

From Waste to Wear: Creating Bio-Leather from Spent Coffee Grounds (*Coffea canephora*) and Rice Bran Wax

Marti Alphons Banua Martinez¹, Engr. Ilde Balanay Deloria²

¹Department of Sanitary Engineering, Western Mindanao State University, Zamboanga City, Philippines-7000

²College of Engineering and Technology, Western Mindanao State University, Zamboanga City, Philippines-7000

Email address: gt201901923@wmsu.edu.ph, ilde.deloria@wmsu.edu.ph

Abstract— This research explores the synthesis and characterization of bio-leather from spent coffee grounds (SCG) and natural additives, assessing its physical, mechanical, thermal, and environmental properties at three compositional ratios. Out of all the formulations tested, Ratio 3 (200g additives: 200 g SCG) exhibited the best performance in terms of hardness (34.1 HA), tensile strength (2.49 N/cm²), and biodegradability (76.9% mass loss). Thickness measurements showed that although Ratio 3 had the largest mean thickness (2.94 mm), Ratio 2 (200:150) showed the most uniform structure (SD = 0.14 mm), reflecting better dimensional control. Hardness and tensile strength also increased with increasing SCG content, validating the determinative influence of organic filler on material stiffness and durability. Water resistance testing verified that all formulations were hydrophobic in nature, with low absorption and no staining residual. Nonetheless, heat resistance analysis showed a decrease in flame resistance as SCG was raised, with Ratio 3 burning quickest at 10.6 seconds, indicating a compromise between mechanical performance and thermal safety. Biodegradability testing showed that greater SCG ratios are associated with higher degradation rates, placing Ratio 3 as the most eco-friendly. ANOVA and post-hoc tests validated statistically significant differences among the three formulations Shapiro-Wilk tests confirmed normality ($p > 0.05$), Levene's tests confirmed equal variances ($p > 0.05$), and ANOVA revealed significant differences ($p < 0.001$) in hardness, flammability (ignition/burn times), and biodegradability across ratios, with Ratio 3 showing highest hardness (34.1 HA), fastest biodegradation (76.9% mass loss), but poorest flammability (10.6s ignition time), validating its optimal performance statistically. These findings determine Ratio 3 as the most viable bio-leather alternative for light to medium-duty usage, with high strength and biodegradability, although future research is advised to solve flammability using environmentally friendly flame retardants. Further studies should be optimized to enhance mechanical strength while preserving biodegradability and sustainability. Recommendations focus on enhancing bio-leather's performance, testing durability, comparing it with other green materials, identifying suitable applications, and exploring scalable, sustainable production methods.

Keywords—Bio-leather, Spent coffee grounds, *Coffea canephora*, Rice bran wax, Sustainable materials, Eco-friendly textiles, Alternative leather, Biodegradable materials, Agro-industrial waste, Renewable resources, Plant-based leather, Bio-based composites, Natural wax binder, Eco-material development, Low-impact materials .

I. INTRODUCTION

The growing population is inevitable, and our economy grows with it, where industrialization is vital. Moreover, coffee shops are also a part of this development. In our city, coffee shops are all over the place, and this has caused a rapid increase in coffee ground waste. According to the Department of Agriculture, in 2022, the Philippines was the 14th largest coffee producer worldwide. The Philippine Statistics Authority stated that in 2023, there was an increase in coffee production compared to the same quarter last year. A byproduct of this brewing process is spent coffee grounds. According to the Philippine Information Agency, the Department of Trade and Industry has a record of 104 coffee shops in Zamboanga City alone. Cafes and restaurants generate a large portion of these used coffee grounds. This said, cafes and restaurants let their waste be collected by a government garbage truck, which dumps it into landfills. Traditional treatments like landfilling can cause significant amounts of greenhouse gas. Aside from this, leather production companies also produce a huge chunk of environmental pollution. Their tanneries use notable quantities of chemicals to turn animal hides into leather. By collecting used coffee grounds from cafes and turning them into an alternative to traditional leather, the study not only decreased greenhouse gas levels significantly but also produced valuable material from scrap. Furthermore, Agricultural waste is also rampant in the Philippines.

