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Experimental Characterization of a Starch-Based Bioplastic Reinforced with Coffee Processing Residues

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Abstract*– Coffee-industrial residues have gained attention as reinforcement materials in biodegradable polymers due to their availability and environmental compatibility. In coffee-producing regions, large quantities of pulp and husk are generated during wet processing, representing a potential raw material for bioplastic production. This study evaluates a starch-based bioplastic reinforced with coffee residues through experimental variation of mixture composition. Twenty-five samples were prepared using coffee pulp and husk, glycerin, cornstarch, sodium alginate, and water, maintaining a total mass of 50 g per treatment. The material was characterized through density, tensile resistance, opacity, and biodegradability tests under natural environmental exposure. The best formulation reached a resistance of 2072 Pa (≈4 lb), density values comparable to conventional plastic, and more than 50% degradation after 19 days. Results indicate that increasing fiber content improves rigidity but reduces flexibility, while higher glycerin content increases flexibility and accelerates degradation. Although the material does not yet match the mechanical strength of conventional plastics, its behavior is consistent with low-load biodegradable applications such as disposable packaging. The study demonstrates the technical feasibility of valorizing coffee processing residues as reinforcement in biodegradable polymer matrices.

***Keywords*-- Bioplastic, Coffee residues, Starch-based composites, Biodegradability, Agro-industrial waste.**

I. INTRODUCTION (HEADING 1)

Over the years, increasing awareness has emerged regarding the impact of human production systems on natural resources and ecosystems. Conventional plastics, widely used due to their low cost and durability, have generated significant environmental concerns due to their persistence and inadequate disposal. These issues have promoted the development of biodegradable materials as sustainable alternatives, particularly in countries where agro-industrial residues are abundant [1].

In coffee-producing countries such as Honduras, coffee processing generates large quantities of organic waste including pulp and husk that are frequently discarded without controlled treatment. These residues contain lignocellulosic compounds and natural fibers capable of interacting with polymeric matrices and modifying the mechanical and degradation behavior of biodegradable materials [2] [3].

Therefore, this study investigates the development of a bioplastic based on coffee residues obtained in Honduras and evaluates its physical and biodegradable properties through controlled variation of mixture compositions. The objective of this research is to experimentally analyze mechanical resistance, density, opacity, and degradation behavior in order to determine the influence of formulation parameters on material performance and assess its technical feasibility as an environmentally friendly material alternative aligned with Sustainable Development Goal 12: Responsible Production and Consumption.

II. BACKGROUND

The coffee fruit is a berry composed of several layers. The outer exocarp or skin covers the mesocarp or pulp, followed by a mucilage layer rich in pectins and sugars, and finally the endocarp or parchment that surrounds the seed. Inside this structure are natural fibers and organic compounds that form lignocellulosic material [2] [3].

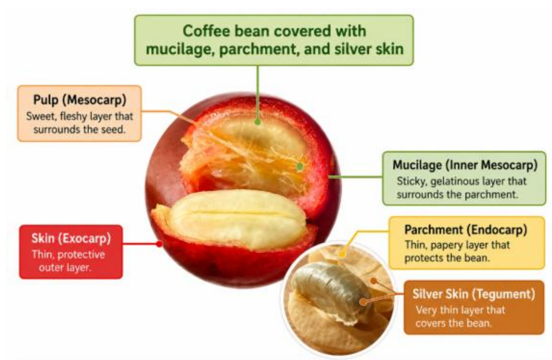

Fig. 1 Anatomical structure of the coffee fruit showing exocarp, mesocarp (pulp and mucilage), endocarp (parchment), and silverskin covering the bean.

Western Western Honduras is strongly associated with coffee production, which generates large quantities of organic residues during the wet processing of the fruit. During the depulping stage, the pulp and husk are separated from the seed and commonly discarded in surrounding environments, producing contamination problems but also representing a potential raw material due to its organic composition [1] .

These components can interact with polymeric matrices and modify mechanical resistance, density, and degradation behavior when incorporated into biodegradable materials.

In this context, a bioplastic is a polymeric material derived partially or entirely from renewable biological sources and capable of degrading under natural conditions through biological activity (Fernández-Cortés et al., 2020). Starch-based bioplastics are widely studied due to their availability and low cost; however, their mechanical performance depends on formulation and reinforcement materials.

Because coffee processing residues contain natural fibers and organic compounds, they can be incorporated into biodegradable polymer mixtures as reinforcement or filler material [3]. Therefore, experimental evaluation of their physical and degradation properties is necessary to determine their potential use as an alternative material.

Fig. 2 Coffee processing stages illustrating dry and wet processing routes and the generation of pulp and husk residues used as raw material..

II METHODOLOGY

The objective of the experimental development was the recovery of coffee residues, specifically pulp and husk obtained after the wet processing stage. The material was collected, dried, and prepared prior to the mixture process.

