https://doi.org/10.1051/e3sconf/202669002003

Fabrication of Eco-Friendly Pineapple Leaf Fiber-Based Vegan Leather for Environmental Sustainability

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Abstract. The environmental impact of synthetic leather production has raised global concerns due to its reliance on petroleum-based polymers and poor biodegradability. Therefore, the development of sustainable, eco-friendly alternatives using renewable resources has become increasingly important. A biodegradable vegan leather was developed from natural rubber and pineapple leaf fibers (PALF), with properties analyzed using Response Surface Methodology (RSM). The effects of fiber content (X1), compression time (X2), and compression temperature (X3) were studied on biodegradation (Y1), water absorption (Y2), and tensile strength (Y3). Results showed that all three factors significantly influenced Y1, with the predictive model demonstrating high reliability ($R > 90\%$). The optimum condition for Y1 was $X1 = 3.0$ g, $X2 = 70.0$ min, and $X3 = 110.0$ °C, yielding a maximum predicted biodegradation of about 21%. In contrast, the models for Y2 and Y3 were statistically unreliable ($P > 0.05$) due to low R^2 values. However, Y2 passed the lack-of-fit test, suggesting an adequate model form, while Y3 failed ($P < 0.05$), indicating an inadequate prediction model. These findings suggest future experiments should narrow factor ranges and include additional control variables to improve the predictability of Y2 and Y3. Despite these limitations, the study highlights a sustainable alternative to conventional synthetic leather, aligning with circular economy principles and supporting the United Nations Sustainable Development Goals (SDGs). Importantly, the process is resource-efficient: from 1 kg of pineapple leaves, only 20 g of fibers is obtained, and just 75 g of PALF was used in 15 experimental runs. This minimal material requirement underscores the potential of the approach for sustainable production, while highlighting potential applications in sustainable fashion, packaging, and eco-friendly product design.

Keywords: Vegan leather, Natural rubber, Pineapple leaf fiber, Response surface methodology, Circle Economy and SDGs

1 INTRODUCTION

The 2030 Agenda for Sustainable Development, announced by the United Nations in 2015, established 17 Sustainable Development Goals (SDGs) to address critical global challenges, including poverty, inequality, injustice, and climate change.

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Among these, SDG 12 emphasizes responsible consumption and production, promoting a transition from a linear economic model to a circular economy. The valorization of agricultural wastes and by- products presents significant opportunities for sustainable development by converting residues into valuable products, offering both ecological and socio-economic benefits. In this context, the bioeconomy refers to the recycling and valorization of renewable agro-industrial waste into novel products, such as animal feed, food, chemicals, energy, and bio-based materials, whereas the circular economy aims to close the loop of production and consumption [1]. In the food industry, large quantities of by-products can serve as renewable resources when processed using green technologies. For instance, fish farming a rapidly growing sector, utilizes only 30-40% of the fish as food, leaving 60-70% as by-products. One valorization approach is upcycling fish skin into leather [2]. The increasing industrial demand for animal leather in the fashion industry has driven research into alternative materials, such as vegan or artificial leather, produced from natural or synthetic sources. These materials mimic the appearance of animal leather without using animal skins. While the leather industry has expanded over recent decades, the associated environmental impacts have also grown due to greenhouse gas (GHG) emissions primarily originating from animal-based feedstock. Developing bio-based materials, containing at least one biologically produced and fully biodegradable component, is a promising strategy to reduce environmental impacts [3]. Ethical awareness among consumers has led to growing interest in vegan materials, driven by concerns for animal welfare, environmental sustainability, and ethical production practices [4]

Agriculture plays a significant role globally, with approximately 25% of senior executives involved in agriculture and land management. An example, as illustrated in the Fig.1, can be seen in the pineapple cultivation areas of Prachuap Khiri Khan Province, Thailand. Thailand, as one of the world largest agricultural producers, is a key hub for tropical crop production. Pineapple is widely cultivated in tropical and subtropical regions, including Thailand, Malaysia, and the Philippines. According to the Food and Agriculture Organization (FAO), global pineapple production reached over 28.18 million tons in 2018 and has continued to grow over the past decade. Processed pineapple products such as canned pineapple, juice, and juice concentrate constitute major exports, with Thailand ranked as the largest exporter of canned pineapple in 2018. Recent FAO data indicate that global pineapple exports are projected to grow by approximately 4% in 2023 [5]. Despite economic benefits, intensive pineapple cultivation generates large volumes of agricultural waste, including leaves, crowns, peels, and cores. Much of this waste is discarded or openly burned, contributing to greenhouse gas emissions and air pollution, particularly PM2.5, which adversely affects environmental quality and public health. Therefore, responsible agricultural waste management and the development of value-added products from pineapple residues are urgently needed. Utilizing pineapple leaf fibers (PALF) and other by-products for innovative applications such as textiles, bio-composites, and vegan leather can reduce environmental impacts, lower disposal costs, generate additional income for farmers, and support the transition toward a sustainable circular economy [6-7].

