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Unlocking the Potential of Tropical Fruit Waste to Develop a Biobased Material: An Environment-Friendly Approach

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ABSTRACT
For the sustainable fashion manifesto, biobased material is a novel creation that is made from leftovers and growing biological cells. As the need to develop sustainable biomaterials is on the rise many researchers have focused their studies on microbes and other biological organisms such as plants to offer cleaner, greener processes and entirely new products. The majority of leather items are produced from the skins of cows and calves, that are killed for their flesh. Bio-based materials with Tropical fruit waste were developed using Bacterial Cellulose (Gluconacetobacter) and leftover peels and rinds of mango, papaya and jackfruit. For the production of Bacterial Cellulose (BC), the use of agricultural leftovers can be a cheap and sustainable method. The basic physical tests show that matrices with BC have higher physical and abrasion resistance compared to the other samples. The research indicates that the presence of BC in the matrix increases the biobased material's strength and elongation twofold. The manufacturing processes are using up the natural resource and cause negative environmental effects, this can be reduced by using waste as raw materials. This study has opened new ways of creating biomaterials without using up resources and meeting consumers' sustainability concerns.

KEYWORDS
tropical fruit, waste, bio-based materials, bacterial cellulose, sustainability

INTRODUCTION

From ancient times, leather production has been a practised art that utilises both skilled and unskilled labour across all unit operations. It creates a vast variety of finished goods, including footwear, bags, clothing, wallets, and other items used every day. The tanning process is essential to the leather business, and the majority of tanneries worldwide (about 90%) employ chromium salts to improve the flexibility, water resistance, and shrinkage temperature of leather. Regretfully, skins do not entirely fix chromium salts; the remaining amount, which is around 30% of the original amount, is left in the discarded tanning fluid [1] and elevated levels of Cr(VI) have been linked to teratogenic, mutagenic, and carcinogenic effects in humans, variety of aquatic plants, animals, and bacterial species [2]. Although animal skin is no longer needed, millions of furry animals have their skin taken every year to make collars for coats, furry parts of hat tips, furry parts of bags and shoes, and even toys, key chains, and decorative items. Skins from crocodiles, snakes, ostrich and fish are frequently used to make purses, shoes, jewellery for the fashion industry, automotive upholstery, and other items [3]. The market for leather goods was valued at USD 245 billion in 2022, and it is projected to increase significantly at a compound annual growth rate (CAGR) of over 9.5% from 2023 to 2032 due to the growing demand for luxury leather clothing [4].

The leather business is increasingly the target of activists and campaigns concerned with environmental, animal welfare, and human health risks [5,6]. Due to societal concerns, the leather sector is experiencing new manufacturing and consumption patterns. The circular economy proposes a shift away from the existing economic model and towards one that is more sustainable. Biobased materials are composed of whole or partial parts of biological products (reusable agricultural materials) and these are promising materials in the fashion business as these can be grown using food waste and bacterial cellulose. Today, unique materials are gaining inspiration and popularity in various disciplines due to their low to zero waste production process. The typical solvent-based synthetic leather is incapable of avoiding organic solvent contamination, and the resulting items may pose chemical dangers to users [7,8]. The leather industry employs over 130 different types of chemicals like synthetic and natural re-tanning agents, synthetic and natural oils, surfactants, dyes, chemical auxiliaries [9-12].

The use of leather or synthetic leather is neither ethical nor environmentally sound. Finding leather alternatives could help to reduce the environmental impact. Many innovative businesses are introducing new leather-like materials with mushrooms, pineapples, and potato peel, which offers a more sustainable future for fashion. Indeed, much research on the use of agro-wastes for BC production has been conducted in recent years; The BC membrane is used in many fields, including wastewater treatment, biotechnology, pharmaceuticals, biomedical sciences, cosmetics sector, paper, bio-based packaging, and the food industry [13]. In a study done by Machado et al., Komagataeibacter rhaeticus, a bacterium isolated from Kombucha tea, was used to produce bacterial cellulose (BC) through its cultivation in a static sugarcane molasses (SCM) supplemented-culture medium (totally or partially), as an alternative carbon source [14]. Researchers used pineapple leftovers for their experiments in Indonesia. The authors report that 128,000 tonnes of pineapple peel trash were produced annually by Indonesian pineapple growers. A different way to recycle pineapple peel waste is to use it as a culture medium for the production of bacterial cellulose (BC). Pineapple peels are rich in carbohydrates like sucrose, fructose, and glucose that are helpful for the manufacture of cellulose, as well as a notably high concentration of important elements like nitrogen. BC made with pineapple peel waste juice as a culture medium will be less expensive for large-scale industrial manufacturing and have qualities comparable to BC made with standard culture medium (HS) [15].