The bioplastic was produced using the following components:

- Coffee residues (pulp and husk)
- Glycerin
- Water
- Sodium alginate
- Cornstarch

For better use of resources and time, each treatment was prepared with a total composition of 50 g distributed among all components. Preliminary pilot tests were carried out to determine workable proportions, since early mixtures prepared with equal proportions produced a dry and doughy material that could not be converted into bioplastic.

After defining feasible ranges, different combinations of the components were generated and analyzed using Stat Ease 360 to study the treatments that best satisfied the research objective. A total of 25 experimental samples were produced and dried at room conditions.

The experimental variables considered were:

Independent variables

- Proportion of coffee residues and components in the mixture

Dependent variables

- Physical properties (resistance, density, transparency/opacity)
- Biodegradability behavior

After drying, each sample was subjected to physical tests to evaluate the material performance compared with conventional plastic. The density of the mixtures was obtained by measuring mass and occupied volume of each sample and comparing it with a plastic bag of similar dimensions. A progressive load was applied to each sample until fracture occurred. Stress was calculated using the applied force and the total area:

$$\sigma = \frac{F}{A}$$

The mixtures that supported the highest loads were identified and compared to conventional plastic behavior. The thickness of each sample was measured and its opacity was evaluated as a possible property for packaging applications such as protection from light or content concealment.

The biodegradability test was performed under natural environmental exposure. Samples were placed outdoors and observed for 19 days, recording changes in structure, cracking, fragmentation and softening. It was observed that exposure to water accelerated degradation, while sunlight caused hardening and brittleness. Decomposition percentage was estimated according to the loss of structural integrity of the material.

The results obtained from the 25 treatments were analyzed to determine how mixture composition affects: Resistance capacity, Density behavior, Opacity characteristics and Degradation rate. the purpose was to evaluate whether the material properties approach conventional plastic behavior and determine its possible application.

III. RESULTS AND ANALYSIS

Collection of all supplies and materials necessary for the development of the experiment. 80Lb of coffee husk and pulp were purchased (much more material than necessary in case of contingencies). In addition to this, all the necessary materials are mentioned above. It is worth mentioning that the pulp and husk of the coffee were obtained in a dry way and processed by Vía Húmeda. It is worth mentioning that many of the materials were provided or are equipment from the University. Avoid combining SI and CGS units, such as current in amperes and magnetic field in oersteds. This often leads to confusion because equations do not balance dimensionally. If you must use mixed units, clearly state the units for each quantity that you use in an equation. Prepare everything is the space to use, reserve a laboratory at the university if necessary. Prepare each of the treatments since these will be carried out at the same time for each test.

Fig. 3. Preliminary preparation steps including residue conditioning, laboratory setup, and proportioning prior to bioplastic processing.

Once there is a series of justified data on the possible combinations and proportions of the factors, with the help of Stat Ease 360, an analysis can be carried out on which treatments can be studied to meet our research objectives. The factors in this case are coffee residues, glycerin, sodium alginate, water, and cornstarch.

Fig. 4. Experimental workflow showing mixture composition analysis, computational treatment design, and preparation of bioplastic samples.

Once the results of the treatments were obtained, the next step was to proceed with the physical testing phase. It is important to note that if any of the physical tests could not be completed, they may be considered for future application on the same bioplastic formulation. Some of these tests were conducted in the university laboratory facilities, while others were performed in certified external laboratories to ensure reliability of the results.

For data entry in *Stat-Ease 360*, a preliminary study was conducted to define the appropriate proportions of the mixture components for each treatment. to optimize resources and time, each formulation was standardized to a total mass of 50 g, distributed among all components.

Previous studies suggested a 1/5 ratio for each component with variations of up to 15%. However, during the initial pilot tests, this proportional approach was found to be unsuitable. The main issue observed was that the resulting mixture exhibited excessive dryness and a dough-like consistency, which significantly limited its processability into a bioplastic material.

To address this limitation, four pilot tests were performed using different ingredient compositions. This stage of the research followed a trial-and-error methodology to identify feasible formulations. Based on the outcomes of these preliminary tests, a more suitable reference formulation for bioplastic production was established. Subsequently, an experimental design was developed considering different combinations of components. Using *Stat-Ease 360*, the data were input to ensure approximately 30% variation among components across the different treatment

Table 1.
Composition of bioplastic mixtures showing the proportions of coffee, cornstarch, glycerin, sodium alginate, and water for each treatment.

