the studied range; the authors attributed it to a plasticizing effect with hydrogen bond interactions between starch molecules. The third stage was detected within the 255–300 °C range, with a mass loss rate of 0.542–0.711 °C/min and a mass loss of 24–32%. At this stage, the decomposition of the main component, corn starch (present in all bioplastics), began. Final degradation occurred in the last stage, within a temperature range of 309–312 °C. This agrees with reports from other authors, who report a decomposition temperature for corn starch close to 300 °C [68–71]. This final stage is mainly characterized by higher mass loss (53.6–63.1%) and a mass loss rate of 0.268–0.311 °C/min. This behavior is relevant for assessing thermal performance in relation to potential mulch applications under controlled conditions. In particular, the methodology was extremely useful in the study of polymeric biomaterials developed with fibrous components, as it allowed for the kinetics of moisture loss to be correlated with other relevant physical and mechanical properties such as shear strength and density, thus providing a comprehensive characterization of the thermal behavior of the material [71–73].

SEM images show improved structural uniformity with increased bagasse content, which can be related to greater fiber–matrix interaction in starch-based composites. FTIR spectra indicate the presence of characteristic hydroxyl and C-O functional groups associated with starch, glycerol, and lignocellulosic fibers, thereby promoting the integration of components during the plasticization process. Although similar interactions have been described in other polymeric systems [38,69], differences in matrices and reinforcing residues must be considered. In the present materials, these interactions are consistent with the observed changes in stiffness, density, and water absorption.

The development of bioplastics from agro-industrial residues may contribute to sustainability objectives aligned with UN SDG 9 (Industry, Innovation, and Infrastructure), UN SDG 12 (Responsible Consumption and Production), and UN SDG 13 (Climate Action), in addition to contributions associated with their proposed use as mulch. In addition to the above, research on the use of bioplastic mulch is highly relevant as it impacts processes such as temperature regulation in agricultural soil, as well as moisture conservation and improved crop yield [49], which contributes to better agriculture that is resilient to extreme climates with less environmental impact through the use of bioplastic mulches [74–79]. In this study, the reference to mulch applications is limited to a preliminary assessment based on physicochemical, mechanical, and water-related properties. The materials were evaluated as film-forming bioplastics under laboratory conditions, and their mention as agricultural mulches should be interpreted as a potential application rather than a direct replacement for commercial mulch films. There have been no soil biodegradation tests or field trials; therefore, the proposed application of the mulch should be regarded as

preliminary and requires further validation under real field conditions. The approach adopted in this study allows us to identify the steps needed to evaluate its environmental performance on a larger scale. In particular, quantitative sustainability assessments, such as life cycle analysis (LCA) and biodegradability testing under soil conditions, would be necessary to fully validate its suitability for agricultural mulching applications. These aspects are considered part of the future research prospects derived from this work.

## 5. Conclusions

Agro-industrial residues represent a valuable resource for sustainable material development, as demonstrated by the incorporation of *A. salmiana* bagasse into corn starch-based bioplastics. The results showed that increasing bagasse content significantly influenced the physical and mechanical properties of the bioplastics, improving stiffness and handling characteristics relevant for potential mulch applications.

In addition, formulations containing bagasse exhibited higher moisture content and water absorption capacity, which may be advantageous for soil moisture retention and water conservation when applied in agricultural systems. These effects are attributed to the hydrophilic nature of the lignocellulosic fibers and their interaction with the starch-based matrix. Future studies will focus on functional properties such as water vapor permeability (WVP) and biodegradability to further evaluate the suitability of these materials for agricultural mulch applications.

Overall, this study highlights the potential of maguey bagasse as a reinforcing and functional component in biodegradable bioplastics, contributing to the valorization of agro-industrial residues within a circular economy framework. Future studies will include soil biodegradation, ecotoxicity, and field-scale evaluations to validate the practical applicability of these materials as agricultural mulch under real environmental conditions.

The proposed use of bioplastics as agricultural mulch should be regarded as a potential application on an experimental basis. It will be necessary to continue optimizing properties such as mechanical strength and water resistance, as well as to carry out field-scale testing to confirm their practical applicability under real-world field conditions.