Vegan leather or artificial leather is environmentally friendly and animal-free, it is an alternative that can be developed by using plant-based materials or enzymes. Mango is the most popular tropical fruit, with an annual production record of 30 million tonnes generated by three major countries namely India, China, and Thailand. Other popular tropical fruits include pineapple, papaya, and jackfruit [16]. These fruits have a substantial amount of waste as rinds and peels i.e. Mango flesh 60 - 75%, skin 11 - 18%, seed 14 - 22% [16], Jackfruit flesh 30 - 35%, rind 55 - 62% and seed 8 - 10% [17] and Papaya flesh 80 - 90%, skin 10 - 20% and seed 15 - 22% [18,19]. The disposal of this waste without proper treatment can be a suitable breeding ground for bacteria and causes greenhouse gas emissions [20]. Disposal of tropical fruit waste can be difficult because segregation is important. Hence, the investigator has found a method to utilize this discarded fruit waste to develop a bio-based material that causes zero animal cruelty and is 100% sustainable. The main objectives of the study are (1) to find and utilize low-value substrates (2) to develop a biobased material and (3) evaluation of the developed material.

In addition, the feasibility of the process was verified by testing the physical properties, abrasion resistance and air permeability test.

EXPERIMENTAL PROCEDURE

Materials and Methods

Tropical fruit wastes such as Mango, Jackfruit and papaya were collected from local vendors in and around Coimbatore, Tamil Nadu. These were cleaned and ground to make a smooth paste and stored in the refrigerator. Bacteria-derived cellulose is possibly the strongest and purest form of cellulose compared to plant cellulose [21]. Raw SCOBY (Symbiotic culture of bacteria and yeast) was purchased from Natural Superfoods LLP, India. The SCOBY was placed in a dark area for 15 days, forming Bacterial Cellulose (BC) membranes that were harvested and washed with distilled water and stored at 4 °C for further usage. The harvested BC along with fruit waste pulp was dried in a hot air oven for five hours and a total of four combinations were prepared for the experiment as mentioned in Table 1.

Table 1. Material combinations

Samples	Components and weight percentage of each composition (w/w%)			
	Tropical Fruit waste	BC	PVA	Glycerol
S1	80	-	-	20
S2	70	-	15	15
S3	50	25	15	10
S4	40	40	10	10

Note: PVA = Poly Vinyl Alcohol

Among these four material combinations (Table 1) polymer matrix BC and PVA were not added for S1 and it was found that the sample lacks strength and flexibility. In subjective evaluation, compared to S1, S2 had greater strength and flexibility. Sample S3 and S4 had BC in the polymer matrix which has been a factor for more strength than the S2 sample and good elongation. Hence S2 and S3 samples were selected for further evaluation.

Material Testing Procedure

The material testing procedures were selected based on the comfort properties of wearers like basic properties, mechanical properties and abrasion resistance. Properties of each material were analysed separately and based on the testing procedure it was cut into desired size and shape. The three properties to be tested were examined three times.

Basic Properties

Weight (GSM), Thickness (mm) and Stiffness (cm) were tested to find the basic physical properties of the material. Grams per square meter are the important product quality in the field of textile fabrics. The weight of the fabric was calculated using Fabric GSM means the weight of one square meter of fabric in grams. The circular pressing plates' surfaces are kept parallel to one another. The samples are examined at a particular pressure using ASTM D1777-96 standards. The fabric stiffness tester uses simple calculations and techniques to determine a fabric's bending height, flexural stiffness, and bending modulus, using the ASTM D1388 method the material was cut 25 mm wide and 200 mm long.

Mechanical properties

The breaking force (N) and elongation (%) of each specimen of size 300 x 150 x 3 mm were determined by averaging the obtained values using tensile-testing equipment (Zwick Roell- Z010), following ASTM D-5034 which determines the maximum force necessary to break a material. The test speed was set to 5 mm/min.

Abrasion Resistance

Abrasion testing is the process of rubbing a material at a certain weight and speed to ascertain when the material starts to wear. The specimen is secured to the platform, and the specimen is rubbed by a specific abrasion substance under a defined amount of pressure and friction. The material was cut into 50 x 200 mm size.