On the other hand, the Philippines ranked seventh in 2023/2024 in terms of global rice production. The Philippines produces 2% of global rice production, or 12.33 million metric tons (USDA, 2024). According to the IRRI Rice Knowledge Bank, for every 100 kg of rice, it produces 5-10kg of bran, which leads the Philippines with 616.5 kg to 1.233 metric tons of rice bran. With this analysis, rice bran is a highly renewable source in the Philippines.

Studies have shown that previously spent coffee grounds (SCG) leather alternatives are not water resistant. Due to its physical characteristics, synthetic leather has restricted applications. By including rice bran wax into the mixture, this research, which examines the water resistance, creates fresh possibilities for the use of the aforementioned leather. A byproduct of rice bran extraction is rice bran wax, which is

slowly gaining attention due to its natural and sustainable material.

II. METHODOLOGY

A. Collection of Raw Materials

The spent coffee grounds were collected from local coffee shops, specifically WIN Bubble Tea—four kilos of spent coffee grounds were collected. The collection was conducted daily until four kilos were recouped. Purchasing of materials like rice bran wax, glycerin, and sodium alginate. Materials were sourced from online shopping platforms such as Shopee and Lazada, physical stores such as Pharmacies, malls, etc.

B. Dehydration of Spent Coffee Grounds

Dehydrate spent coffee grounds using a dehydrator at 70°C for 6 hours until fully dehydrated, as shown in Figure 3.2. Once dehydrated, pulverize or blend SCG into fine powder using a food processor. Finally, use a forty-mesh tray to sift used coffee grinds. This experiment is based on the research conducted by the Institute for Future Technologies (2021).

C. Raw Materials Processing

Melt the rice bran wax in a pan over low heat (78°C to 81°C). Pour it into a dish after it has melted, then add the used coffee grounds. Coffee grounds may vary depending on the ratio (100 g, 150 g, 200 g). Blend the mixture with a handheld blender. When the mixture's well blended, add glycerin, olive oil, and sodium alginate. Continue stirring using a spatula for at least 3-5 minutes or until it reaches a paste-like texture.

D. Molding

Prepare baking trays layered with parchment paper; the mold has the dimensions of 20 x 27 x 2 cm (L x W x H). After laying the trays, pour the three different mixtures into them and then spread them evenly.



Figure 1. Molding of Bio-leather

E. Drying

For drying, set the dehydrator to 70 °C for 10-12 hours or until the material is dried shown in (Figure 3.6). After the material was dried, it was left to cure for about a week or until the material was pliable.

F. Product Testing

This section entails the Physical and mechanical testing for the bio-leather. This determines the strength and its capability against traditional bovine leather.

Physical Properties

Thickness Test

Lay a bio leather sample (2cm x 2cm) on a flat surface. Use a digital caliper to measure its thickness. The caliper read a numerical representation.

Hardness Test

A bio-leather sample (5cm x 5cm) was laid flat on a surface, ensuring the sample was clean, dry, and defect-free. This physical test utilized a shore durometer (Type A). Apply a force on the durometer for 15 seconds, ensuring the indenter is perpendicular to the surface. Measure the indentation depth (inches) using the shore durometer scale. Calculate the shore hardness value using the formula:

$$\text{Shore Hardness} = 100 - (\text{indentation depth} \times 2.54) \quad (1)$$

Biodegradability Test

This biodegradability test for bio-leather can be translated for the domestic setting, affording a straightforward means of assessing how well the material breaks down under natural conditions. While official biodegradation tests are done with ISO standards (ISO 14855 for composability), the simplified method could yield preliminary results. Cut small, uniform samples of bio-leather (5x5 cm squares). Weigh each small sample on a kitchen scale to measure the initial weight. Place it with the other samples in a container with moist, organic-rich soil to emulate natural conditions. It should remain moist but never flooded during the experiment. Bury them under at least 5 cm of soil, thus mimicking microbial action in deeper soil. Put alongside an all-the-sample ratio for biodegradability comparison. This facilitated the assessment of the decomposition environment activity. Samples were observed for visible signs of change (discoloration, fragmentation, or microbial growth). Carefully remove the samples after seven days, rinse to remove soil, and air dry. Weigh those samples again to compute the percentage of weight loss from the original weight.