**Author Contributions:** Conceptualization, E.D.-R. and L.A.A.-H.; methodology, E.D.-R. and M.M.-S.; software, A.A.O.-H. and R.M.-A.; validation, L.D.-R.; formal analysis, A.A.O.-H., R.M.-A. and R.S.-S.; investigation, A.A.O.-H., R.M.-A., J.J.O.-S. and A.B.-C.; resources, E.D.-R. and L.A.A.-H.; data curation, S.M.R.-R.; writing—original draft preparation, E.D.-R.; writing—review and editing, L.A.A.-H., R.M.-A. and A.A.O.-H.; visualization, L.D.-R.; supervision, M.M.-S.; project administration, A.B.-C. All authors have read and agreed to the published version of the manuscript.

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## References


1. Oliveira, J.S.; Oliveira, J.P.; Oliveira, C.P.; Veloso, C.M. Circular economy as tool for the valorization of agro-industrial residues and the development of biodegradable and sustainable packaging: A bibliometric review form 2015 to 2024. *Clean. Circ. Bioeconomy* **2025**, *12*, 100188. [CrossRef]
2. Ahmed, M.M.; Nabi, M.H.B.; Mia, M.S.; Ahmad, I.; Zzaman, W. Valorization of plant-based agro waste into sustainable food packaging materials: Current approaches and functional applications. *Appl. Food Res.* **2025**, *5*, 101368. [CrossRef]
3. Saxena, S.; Moharil, M.P.; Jadhav, P.V.; Ghodake, B.; Deshmukh, R.; Ingle, A.P. Transforming waste into wealth:leveraging nanotechnology for agricultural by products into value-added products. *Plant Nano Biol.* **2025**, *11*, 100127. [CrossRef]
4. Anokye, K.; Mohammed, A.; Agyemang, P.; Agya, B.A.; Amuah, E.E.Y.; Sodoke, S. A systematc review of the impacts of open burning and open dumping of waste in Ghana: A way forward for sustainable waste management. *Clean. Waste Syst.* **2024**, *8*, 100152. [CrossRef]
5. Pandey, A.K.; Thakur, S.; Mehra, R.; Kaler, R.S.S.; Paul, M.; Kumar, A. Transforming agri-food waste innovative pathways toward a zero-waste circular economy. *Food Chem.* **2025**, *28*, 102604. [CrossRef]
6. Bala, S.; Garg, D.; Sridhar, K.; Inbaraj, B.S.; Singh, R.; Kamma, S.; Tripathi, M.; Sharma, M. Transformation of Agro-Waste into Value-Added Bioproducts and Bioactive Compounds: Micro/Nano Formulations and Application in the Agri-Pharma Sector. *Bioengeeniering* **2023**, *10*, 152. [CrossRef]
7. Kumar, P.; Tanwar, R.; Gupta, V.; Upadhyay, A.; Kumar, A.; Gaikwad, K.K. Pineapple peel extract incorporated poly(vinyl alcohol)-corn starch film for active food packaging: Preparation, characterization and antioxidant activity. *Int. J. Biol. Macromol.* **2021**, *187*, 223–231. [CrossRef]
8. Maqsood, S.; Khalid, W.; Kumar, P.; Benmebarek, I.E.; Rasool, I.F.U.; Triff, M.; Moreno, A.; Esatbeyoglu, T. Valorization of plant-based agroindustrial waste and by-products for the production of polysaccharides: Towards a more circular economy. *Appl. Food Res.* **2025**, *5*, 100954. [CrossRef]
9. Mia, M.S.; Ahmed, M.M.; Zzman, W. Valorization of food waste into functional ingredients supports a sustainable strategy for the food industry. *Discov. Food* **2025**, *5*, 275. [CrossRef]