Morphological Analysis

Fe-SEM was used to observe the morphology of bio-based materials. The morphological analysis was carried out using Zeiss Fe-SEM Sigma VP 03-04 model equipment.

Swelling Index

The swell index test procedure is used to determine the general swelling characteristics of any material. From each biobased material sample, a circular test specimen with an approximate diameter of 22 mm was cut out. Using a thickness measurement gauge, thickness was determined for all the samples prepared. The material was kept to swell in distilled water at 25 °C for 24 hours to ensure the attainment of equilibrium swelling state. Thereafter, as the swelled samples reached the equilibrium state, were allowed to deswell for further 24 hours in open air [22].

RESULTS AND DISCUSSION

To fabricate a biobased leather material that could be an alternative to conventional leather, we examined its basic and mechanical properties. The results on the following are discussed under the following subheadings:

Basic Properties: Thickness, Weight and Stiffness

The thickness of the bio-based materials readings was taken at five randomly chosen spots using a thickness gauge. Each fabric sample's thickness in mm was estimated using the arithmetic mean of these readings. Among the four sample combinations S3 sample has having higher thickness which may be due to the presence of bacterial cellulose. As depicted in Table 2, the weight and stiffness of the S1 sample is the least and S3 is the most. Higher stiffness value best suits accessories like armour, and handbags and increases durability.

Table 2. Basic physical properties

Samples	Weight (GSM)	Thickness (mm)	Stiffness (cm)
S1	13.02	0.89	4.87
S2	13.51	1.22	5.34
S3	17.05	2.35	6.06
S4	15.45	2.01	5.92

It is also worth noting that the four different combinations of bio-based material had different surface morphologies when visually examined. The matrix S3 had an undulating surface.

Tensile strength and elongation

The tensile test was performed at 5mm/min with a 10 KN load cell. The specimens were prepared according to ASTM D-3039. The results of the tensile test using 25% BC and 15% PVA showed better tensile strength and elongation in comparison with S2 material. Tropical fruit waste filler with BC and PVA matrix had a higher elongation percentage (25.4%) than Tropical Fruit waste and PVA material. Tear resistance is one of the important mechanical parameters for evaluating the resistance of biobased material against tearing and the S3 matrix has 32.6 N Tear strength which shows double the strength of S2. Hence it could be concluded that the S3 sample could be used for making fashion accessories which will be exposed to higher stress and tear.

Table 3. Tensile strength and Elongation

Samples	Tensile strength (MPa)	Elongation (%)	Tear strength (N)
S2	29.1	14.8	16.2
S3	62.5	25.4	32.6

Abrasion Resistance

For abrasion resistance, the sample material is fixed on a platform and a specified abrasion material rubs the sample under specified time, pressure and speed. After each cycle, the weight of the biobased material is noted. Sample S2 was torn at 1st cycle last session at 50 rpm. Sample S3 had very good abrasion resistance even in the 2nd cycle of 100 rpm there were no abrasion or very minute abrasions (Table 4). The superior abrasion performance of BC could render it useful in clothing for protection [23].

Table 4. Abrasion sample appearance at the end of the test

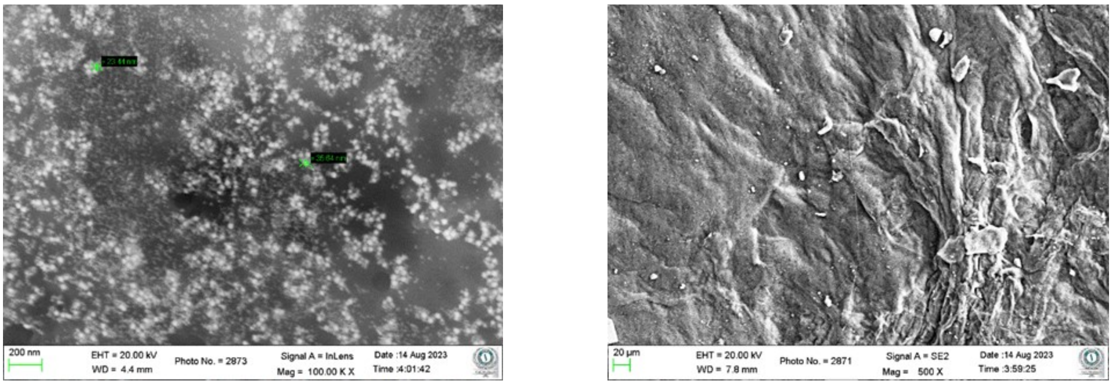
Sample	Initial weight (gms)	1st cycle 50 rpm			2nd cycle 100 rpm		
		50	50	50	100	100	100
		15.19	15.06	14.90	14.72	14.29	
S2	15.25						