Run	Coffee (g)	Maize Starch (g)	Glycerin (g)	Sodium Alginate (g)	Water (mL)
1	1.3	0.9	2.6	3.4	41.7
2	2.0	1.0	4.9	4.0	38.0
3	1.0	1.4	2.6	2.3	42.8
4	1.4	1.4	4.3	3.7	39.3
5	1.7	1.1	3.6	2.3	41.3
6	1.0	0.7	3.6	2.3	42.5
7	2.0	0.9	4.4	3.5	39.2
8	1.0	0.7	4.0	3.6	40.8
9	1.8	1.1	5.4	4.7	37.0
10	1.3	0.9	2.6	3.4	41.7
11	2.0	1.4	5.4	2.3	39.0
12	1.6	0.7	5.4	2.3	40.7
13	2.0	1.4	2.6	4.7	39.3
14	1.7	1.1	3.6	2.3	41.3
15	2.0	1.4	3.7	4.7	38.2
16	1.4	1.4	4.3	3.7	39.3
17	2.0	1.2	2.9	3.6	40.3
18	1.7	0.7	3.2	4.7	39.7
19	2.0	0.7	2.6	2.3	42.5
20	1.0	1.2	5.4	2.4	40.0
21	2.0	0.9	4.4	3.5	39.2
22	1.0	1.2	3.3	4.7	39.8
23	1.0	0.7	4.8	2.3	41.3
24	1.0	0.7	5.4	4.1	38.8
25	1.7	0.7	3.2	4.7	39.7

The results of the Density of the Mixtures showed variability, the composition of the mixtures greatly influences the density since we can see the graph maintains an oscillation that gradually goes upwards. With these results, it can be concluded that, despite the mixtures and their preparation process, there is not much variability in density, even though the preparation of the mixtures was carried out with a 30% variability in ingredient composition, since most mixes range between 0.1 and 0.44.

Something that stood out from this part of the experimentation is that the density of the bioplastic mixtures is a bit high compared to a particular plastic bag. The density of a plastic bag with approximately the same circumference as the average of the mixtures resulted in 0.15 g/cm³. The minimum value among the results of the mixtures is 0.1212 g/cm³ and the highest value is 0.5100 g/cm³. The mean of these treatments is 0.2620 g/cm³.

Based on Minitab's experimentation and data analysis, the data shows that the bioplastic tested is very heavy compared to conventional plastic. But in terms of density, it is quite similar, which is an advantage. Therefore, bioplastics have a greater mass that occupies approximately the same volume as conventional plastic.

a. Biodegradability Test

In summary, after an analysis of each one of the tests, it is concluded that during a nineteen-day process, more than 50% of the composition of each one of the mixtures is decomposed, leaving a small percentage less than half that is practically useless.

The observations that could be observed is that the bioplastic with the sun is toasted and becomes hard or toasted while it can break easily. On the other hand, with exposure to water, the mixtures degrade much faster and become viscous while they merge with the leaves, sand, or others that are around them.

Table 2.
Density measurements of the bioplastic samples obtained from mass displacement method and corresponding volume calculations.

Run	Net Weight (g)	Water (mL)	Water Added (mL)	Volume of the Piece (cm³)	Density (g/cm³)
1	10.9	400	445	45	0.2725
2	13.1	400	455	55	0.262
3	4	400	425	25	0.2
4	10.3	400	490	90	0.1211
5	7.4	400	450	50	0.1644
6	6.6	400	445	45	0.165
7	9.9	400	465	65	0.165
8	8.2	400	440	40	0.2342
9	13.2	400	475	75	0.1885
10	7.2	400	445	45	0.18
11	10.4	400	440	40	0.2971
12	9.4	400	440	40	0.2685
13	13.7	400	455	55	0.274
14	8.2	400	440	40	0.2342
15	11.2	400	455	55	0.224
16	9.3	400	425	25	0.465
17	7.2	400	445	45	0.18
18	8.2	400	435	35	0.2733
19	6.3	400	430	30	0.252
20	8.6	400	425	25	0.43
21	9.7	400	430	30	0.388
22	9.9	400	430	30	0.396
23	7.8	400	425	25	0.39
24	11.3	400	435	35	0.3766
25	10.2	400	425	25	0.51

During rainy days, it was when they cracked faster and began to decompose. Another observation is that thanks to the coffee husk, the samples chipped or cracked much faster, since right where there were suddenly larger pieces of husk, they began to crack faster.

b. Axial Force Test

It can be clearly seen that this was one of the tests with the highest variation indices. There is no stability within the control lines. All the results were quite different. It means that the composition of the mixture greatly influences the resistance indices.

The stress results indicate that the best tests or mixtures were the following:2, 4, 15, 16, 17, 18, 22, 23, and 25 since they are the ones that support the greatest weight, with mix #17 being the one that supports a much greater weight of 2072Pa, equivalent to approximately 4Lb. Conventional plastic supports almost 6 Lb. with the same average measurements as bioplastic; therefore, bioplastic still requires a formula that results in a support capacity equal to or greater than conventional plastic.

The Opacity test is more of an aesthetic feature, however, the fact that the color is brown and has an opacity index is something that can be taken advantage of, for plastic. example its uses are to hide the content within it, protection of the content against UV light (since certain foods, medicines or chemical products often require it), or merely aesthetic purposes.