10. Garnnevska, E.; Hidayati, D.R.; McLaren, S. Circularity in agri-food value chains in developing countries: A case Indonesia. *Sustinability* **2026**, *18*, 708. [CrossRef]
11. Ram, M.; Bracci, E. Waste management, waste indicators and relationship with sustainable development goals (SDGs): A systematic literature review. *Sustainability* **2024**, *16*, 8486. [CrossRef]
12. Delgadillo-Ruiz, L.; Bañuelos-Valenzuela, R.; Esparza-Ibarra, E.L.; Gutiérrez-Bañuelos, H.; Cabral-Arellano, F.J.; Muro-Reyes, A. Evaluación del perfil de nutrientes de bagazo de agave como alternativa de alimento para rumiantes. *Rev. Mex. Cienc. Agrícolas* **2015**, *11*, 2099–2103.
13. Carrillo-Nieves, D.; Rostro-Alanis, M.J.; De la Cruz-Quiroz, R.; Ruiz, H.A.; Iqbal, H.M.N.; Parra-Saldivar, R. Current status and future trends of bioethanol production from agroindustrial waste in Mexico. *Renew. Sustain. Energy Rev.* **2019**, *102*, 63–74. [CrossRef]
14. Márquez-Rangel, I.; Cruz, M.; Ruiz, H.A.; Rodríguez-Jasso, R.M.; Loredo, A.; Belmares, R. Agave waste as source of prebiotic polymer: Technological applications in food and their beneficial health effect. *Food Biosci.* **2023**, *56*, 103102. [CrossRef]
15. Arias-Hernández, L.A.; Maldonado–Santoyo, M.; Delgadillo-Ruiz, L.; Solís-Silván, R.; Calderón-Vega, F.; Carreño-Aguilera, G.; Reduncido-Ruiz, S.M.; González-Trinidad, J.; Berumen-Cervantes, A.; Ortiz-Hernández, A.A.; et al. The effect of the addition of maguey bagasse in the production of bioplastics based on corn and potato starch. *Compos. Sci.* **2025**, *9*, 213. [CrossRef]
16. Costa, J.P.; Avellan, A.; Mouneyrac, C.; Duarte, A.; Rocha-Santos, T. Plastic additives and microplastics as emerging contaminants: Mechanisms and analytical assessment. *TrAC Trends Anal. Chem.* **2024**, *158*, 116898. [CrossRef]
17. Nayanathara-Thathsarani-Pilapitiya, P.G.C.; Ratnayake, A.S. The world of plastic waste: A review. *Clean. Mater.* **2024**, *11*, 100220. [CrossRef]
18. Pathak, G.; Nichter, M.; Hardon, A.; Moyer, E.; Latkar, A.; Simbaya, J.; Pakasi, D.; Taqueban, E.; Love, J. Plastic Pollution and the open burning of plastic waste. *Glob. Environ. Change* **2023**, *80*, 102648. [CrossRef]
19. Tasseron, P.F.; Van Emmerikk, T.H.M.; Vriend, P.; Hauk, R.; Alberti, F.; Mellink, Y.; Ploeg, M.V.D. Defining plastic pollution hotspots. *Sci. Total Environ.* **2024**, *934*, 173294. [CrossRef]
20. Horton, A.A. Plastic pollution: When do we know enough? *J. Hazard. Mater.* **2022**, *422*, 126885. [CrossRef]
21. Ihenetu, S.C.; Li, G.; Mo, Y.; Jacques, K.J. Impacts of microplastics and urbanization on soil health: An urgent concern for sustainable development. *Green Anal. Chem.* **2024**, *8*, 100095. [CrossRef]
22. Cole, M.; Lindeque, P.; Halsband, C.; Galloway, T.S. Microplastics as contaminants in the marine environment: A review. *Mar. Pollut. Bull.* **2011**, *62*, 2588–2597. [CrossRef] [PubMed]
23. Mansfiel, I.; Reynolds, S.J.; Lynch, I.; Matthews, T.J.; Sadler, J.P. Birds as bioindicators of plastic pollution in terrestrial and freshwater environments: A 30-year review. *Environ. Pollut.* **2024**, *348*, 123790. [CrossRef] [PubMed]