However, previous studies on bio-based leather alternatives have primarily focused on either synthetic polymers or single-source natural fibers, often overlooking the synergistic potential of combining natural rubber with agricultural residues such as PALF. Moreover, few studies have systematically optimized processing parameters to simultaneously maximize mechanical performance, water resistance, and biodegradability using statistical design tools like RSM. This study addresses these gaps by developing and optimizing a PALF natural rubber composite leather substitute, aiming to achieve a balance between sustainability, functionality, and scalability for potential industrial applications.

Fig. 1. Pineapple leaves from Prachuap Khiri Khan Province

2 LITERATURE REVIEW

With the world warming, habitats destroyed and synthetic materials impacting the environment, effective waste sorting is essential, with monitoring stations in Surat Thani and Songkhla provinces, key southern hubs in Thailand, being assessed for their overall waste volume before it is released into the ocean. Waste classification is therefore crucial [8]. The production of vegan leather, an invention for sustainable fashion policy, is created by using waste materials instead of animal skins and furs to produce expensive fashion clothing. The leather that will replace animal skins will be artificial leather from the polyurethane and polyester groups and leather plants-based; each group has different advantages and disadvantages [9]. In artificial leather production, mechanical properties play a crucial role in determining suitable materials for various applications and influencing consumer preferences. Consequently, classifying artificial leather types based on their mechanical properties has been widely studied, as each type exhibits unique characteristics that impact user preferences and market sustainability. Therefore, the production process must carefully consider these characteristics and material compositions to ensure both functionality and long-term demand. [10]. There is also a study that investigated the effects of outdoor exposure on the tensile properties and water absorption behavior of synthetic leather made from polyurethane (PU) and polyester. The experiments were conducted under general environmental conditions at room temperature, following the Japanese Industrial Standard (JIS) Z 2381. In addition, the study considered optical degradation under outdoor exposure. The results indicated that the tensile properties of synthetic leather are primarily influenced by optical degradation caused by ultraviolet (UV) irradiation during outdoor exposure. [11]. The foundation for developing eco-friendly artificial leather focuses on creating sustainable alternatives in the synthetic leather industry through the recycling of organic waste materials. Previous studies have explored the utilization of fruit peels, including pomelo, Sunkist orange, and grapefruit, as components in artificial leather production. These studies primarily emphasized the mechanical properties of the resulting material, reporting a tensile strength of 472 N/cm², an elongation value of 67.28%, and a tear resistance of 14.28 N/cm². These findings highlight the potential of plant-based materials as viable and sustainable alternatives to animal-derived leather [12]. There has been a study on the treatment of PALF with liquid smoke and its effects on both tensile strength and impact strength. The results indicate that liquid smoke treatment can enhance the strength and toughness of PALF. The tensile strength test was conducted in accordance with the ASTM D638 Type IV standard. The study showed that a 1-hour immersion resulted in a tensile strength of 64.42 MPa, which increased to 72.53 MPa after 2 hours, and further increased to 74.65 MPa after 3 hours of immersion. For the impact strength test, which followed the ASTM D5942 standard, the composite reinforced with PALF exhibited an impact strength of 9.32 J/m² after 1 hour of treatment. This value increased to 13.44 J/m² after 2 hours but decreased to 10.21 J/m² after 3 hours of immersion.

These findings demonstrate that liquid smoke treatment can significantly improve the mechanical properties of PALF, with the most notable enhancement in tensile strength occurring at 3 hours and the highest impact strength observed at 2 hours of treatment [13]. There has been a study on the development of plant-based leather alternatives and natural rubber (NR)-based leather substitutes reinforced with PALF. A simple process was employed, in which PALF was extracted from pineapple leaf waste using a mechanical method. Both untreated PALF (UPALF) and PALF treated with sodium hydroxide (TPALF) were fabricated into fiber mats using a paper-making process. Subsequently, the PALF mats were coated with natural rubber latex at three different NR/PALF ratios: 60/40, 50/50, and 40/60. The resulting bio composite leathers were then evaluated for their tensile strength, tear resistance, and hardness. In addition, the internal microstructure of the leather was observed using a scanning electron microscope (SEM) and compared across samples. The results showed that the leather with an NR/PALF ratio of 50/50 produced the most satisfactory outcome. Therefore, this type of alternative leather demonstrates unique characteristics, being a biobased leather with a lower carbon footprint [14].

To raise awareness within the community, promote the utilization of agricultural waste from local harvests, and support local waste management, the aim is to maximize the value of all materials and ensure their sustainable use. This also encourages the sustainable use of natural rubber and creates opportunities for future development. Furthermore, previous studies have not considered statistical analysis using response surface methodology (RSM). In this work, RSM is applied through a Box–Behnken experimental design to enhance environmental sustainability

3 MATERIALS AND METHODS

This research aimed to investigate the fabrication process of bio-based artificial leather using natural rubber latex and PALF. The study applied RSM through a Box–Behnken design to optimize three critical properties: biodegradability (Y_1), water absorption (Y_2), and tensile strength (Y_3). Three key factors were considered: the amount of PALF (X_1: 3 g, 5 g, 7 g), The compression temperature (X_2: 70 °C, 90 °C, 110 °C) was monitored using a FLIR E60 non-contact infrared thermometer, which is specifically designed for high-temperature measurement without direct sample contact and provides a thermal resolution of 320 × 240 pixels, and compression time (X_3: 10 min, 20 min, 30 min) as illustrated in Fig 2.