Sample	Initial weight	1st cycle 50 rpm			2nd cycle 100 rpm		
	(gms)	50	50	50	100	100	100
S3*	23.0	22.98	22.80	22.71	22.7	22.7	22.69
							

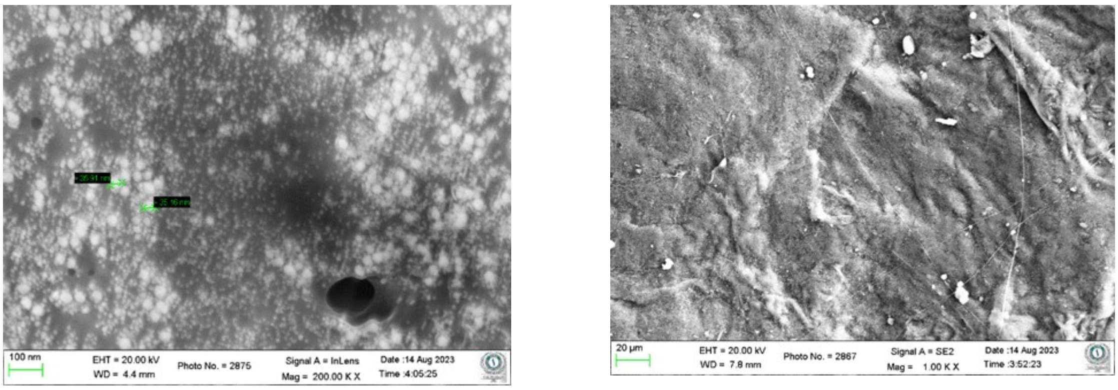
*No failure, specimen still intact – test abandoned. BC: bacterial cellulose

Morphological Analysis

The surface morphology of the three-dimensional network structure of bio-based material is shown in Figure 1. The images present a good adhesion interaction between the blended materials and particulates of the different mixture components. Notably, persistent adhesion and strong mechanical qualities need homogenous dispersion of all components in a particular matrix [24]. Additionally, all examined biocomposites polymeric matrix exhibited voids and pores in the results. The cross-section area of bio-based material S2 shows a more disordered structure than S3. Higher voids or pores can be seen in S3 (35.91 nm) with more free space to absorb water.



a)



b)

Figure 1. Fe-SEM images of the surface layer of Bio-based material a) Sample S2; b) Sample S3

Swelling Index

As leather is essentially a fibrous collagen material, its swelling characteristics are determined by many variables, including the sample's hydrophobicity and hydrophilicity, crosslink density, crosslink type and stability, pH, temperature, void space extent, fibre-filler interactions, and so on [25]. The following equation [26] is used to calculate the equilibrium swelling or swelling index of leather samples:

$$\text{Swelling index }(\%) = \frac{W_f - W_0}{W_0} \times 100 \tag{1}$$

Where W_f and W_0 are the weights of bio-based material samples before and after swelling. The swelling index of S2 and S3 materials were measured at a specific time i.e. at 30, 60, 120, 240, 360 and 1440 minutes and the percentage swelling is depicted in Figure 3. From the figure, it is clear that the swelling index is high for S3 bio-based material due to the presence of bacterial cellulose and after 120 minutes the swelling is gradually reduced or at 120 minutes the material has reached an equilibrium swelling rate. Regarding S2 material the swelling index is more or less the same weight at each measured time.