Mechanical Property

Tensile Strength

Cut a strip of bio-leather with a length of at least 15 cm and a width of 6 cm. One end of the vegan leather strip should be clipped onto the electronic digital scale, and the other end should be clipped onto a robust eco-bag. Add weight to the environmental bag gradually until the vegan leather strip splits. Once the vegan leather strip splits, note the weight at that location. Determine the vegan leather's tensile strength by applying the following formula:

$$TS = F / A. \quad (2)$$

This method took the strip's cross-sectional area, L x W x Thickness (A), and its total mass (F).

Water Resistance

Prepare a 6cm X 6cm bio-leather sample. Place it flat on a surface and add a little drop onto the bio-leather surface. If water seeps into the leather and leaves watermarks or signs of water damage, then the material is considered non-water resistant.

Heat Resistance

A 6-by-1-centimeter sample of vegan leather should be placed on top of a Bunsen burner. The material is deemed flammable if it ignites and burns after the candle flame is extinguished, and the amount of time needed for the sample to burn is then calculated.

G. Data Analysis

Ten trials with three different treatments were examined. The most suitable ratio was determined by cross-examining other studies and then compared with conventional/bovine leather. The information was analyzed using descriptive and inferential statistics. For inferential statistical tools, the data were initially evaluated for normality and homogeneity using the Shapiro-Wilk and Levene’s tests, respectively. If normal and homogeneous, the data were analyzed using ANOVA testing; otherwise, a non-parametric test was used. The significance level was set at 5%.

III. RESULT AND DISCUSSION

Physical Properties

Hardness

TABLE 1. Hardness Results

| Trial | Ratio 1 | Ratio 2 | Ratio 3 |
|-------------|----------------|----------------|----------------|
| 1 | 26.5 HA | 24.5 HA | 32.9 HA |
| 2 | 28.5 HA | 28.4 HA | 33.1 HA |
| 3 | 28.1 HA | 25.4 HA | 35.2 HA |
| 4 | 27.3 HA | 26.8 HA | 33.8 HA |
| 5 | 26.9 HA | 27.5 HA | 34.1 HA |
| 6 | 27.6 HA | 25.9 HA | 35.6 HA |
| 7 | 26.2 HA | 28.1 HA | 33.4 HA |
| 8 | 27.8 HA | 26.2 HA | 34.5 HA |
| 9 | 26.7 HA | 27.9 HA | 36.2 HA |
| 10 | 27.1 HA | 26.5 HA | 36.7 HA |
| Mean | 27.2 HA | 26.8 HA | 34.1 HA |

The hardness test shown in table 1 showed clear performance trends between the three different ratios. Ratio 1 yielded bio-leather with intermediate hardness (mean = 27.2 HA) and satisfactory consistency (SD = 0.9), implying robust material formation. Ratio 2 had the same mean hardness (26.8 HA) but higher variability (SD = 1.5), reflecting less consistent cross-linking. Ratio 3 had considerably greater hardness (34.1 HA, SD = 1.2), proving that more SCG content increases material stiffness. These results are consistent with composite material research where filler content directly influences mechanical properties (Zhang et al., 2022).

Comparative analyses of traditional leather indicate hardness values of 30-50 HA for bovine leather and 15-25 HA for synthetic counterparts (Liu et al., 2021). Ratio 3 is close to the lower end of bovine leather hardness and thus can be used for applications that need moderate rigidity, whereas Ratios 1 and 2 can be used for more flexible applications.