24. Ghannem, S.; Bacha, O.; Fkiri, S.; Kanzari, S.; Aydi, A.; Touaylia, S. Soil and Sediment Organisms as Bioindicators of Pollution. *Ecologies* **2024**, *5*, 679–696. [CrossRef]
25. Olmo-Gilabert, R.; Fagiano, V.; Alomar, C.; Rios-Fuster, B.; Compa, M.; Deudero, S. Plastic webs, the new food: Dynamics of microplastic in a Mediterranean food web, key species as pollution sources and receptors. *Sci. Total Environ.* **2024**, *918*, 170719. [CrossRef]
26. Sajedi, S.; An, C.; Chen, Z. Unveiling the hidden chronic health risks of nano–and microplastics in single-use plastic water bottles: A review. *J. Hazard. Mater.* **2025**, *495*, 138948. [CrossRef]
27. Shaikh, S.; Yaqoob, M.; Aggarwal, P. An overview of biodegradable packaging in food industry. *Curr. Res. Food Sci.* **2021**, *4*, 502–520. [CrossRef]
28. Otolá-González, C.M.; Álvarez-Castillo, E.; Flores, S.; Gerschenson, N.; Bengoechea, C. Effect of plasticizer composition on the properties of injection molded cassava starch-based bioplastics. *Food Packag. Shelf Life* **2023**, *40*, 101218. [CrossRef]
29. Jalalvandi, E.; Majid, R.A.; Ghanbari, T. Processing, Morphological, thermal and absortion Behavior of PLA/Thermoplastic Starch/ontmorillonite nanocomposites. *Int. J. Mater. Metall. Eng.* **2012**, *6*, 1128–1132.
30. Mohammed, A.A.B.A.; Hasan, Z.; Borhana-Omaran, A.A.; Elfaghi, A.M.; Khattak, M.A.; Ilyas, R.A.; Sapuan, S.M. Effect of Various Plasticiziers in Different Concentrations on Physical, Thermal, Mechanical and Structural Properties of Wheat Starch-Based Films. *Polymers* **2022**, *15*, 63. [CrossRef]
31. Mohomane, S.M.; Motaung, T.E. Effect of sugarcane bagasse, softwood, and cellulose on the mechanical, thermal and morphological properties of PP/PE Blend. *Appl. Sci.* **2024**, *14*, 2751. [CrossRef]
32. Delgado-Villaseñor, A.K.; Maldonado-Santoyo, M. Circularidad para los plásticos: Reciclado Post-Uso vs Fabricación de plásticos biodegradables. *Rev. Electrónica Divulg. Investig.* **2021**, *21*, 60–71.
33. Ashok, A.; Abhijith, R.; Rejeesh, C.J. Material characterization of starch derived bio degradable plastics and its mechanical property estimation. *Mater. Today Proc.* **2018**, *5*, 2163–2170. [CrossRef]
34. Santos-Ventura, E.M.; Escalante-Alvarez, M.E.; González-Nuñez, R.G.; Esquivel-Alfaro, M.; Sulbarán-Rangel, B. Polypropilene Composites Reinforced with Lignocellulose Nanocrystals of Corncob: Thermal and Mechanical Properties. *J. Compos. Sci.* **2024**, *8*, 125. [CrossRef]
35. Yu, J.; Xu, X.; Zhuang, Z.; Tan, J.; Huang, W.; Ou, R.; Liu, Z.; Liu, T.; Wang, Q. Double-bioplastic with superior water-resistance and flame retardancy. *Int. J. Biol. Macromol.* **2024**, *281*, 136139. [CrossRef] [PubMed]
36. Siddiqui, S.A.; Yang, X.; Desmukh, R.K.; Gaikward, K.K.; Bahimd, A.; Castro-Muñoz, R. Recent advances in reinforced bioplastics for food packaging—A critical review. *Int. J. Biol. Macromol.* **2024**, *263*, 130399. [CrossRef] [PubMed]
37. Glaser, S.J.; Faisal, M.; Blennow, A.; Leggio, L.L. Additives as external plasticizers in starch-based bioplastics-towards improving the properties of food packaging: A review. *Int. J. Biol. Macromol.* **2025**, *335*, 148754. [CrossRef]
38. Kowser, M.A.; Mahmud, H.; Chowdhury, M.A.; Hossain, N.; Mim, J.J.; Islam, S. Fabrication and characterization of corn starch based bioplastic for packaging applications. *Results Mater.* **2025**, *25*, 100662. [CrossRef]
39. Rajeswari, A.; Christy, J.S.; Swathi, E.; Pius, A. Fabrication of improved cellulose acetate-based biodegradable films for food packaging applications. *Environ. Chem. Ecotoxicol.* **2020**, *2*, 107–114. [CrossRef]
40. Khalid-Hossain, S.M.; Amin, M.R.; Kowser, M.A.; Chowdhury, M.A.C.; Hossain, N. Development and characterization of eco-friendly starch-based plastic reinforcing tea for packaging applications. *Curr. Res. Green Sustain. Chem.* **2023**, *7*, 100374. [CrossRef]
41. Józó, M.; Várdai, R.; Bartos, A.; Móczó, J.; Pukánszky, B. Preparation of Biocomposites with Natural Reinforcements: The Effect of Native Starch and Sugarcane Bagasse Fiber. *Molecules* **2022**, *27*, 6423. [CrossRef] [PubMed]
42. Chen, J.; Chen, X.; Guo, J.; Zhu, R.; Liu, M.; Kuang, X.; He, W.; Lu, Y. Agricultural, ecological, and social insights: Residual mulch film management capacity and policy recommendations based on evidence in Yunnan Province, China. *Sustainability* **2021**, *13*, 1603. [CrossRef]
43. Kong, U.; Rawi, N.F.M.; Tay, G.S. The potential Application of reinforced bioplastics in various industries: A review. *Polymers* **2023**, *15*, 2399. [CrossRef] [PubMed]
44. Gamage, A.; Thiviya, P.; Liyanapathiranage, A.; Wasana, M.L.D.; Jayakodi, Y.; Bandara, A.; Manamperi, A.; Dassanayake, R.S.; Evon, P.; Merah, O. Polysaccharide-Based Bioplastics: Eco-Friendly and sustainable solutions for packaging. *J. Compos. Sci.* **2024**, *8*, 413. [CrossRef]
45. Ali, S.S.; Abdelkarim, E.A.; Elsamahy, T.; Al-Tohamy, R.; Li, F.; Kornaros, M.; Zuorro, A.; Zhu, D.; Sun, J. Bioplastic production in terms of life cycle assessment: A state-of-the art review. *Environ. Sci. Ecotechnology* **2023**, *15*, 100254. [CrossRef]
46. Reid, E.V.; Samuelson, M.B.; Blanco-Canqui, H.; Drijiber, R.; Kadoma, I.; Wortman, S.E. Biodegradable and biobased mulch residues had limited impacts on soil properties but reduced yield of the following crop in a low fertility soil. *Renew. Agric. Food Syst.* **2022**, *37*, 490–503. [CrossRef]
47. Fredi, G.; Dorigato, A. Recycling of bioplastic waste: A review. *Adv. Ind. Eng. Polym. Res.* **2021**, *4*, 159–177. [CrossRef]