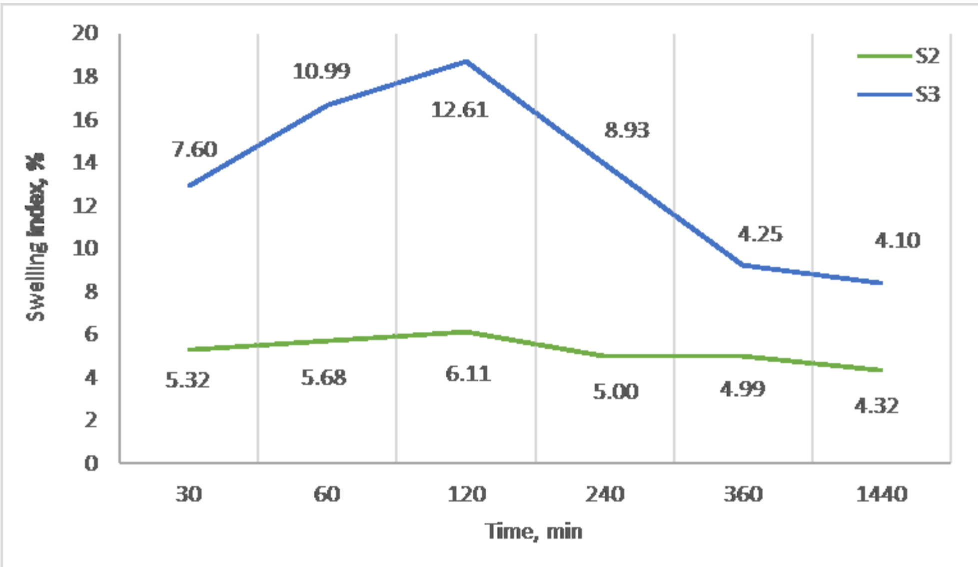


Figure 2. Swelling index of bio-based materials

Implementing Sustainable Engineering Principles in Bio-based Material Development

In this study of developing biobased leather material, we applied Paul Anastas and Julie Zimmerman's [27], engineering principles which outline what would make a greener chemical process or product. Green engineering is the development, commercialization, and application of procedures and goods that reduce pollution, advance sustainability, and safeguard public health without compromising their capacity to be profitable and effective.

According to the “Cradle to Cradle” design concept by Bill McDonough [28], designers must select substances or products composed of substances whose characteristics won't harm people or the environment throughout their life cycle. All of the initially used materials in this study are non-hazardous and throughout the process, this principle is followed. Here, waste products are getting a second life by using it in the development of bio-based materials. After use these can be composted or biodegradable causing zero threat to the environment.

Table 5. Green engineering principles implemented in this research [27]

Principles	Aspects of biobased leather material
Principle 1: Designers need to *ensure that all materials,* energy inputs, and outputs are *non-hazardous*	Non-hazardous materials such as BC and tropical fruit waste are the main materials used in the study
Principle 2: Preventing waste altogether is preferable to treating or cleaning up waste after it has already been created	The investigators have used waste as raw material for this study. The end product is biodegradable also
Principle 4: Maximising the efficiency of mass, energy, space, and time should be a goal while designing new products, procedures, and systems	The simple and logical path has been employed in making the bio-based material
Principle *7*: Not immortality, but targeted durability should be a design objective.	Abrasion resistance and tear strength exhibit the strength of the material developed. Hence it serves the required durability
Principle *8*: Meet Need, Minimize Excess	The materials developed will be used for specific end uses and no surplus produced
Principle *11*: Systems, processes, and products should be planned to function in a commercial "afterlife."	If end-of-life issues are not taken into account, there could be tonnes of materials in landfills or being destroyed in unsafe situations.
Principle *12*: *Renewable rather than depleting*	All of the materials employed in this study are renewable and no virgin raw materials are used

CONCLUSION

This study investigated the use of low-value substrates such as tropical fruit waste in the development of biobased material using BC in the matrix. The study first determined the optimum methods of fabrication of bio-based material using tropical fruit waste and BC. To our knowledge, this is the first study which incorporates waste with BC for the development of biomaterial which finds applications in textiles and apparel. BC is commonly described in the apparel industry as “vegetable leather”, compared to its plant equivalent, it is said to have many "enhanced" qualities, including high tensile strength, high water retention, extreme insolubility to solvents, the ability to be moulded into shape and high degrees of polymerization and high crystallinity. The use of waste as raw materials saves money in production thereby creating an increased profit and the bio-based material after its end use goes back to the soil where it becomes a part of the biological metabolism. The physical test results show that the tensile strength of biobased material with BC in the matrix has almost double the strength and more elongation percentage compared to the S2 sample. The Fe-SEM analysis of the biobased material exhibits voids and pores in the surface; the S3 sample has good to high abrasion resistance compared to the S2 sample material and the swelling index percentage is more of S3 material with BC in matrix. Hence from the study, it is clear that the mechanical properties are better for S3 Biobased material with BC in matrix.

The biomaterial developed is pliable in its original form and hence finds applications in a variety of accessories. It is not sturdy for use in hard composite materials like shoe soles. This is a limitation of this study and provides opportunities for future research. Future research can also find appropriate product designs and applications of the bio-based material. The investigator aims to enhance the material properties by applying various finishing techniques.

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