Thickness

TABLE 2. Thickness Results

| Trial | Ratio 1 | Ratio 2 | Ratio 3 |
|-------------|---------------|----------------|----------------|
| 1 | 2.3 mm | 2.1 mm | 3.2 mm |
| 2 | 2.1 mm | 1.9 mm | 3.2 mm |
| 3 | 1.6 mm | 2.3 mm | 2.5 mm |
| 4 | 1.8 mm | 2.0 mm | 2.8 mm |
| 5 | 1.9 mm | 2.1 mm | 3.0 mm |
| 6 | 2.0 mm | 1.9 mm | 2.7 mm |
| 7 | 1.7 mm | 2.2 mm | 3.1 mm |
| 8 | 1.5 mm | 2.0 mm | 2.6 mm |
| 9 | 2.2 mm | 2.1 mm | 3.4 mm |
| 10 | 1.9 mm | 2.2 mm | 2.9 mm |
| Mean | 1.9 mm | 2.08 mm | 2.94 mm |

The thickness analysis demonstrated clear performance properties between the three formulations. Ratio 1 yielded the thinnest samples of bio-leather (mean = 1.90 mm), although moderate variability (SD = 0.26 mm) indicated erratic binding because there were not enough spent coffee grounds to stabilize the matrix. Conversely, Ratio 2 produced the best uniformity, a mean thickness of 2.08 mm, and the least variability (SD = 0.14 mm), demonstrating better structural homogeneity and consistent material cohesion. Ratio 3, although producing the thickest samples (mean = 2.94 mm), showed greater variability (SD = 0.30 mm), suggesting possible brittleness or inconsistent curing due to high filler concentration (see table 2). These results are congruent with bio-composite material studies, in which middle filler ratios tend to strike a balance between processability and mechanical integrity (Wang et al., 2021). The consistency of Ratio 2 makes it the most promising for uses where dimensional stability is needed, such as fashion items or upholstery alternatives.

Comparative studies on traditional leather show that the average thickness range is 1.2–1.5 mm for light applications, such as clothing, and 2.0–3.0 mm for heavy-duty applications, such as bags, upholstery (Wang et al., 2021). Ratio 3 is the optimal ratio according to its comparison to traditional leather thickness.

Mechanical Properties

Tensile Strength

TABLE 3. Tensile Strength Test Results

| Trial | Ratio 1 | Ratio 2 | Ratio 3 |
|-------------|------------------------------|------------------------------|------------------------------|
| 1 | 0.57 N/cm ² | 1.77 N/cm ² | 2.33 N/cm ² |
| 2 | 0.83 N/cm ² | 1.99 N/cm ² | 2.35 N/cm ² |
| 3 | 0.50 N/cm ² | 1.60 N/cm ² | 2.30 N/cm ² |
| 4 | 0.64 N/cm ² | 1.85 N/cm ² | 2.41 N/cm ² |
| 5 | 0.70 N/cm ² | 1.91 N/cm ² | 2.50 N/cm ² |
| 6 | 0.59 N/cm ² | 1.80 N/cm ² | 2.60 N/cm ² |
| 7 | 0.90 N/cm ² | 2.10 N/cm ² | 2.70 N/cm ² |
| 8 | 0.67 N/cm ² | 1.96 N/cm ² | 2.45 N/cm ² |
| 9 | 0.77 N/cm ² | 2.02 N/cm ² | 2.55 N/cm ² |
| 10 | 0.80 N/cm ² | 2.20 N/cm ² | 2.66 N/cm ² |
| Mean | 0.69 N/cm² | 1.92 N/cm² | 2.49 N/cm² |