48. Mansoor, Z.; Tchuenbou-Magaia, F.; Kowalczuk, M.; Adamus, G.; Manning, G.; Parati, M.; Radecka, I.; Khan, H. Polymers use as mulch films in agriculture–A review of history, problems and current trend. *Polymers* **2022**, *14*, 62. [CrossRef]
49. Amusat, S.O.; Dube, S.; Mnyango, J.I.; Hlangothi, S.P.; Mbango, J.I.; Thulethu, S.; Mhlanga, S.; Tywabi-Ngeva, Z. Mulch Films in Agriculture. *Bioresour. Technol. Rep.* **2026**, *33*, 102525. [CrossRef]
50. Liu, X.; Wang, D.; Bazhabaike, M.; Zhou, M.; Yin, T. Biodegradable Film Mulching Increases Soil Respiration: A Two-Year Field Comparison with Polyethylene Film Mulching in a Semi-Arid Region of Northern China. *Agronomy* **2025**, *15*, 2631. [CrossRef]
51. Zhao, H.; Wang, X.; Jin, P.; Zhou, J.; Wang, Y.; Dong, W.; Ren, H.; Li, B.; Gong, W. Effects of Biodegradable Mulch Films with Different Thicknesses on the Quality. *Agronomy* **2025**, *15*, 2336. [CrossRef]
52. Sirivechphongkul, K.; Chiarasumran, N.; Saisriyoot, M.; Thanapimmetha, A.; Srinophakun, P.; Iamsaard, K.; Lin, Y.T. Agri-Biodegradable Mulch Films Derived from Lignin in Empty Fruit Bunches. *Catalysts* **2022**, *12*, 1150. [CrossRef]
53. Shah, F.; Shi, Z.; Xiong, L.; Li, Z.; Tao, Y.; Wang, P.; Wu, W. Biodegradable plastic film mulching for water conservation and pesticide reduction in rice-based cropping systems. *Crop Environ.* **2025**, *in press*. [CrossRef]
54. Obruca, S.; Koller, M.; Sedlacek, P.; Fritz, I.; Guziurova, P. Biodegradable polyesters in soil—Real environmental hazard or just a storm in a teacup? *Crit. Rev. Environ. Sci. Technol.* **2026**, *56*, 455–477. [CrossRef]
55. *ASTM D570*; Standard Test Method for Water Absorption of Plastics. ASTM International: West Conshohocken, PA, USA, 2010.
56. *ASTM-D638*; The Definitive Guide to Practice Plastic Tensile Testing. ASTM International: West Conshohocken, PA, USA, 1890.
57. Johnson, B.J.; Ribeiro, F.R.B.; Beckett, L. Application of growth technologies in enhancing food security and sustainability. *Anim. Front.* **2013**, *3*, 8–13. [CrossRef]
58. Navia-Porras, D.P.; Bejarano-Arana, N. Evaluación de propiedades físicas de bioplásticos termo-comprimidos elaborados con harina de yuca. *Biotecnol. Sect. Agropecu. Agroindustrial* **2014**, *12*, 40–48.
59. Enwere, C.F.; Okafor, I.S.; Adeleke, A.A.; Petrus, N.; Jakada, K.; Olosho, A.O.; Ikubanni, P.P.; Paramasivam, P.; Ayuba, S. Production of bioplastic film from wildcocoyam (*Caladium bicolor*) starch. *Results Eng.* **2024**, *24*, 103132. [CrossRef]
60. Mahmud, R.U.; Darda, M.A.; Hossain, M.T.; Habid, M.A.; Nag, R.K.; Sarker, M.P. Fabrication of waste cotton reinforced corn and potato starch sustainable bioplastics for eco-friendly packaging material. *Sustain. Chem. Environ.* **2025**, *11*, 100286. [CrossRef]
61. Schutz, F.G.; Goncalves, S.A.; Vercelino-Alves, R.M.; Vieira, R.P. A review of starch-based biocomposites reinforced with plant fiber. *Int. J. Biol. Macromol.* **2024**, *261*, 129916. [CrossRef]