The samples showed stable statistical behavior, with an average thickness of 1.35 mm and values ranging from 0.72 to 3.38 mm. Compared to conventional transparent plastic (9% opacity and 0.026 mm thickness), the bioplastic presented higher opacity (58%) and greater thickness (1.35 mm), indicating a less transparent and more robust material. The results indicate that mixture composition significantly affects mechanical performance and degradation behavior. Samples with higher coffee residue content presented increased brittleness and faster degradation due to the lignocellulosic structure of the material, while higher glycerin content improved flexibility but reduced resistance. Although the material does not yet match the load capacity of conventional plastic, its density and biodegradation characteristics suggest potential application in low-load biodegradable products such as disposable packaging.

Table 3.
Axial load test parameters including thickness, applied force, and cross-sectional area used to calculate tensile stress of the bioplastic samples.

Test	Thickness(cm)	Applied Force (N)	Total Area (m^2)	Stress (Pa)	Stress (k)
1	0.2	6.67	0.0086	775.8214	0.7758
2	0.28	9.81	0.0097	1007.8003	1.0078
3	0.09	3.53	0.0103	343.471	0.3435
4	0.34	15.05	0.0146	1032.7988	1.0328
5	0.09	7.94	0.0181	438.5005	0.4385
6	0.08	5.39	0.0137	394.8457	0.3948
7	0.07	3.92	0.0186	211.2803	0.2113
8	0.09	11.67	0.0193	604.309	0.6043
9	0.15	13.19	0.0168	783.3569	0.7834
10	0.13	8.73	0.015	581.4148	0.5814
11	0.09	3.53	0.0241	146.4982	0.1465
12	0.08	2.94	0.0249	118.285	0.1183
13	0.14	14.71	0.0175	842.797	0.8428
14	0.09	6.67	0.0179	371.6657	0.3717
15	0.1	19.61	0.0145	1355.709	1.3557
16	0.09	15.49	0.0151	1028.828	1.0288
17	0.11	19.61	0.0095	2072.2385	2.0722
18	0.14	19.61	0.0131	1496.0223	1.496
19	0.08	19.61	0.0193	1017.065	1.0171
20	0.11	8.04	0.0174	463.1392	0.4631
21	0.16	9.71	0.0105	927.9809	0.928
22	0.16	19.61	0.0112	1744.5054	1.7445
23	0.13	19.61	0.0177	1106.0497	1.106
24	0.15	10.1	0.0117	860.4578	0.8605
25	0.23	19.61	0.0102	1913.8877	1.9139

IV. Discussion

The obtained results confirm that the mechanical behavior of the material is strongly influenced by the proportion of natural fibers and plasticizer within the matrix. Similar behavior has been reported in starch-based biocomposites reinforced with lignocellulosic residues, where the addition of fibers increases stiffness but also introduces brittleness due to heterogeneous bonding between phases. Studies on natural-fiber composites indicate that cellulose particles act as rigid inclusions that improve structural stability but reduce elongation capacity when the plasticizer content is insufficient [4],[5],[6]. Additionally, coffee-based biocomposites have shown that resistance depends primarily on residue proportion rather than polymeric binder content, explaining the variability observed among treatments [7]. This behavior is consistent with the known difficulty of predicting effective properties in bio-composites due to heterogeneous microstructure and weak interfacial adhesion [8].

Regarding degradation, the rapid decomposition observed under humidity conditions is consistent with the hydrophilic nature of starch matrices and organic residues. Previous studies have reported that coffee processing by-products accelerate microbial activity and water absorption, promoting fragmentation and mass loss in biodegradable materials [3][1]. Plasticizers such as glycerin improve flexibility but also increase water diffusion, which explains the faster degradation of flexible samples compared to rigid ones [9]. Therefore, the material produced in this study does not yet match the mechanical capacity of conventional plastics but behaves similarly to low-load biodegradable packaging materials reported in other agro-residue composites [10][11] [12], suggesting potential applications in disposable or short-life products.

V. Conclusion

The experimental evaluation demonstrates that coffee processing residues can be incorporated into biodegradable polymer mixtures to obtain a functional material with measurable mechanical and degradation properties.

It was possible to produce bioplastic samples and subject them to different physical tests, where the material supported approximately 4 lb before fracture, showed density values close to conventional plastic, and reached more than 50% decomposition after 19 days under natural conditions. Although the resistance is still lower than conventional plastic, the results confirm that the formulation and mixture composition directly influence the behavior of the material and that the characteristics can be improved through further adjustments.

Therefore, coffee-based bioplastic represents a feasible alternative for low-load applications and constitutes a starting point for future research focused on optimizing formulation parameters and improving mechanical performance while maintaining biodegradability.

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