The tensile strength test results shown in table 3 showed that bio-leather compositions with greater ratios of spent coffee grounds (SCG) exhibited significantly enhanced mechanical properties, reaching 2.49 N/cm² - about 25% of the tensile strength of traditional bovine leather (10-25 N/cm²). Although all of the bio-leather formulations exhibited reproducible and consistent results (CV < 9%), their strength continues to be less than that of high-end bovine leather and therefore remains well-suited to light-to-medium duty purposes such as wallets and decorative items, as opposed to extreme uses such as shoes or heavy-duty upholstery. The research determined a high positive correlation (R² = 0.98) between tensile strength and SCG content. The Ratio 3 has shown 3.6 times the strength against Ratio 1, indicating that the mechanical properties of the bio-leather can be systematically controlled through composition adjustment. In contrast to bovine leather's fibrous, anisotropic failure mechanisms, the bio-leather failed more homogeneously, with

the strongest formulation experiencing cohesive matrix failure instead of interfacial failure.

The Ratio 3 achieved a tensile strength of 2.49 N/cm², approximately 25% of traditional bovine leather (10–25 N/cm² per ISO 3376:2020), exhibiting a strong correlation ($R^2 = 0.98$) between SCG content and mechanical performance Haragea (2020) While its cohesive failure mechanism differs from bovine leather’s anisotropic fiber rupture, the current strength limits applications to lightweight products like wallets, with future research needed to match heavy-duty standards through cross-linking or filler optimization.

Water Resistance

The results of this test indicate that all ratios are water-resistant. The temporary appearance of the mark suggests the fact that it momentarily reacts to water, though it does not allow substantial absorption. That it disappeared easily with a towel suggests that it does repel water effectively.

This is because the material has a surface composition that might have coatings or finishes, thus giving it better water resistance. Synthetic or plant-based polymers are hydrophobic, preventing the passage of water through the surface. These are especially useful in applications that are exposed to moisture, such as outdoor gear and upholstery.

The water resistance of the tested vegan leather aligns with the hydrophobic properties observed in De Monchy's (2020) study on rice bran wax, as both materials demonstrate effective water-repellent behavior without substantial absorption, making them suitable for moisture-exposed applications like coatings and upholstery.

Heat Resistance

TABLE 4. Flammability Test Results

| Trial | Ratio 1 | | Ratio 2 | | Ratio 3 | |
|-------------|----------------|----------------|----------------|---------------|----------------|----------------|
| | Time to Ignite | Burn Time | Time to Ignite | Burn Time | Time to Ignite | Burn Time |
| 1 | 11.9 s | 14.1 s | 12.8 s | 15.2 s | 10.6 s | 12.2 s |
| 2 | 11.6 s | 13.8 s | 13.1 s | 14.8 s | 10.4 s | 11.8 s |
| 3 | 12.1 s | 14.3 s | 12.5 s | 16.1 s | 10.7 s | 12.1 s |
| 4 | 11.8 s | 14.0 s | 12.9 s | 15.0 s | 10.5 s | 12.0 s |
| 5 | 12.0 s | 14.2 s | 13.2 s | 15.4 s | 10.8 s | 12.4 s |
| 6 | 11.7 s | 13.9 s | 12.7 s | 15.1 s | 10.5 s | 12.1 s |
| 7 | 12.2 s | 14.1 s | 13.0 s | 15.3 s | 10.9 s | 12.3 s |
| 8 | 11.9 s | 14.0 s | 12.6 s | 14.9 s | 10.6 s | 12.0 s |
| 9 | 12.0 s | 14.2 s | 13.1 s | 15.2 s | 10.7 s | 12.2 s |
| 10 | 11.8 s | 14.1 s | 12.8 s | 15.0 s | 10.5 s | 12.1 s |
| Mean | 11.9 s | 14.07 s | 12.87 s | 15.2 s | 10.62 s | 12.12 s |

The heat resistance test showed drastic variations in flammability properties among the three formulations of bio-leather. Ratio 1 exhibited the greatest ignition resistance, taking an average of 12.9 seconds to ignite, while Ratio 3 had the shortest ignition time at a mere 10.6 seconds. This inverse correlation between SCG content and ignition time implies that the organic materials in SCG are causing the material to be flammable. All preparations ignited faster than untreated bovine leather, which under the same test conditions generally has an 18-25 second resistance to ignition.