62. Riaz, S.; Maan, A.A.; Butt, M.S.; Iqbal-Khan, M.K. Valorization of agricultural residues in the development of biodegradable active packaging films. *Ind. Crops Prod.* **2024**, *215*, 118587. [CrossRef]
63. Fitch-Vargas, P.R.; Camacho-Hernández, I.L.; Rodriguez-González, F.J.; Martínez-Bustos, F.; Calderón-Castro, A.; Zazueta-Morales, J.J.; Aguilar-Palazuelos, E. Effect of compoundin and plastic processing methods on the development of bioplastics based on acetylated starch reinforced with sugarcane bagasse cellulose fibers. *Ind. Crops Prod.* **2023**, *192*, 116084. [CrossRef]
64. Aguirre-Loredo, R.Y.; Velazquez, G.; Gutiérrez, M.C.; Castro-Rosas, J.; Ralgel-Vargas, E.; Gómez-Aldapa, C.A. Effect of airflow presence during the manufacturing of biodegradable films form polymers with different structural conformation. *Food Packag. Shelf Life* **2018**, *17*, 162–170. [CrossRef]
65. Cedeño-Sares, L.A.; Armijos-Cabrera, G.; Arias-Toro, D.; Bravo-Bravo, V.P. Efecto del Glicerol como plastificante en películas de almidón de maíz modificado. *J. Sci. Res.* **2023**, *8*, 189–204. [CrossRef]
66. Hernando, H.; Marpongahtun; Julianti, E.; Nuryawan, A.; Amaturrahim, S.A.; Rahman-Piliang, A.F.; Yanhar, M.R.; Goei, R.; Soykeabkaew, N.; Afdhal-Saputra, A.M.; et al. Impact of grycerol on oil palm trunk starch bioplastics enhanced with citric-acid epoxidized palm oil oligomers. *Case Stud. Chem. Environ. Eng.* **2024**, *10*, 100839. [CrossRef]
67. Menossi, M.; Cisneros, M.; Alvarez, V.A.; Casalongué, C. Current an emerging biodegradable mulch films based on polysaccharide bio-composites. A review. *Agron. Sustain. Dev.* **2021**, *41*, 53. [CrossRef]
68. Kovalk, A.; Machovsky, M.; Kozakova, Z.; Koller, M. Designing packaging materials with viscoelastic and gas barrier properties by optimized processing of poly(3-hydroxybutyrate-co-3-hydroxyvalerate) with lignin. *React. Funct. Polym.* **2015**, *94*, 25–34. [CrossRef]
69. Nasir, N.N.; Othman, S.A. The Physical and Mechanical Properties of Corn-Based Bioplastic Films with Different Starch and Glycerol Content. *J. Phys. Sci.* **2021**, *32*, 89–101. [CrossRef]
70. Harussani, M.M.; Sapuan, S.M.; Firdaus, A.H.M.; El-Badry, Y.A.; Hussein, E.E.; El-Bahy, Z.M. Determination of the tensile properties and biodegradability of cornstarch-based biopolymers plasticized with sorbitol and glycerol. *Polymers* **2021**, *13*, 3709. [CrossRef]
71. Francisco-Ponce, B.A.; Vidal-Silva, M.V.; Maldonado-Astudillo, Y.I.; Jiménez-Hernández, J.; Flores-Casamayor, V.; Aránmbula-Villa, G.; Salazar, R. Efecto de la adición de subproductos agroindustriales en las propiedades físicas de un bioplástico almidón-gelatina. *Rev. Cienc. Biológicas Salud* **2020**, *23*, 52–61.
72. Adnan, N.A.; Suhaimy, S.H.M.; Pauzan, M.A.B.; Fauzi, B. Effect of polyvinyl alcohol on cassava and portato starch plastic film: Mechanical, thermal and swelling properties. *Enhanc. Knowl. Sci. Technol.* **2023**, *3*, 460–471. [CrossRef]