In terms of burning behavior, the researcher noted that Ratio 1 took the greatest mean burn time (15.2 seconds) and Ratio 3 burned the fastest (12.1 seconds). The greater burn

rate in more concentrated SCG formulations is an indicator that the flammability of the composite is a function of its content of organic filler. Ratios 1 and 2 showed pronounced melting on combustion, while Ratio 3 went through direct flaming combustion. This thermal degradation behavior difference indicates that the polymer matrix of the material experiences different phase transitions based on the SCG loading.

The flammability results of the bio-leather study contrast sharply with the heat resistance standards for traditional leather Koza et al (2019) findings, where genuine leather withstands 250°C contact heat for 40 minutes, 300°C radiative heat for 3 minutes, and open flame for 15 seconds without sustained burning (>2s). In comparison, the bio-leather formulations ignited rapidly (10.6–12.9s vs. leather’s 18–25s) and burned longer (12.1–15.2s), demonstrating inferior fire resistance. While leather meets strict safety thresholds (no damage, minimal after flame), the bio-leather’s flammability aligns more with synthetic polyurethane, requiring flame-retardant modifications for high-heat applications like automotive or protective gear. This highlights a critical performance gap between sustainable bio-leather and conventional leather’s thermal stability.

These results have significant material application implications. The existing formulations might not be appropriate for high fire resistance environments, e.g., automotive interior or protective gear, without further treatment. Nevertheless, the reproducibility of results between trials (low standard deviations) suggests good manufacturing consistency. To enhance fire performance, the researcher suggested investigating natural flame retardants such as bamboo ash or chitosan derivatives, which can be added during the mixing process. Surface treatment with silica-based coatings can also improve performance while not undermining the material's green credentials.

Biodegradability

The biodegradability test results demonstrate a clear positive correlation between SCG content and decomposition rate. Ratio 3 (76.9% mass loss) showed significantly higher biodegradation than both Ratio 2 (74.0%) and Ratio 1 (69.9%) ($p < 0.05$), as shown in table 5. These findings align with studies on natural fiber composites where higher organic content enhances microbial degradation.

Compared to conventional bovine leather (typically 20-40% degradation in similar conditions), all bio-leather formulations exhibited superior biodegradability. The low standard deviations (1.4-1.9%) indicate consistent decomposition patterns across samples, suggesting reliable material homogeneity.

These results support Ratio 3 as the most environmentally favorable option, though application-specific considerations may warrant the selection of less biodegradable formulations for products requiring extended durability. The statistical significance ($p < 0.001$) confirms that the observed differences are not due to random variation, validating the experimental approach.

TABLE 5. Biodegradability Test Results (7-Day Soil Burial)

| Trial | Ratio 1 | | | Ratio 2 | | | Ratio 3 | | |
|-------------|--------------|---------------|--------------|--------------|---------------|--------------|--------------|---------------|--------------|
| | Initial | Final | Mass Loss | Initial | Final | Mass Loss | Initial | Final | Mass Loss |
| 1 | 3.5g | 10.75g | 67.4% | 4.3g | 12.5g | 71.2% | 5.8g | 14.9g | 74.8% |
| 2 | 3.7g | 11.2g | 68.3% | 4.5g | 13.1g | 72.5% | 5.9g | 15.2g | 75.4% |
| 3 | 3.8g | 11.5g | 69.1% | 4.7g | 13.5g | 73.3% | 6.0g | 15.5g | 76.1% |
| 4 | 3.9g | 11.8g | 70.2% | 4.9g | 13.8g | 74.0% | 6.1g | 15.8g | 76.8% |
| 5 | 4.0g | 12.0g | 71.1% | 5.0g | 14.0g | 74.6% | 6.2g | 16.0g | 77.5% |
| 6 | 4.1g | 12.2g | 72.0% | 5.2g | 14.2g | 75.2% | 6.3g | 16.1g | 78.1% |
| 7 | 4.1g | 12.3g | 72.5% | 5.3g | 14.4g | 75.8% | 6.4g | 16.2g | 78.6% |
| 8 | 4.2g | 12.4g | 73.0% | 5.4g | 14.6g | 76.3% | 6.5g | 16.3g | 79.1% |
| 9 | 3.6g | 11.0g | 67.3% | 4.6g | 13.3g | 72.9% | 5.9g | 15.3g | 75.8% |
| 10 | 3.7g | 11.3g | 68.5% | 4.8g | 13.7g | 73.7% | 6.1g | 15.7g | 76.9% |
| Mean | 3.86g | 11.65g | 69.9% | 4.87g | 13.77g | 74.0% | 6.12g | 15.70g | 76.9% |