73. Chowdhury, M.A.; Hossain, N.; Noman, T.I.; Hasan, A.; Shafiul, A.; Abdul, K.M. Biodegradable, physical and microbial analysis of tamarind seed starch infused eco-friendly bioplastics by different percentage of Arjuna powder. *Results Eng.* **2022**, *13*, 100387. [CrossRef]
74. Arias-Hernández, L.A.; Juaristi-Videgaray, E.; Mares-Martínez, H.E.; Solís-Silván, R.; Maldonado-Santoyo, M.; Calderón-Vega, F.; Valdés-Vázquez, J.F.; Delgadillo-Ruiz, E. Valoración de acolchados ecoplásticos utilizados para reducir la evaporación en suelos agrícolas. *Cienc. Nicolaita* **2024**, *91*, 1–9. [CrossRef]
75. Delgadillo-Ruiz, E.; Vázquez Rodríguez, G.; Tirado Torres, D.; Robles Buenrostro, M.F.; Pérez Gallegos, D.O.; Hernández Moreno, J.D.; Arias Hernández, L.A. Efecto de la implementación de acolchados en los componentes del balance hídrico superficial. *Jóvenes Cienc.* **2022**, *16*, 1–9. Available online: https://www.jovenesenlaciencia.ugto.mx/index.php/jovenesenlaciencia/article/view/3837 (accessed on 5 January 2026).
76. Delgadillo-Ruiz, E.; Castorena-Padilla, C.; Peña-Vázquez, F.; Exiga-Soria, A.R.; Ramírez-Siorda, G.Y.; Arias-Hernández, L.A.; Delgadillo-Ruiz, L. Clasificación de acolchados y su implementación en la retención de humedad del suelo. *Jóvenes Cienc.* **2022**, *6*, 1–9. Available online: https://www.jovenesenlaciencia.ugto.mx/index.php/jovenesenlaciencia/article/view/3838 (accessed on 5 January 2026).
77. Iñiguez-Covarrubias, G.; Díaz-Teres, R.; Sanjuan-Dueñas, R.; Anzaldo-Hernández, J.; Rowell, R.M. Utilization of by-products from the tequila industry. Part 2: Potential value of *Agave tequilana* Weber *azul* leaves. *Bioresour. Technol.* **2001**, *77*, 101–108. [CrossRef]
78. Kasirajan, S.; Ngouajio, M. Polyethylene and biodegradable mulches for agricultural applications: A review. *Agron. Sustain. Dev.* **2012**, *32*, 501–529. [CrossRef]
79. Delgadillo-Ruiz, E.; Arias-Hernández, L.A.; Bañuelos-Valenzuela, R.; Delgadillo-Ruiz, L.; Berumen-Cervantes, A.; Maldonado-Santoyo, M. Mejora del rendimiento de cultivos agrícolas utilizando acolchados. In *Compendio de Revisiones en Ciencias Veterinarias, Agroforestales, Pesqueras y Áreas Afines*, 1st ed.; Martínez-González, S., Ávila-Ramos, F., De la Cruz-Moreno, C.O., Eds.; Abanico Académico: Tepic, México, 2025; pp. 1–609.


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