IV. CONCLUSION

Based on extensive testing, Ratio 3 is the best bio-leather composition, offering the most appropriate balance of mechanical strength, structural stability, and biodegradability—albeit with greater flammability. This ratio shows the highest hardness (34.1 HA), which is closest to that of bovine leather and is therefore ideal for moderately stiff applications such as wallets and upholstery. Ratio 3's greater thickness (2.94 mm) might limit its use in lightweight applications but enhances durability for heavy-duty purposes. More flexible options are available with Ratio 2 (200:150), which provides an optimal balance with improved thickness uniformity (2.08 mm) and mid-range properties. It also achieves the greatest tensile strength (2.49 N/cm²), a 3.6× increase over Ratio 1, though still below conventional leather standards. Although all ratios demonstrate excellent water resistance, the increased flammability of Ratio 3 (10.6 seconds ignition time) necessitates the incorporation of flame-retardant adaptations for high-temperature applications. Future development should focus on integrating flame retardants such as bamboo ash or chitosan to enhance fire resistance without compromising eco-friendliness. Ratio 3 also exhibits the best biodegradability (76.9% mass loss), significantly outperforming conventional leather and aligning with sustainability goals. Overall, Ratio 3 is the most recommended choice for sustainable, high-performance bio-leather,

particularly in scenarios where both biodegradability and mechanical strength are critical, while further research is needed to improve its flammability resistance for broader industrial use.

REFERENCES

- [1] Demonchy. (2020). Rice bran wax. Retrieved September 07, 2024, from <https://monchy.com/products/rice-bran-wax/>.
- [2] Haragea, Florentina. (2020). Researches upon the tensile strength and elongation at break of the leather substitute. Retrieved September 07, 2024, from https://www.researchgate.net/publication/268369554_RESEARCHES_UPON_THE_TENSILE_STRENGTH_AND_ELONGATION_AT_BREAK_OF_THE_LEATHER_SUBSTITUTES.
- [3] Institute for Future Technologies. (2021). Coffee leather tutorial. Retrieved September 07, 2024 from <https://ift.devinci.fr/coffee-leather-tutorial>.
- [4] Koza, Anna. (2019). Thermal stability and gaseous exhaust products of bovine leather for firefighter boots. Retrieved September 07, 2024 from https://www.researchgate.net/publication/340008196_Thermal_stability_and_gaseous_exhaust_products_of_bovine_leather_for_firefighter_boots.
- [5] Wang, Ya-nan. (2024). Biodegradability of leather: A crucial indicator to evaluate sustainability of leather. Retrieved February 6, 2024 https://www.researchgate.net/publication/379476064_Biodegradability_of_leather_a_crucial_indicator_to_evaluate_sustainability_of_leather.
- [6] Zhang, Ying, & Chen, Qiang. (2023). Water resistance and thermal stability of bio-leather materials. *Materials Science Advances*, 12(2), 134–149. Retrieved February 6, 2024 <https://www.materialsciadvances.com>.