Besides, these parameters were selected based on their significant influence on the structural integrity and functional performance of the final composite material. The variables were set at three levels: low (-1), medium (0), and high (+1), in order to comprehensively analyse and determine the effects of each factor on the material properties. By employing the Box–Behnken Design (BBD) in conjunction with statistical response analysis, the main objective was to identify the combination of the three variables that would result in a composite material with the desired properties in terms of biodegradability, water absorption, and tensile strength. These properties are crucial to developing sustainable and environmentally friendly alternative materials, as summarized in Table 1. and the experimental design generated 15 experimental runs as summarized in Table 2, enabling statistical modeling and optimization to identify the ideal combination of processing conditions that balances mechanical performance with environmental sustainability.

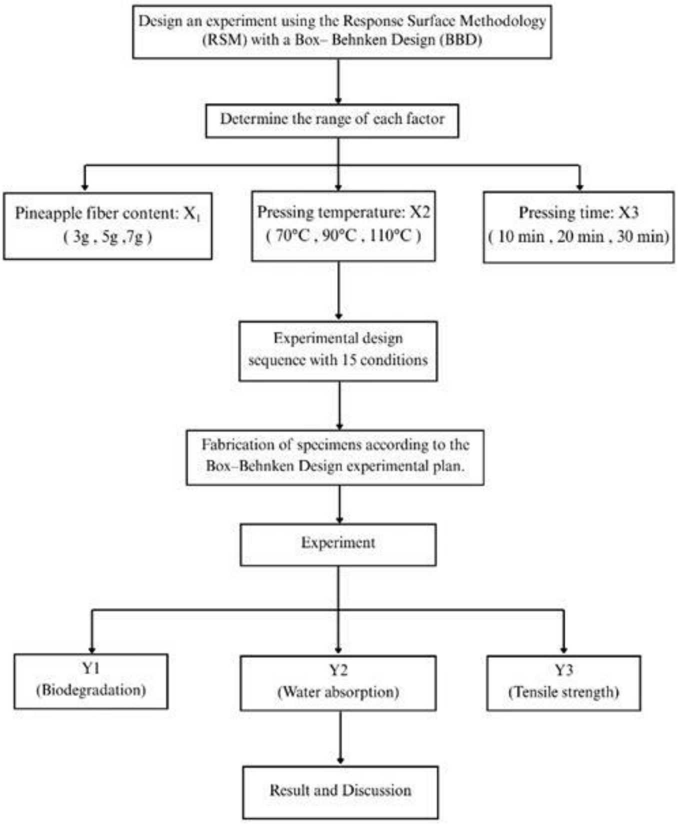


Fig. 2. Flow chart presents studying that sustain for Pineapple Leaf Fiber-Based Vegan Leather

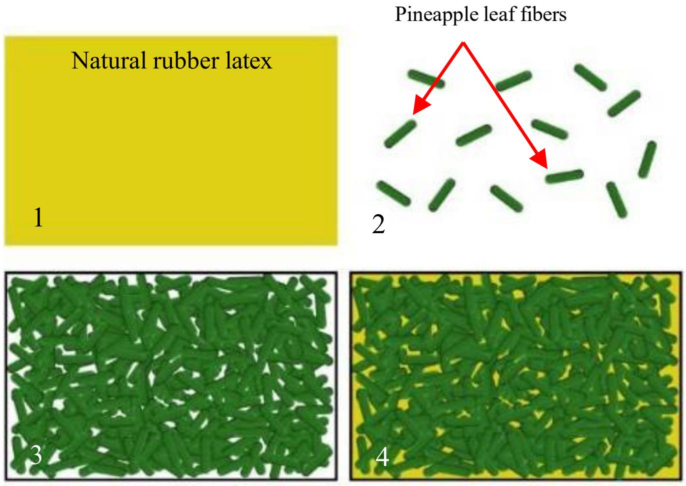


Fig. 3. The main component process began of bio-based artificial leather using natural rubber latex and pineapple leaf fibers.

Table 1. Design Variable Levels

		level		
Type	**Code**	**-1**	**0**	**1**
Amount of pineapple leaf fibers	X_1	3	5	7
Compression temperature	X_2	70	90	110
Compression time	X_3	10	20	30

Table 2. Experimental sequence from the design of Box-Behnken

Numbers	**X_1**	**X_2**	**X_3**
1	3	70	20
2	7	70	20
3	3	110	20
4	7	110	20
5	3	90	10
6	7	90	10
7	3	90	30
8	7	90	30
9	5	70	10
10	5	110	10
11	5	70	30
12	5	110	30
13	5	90	20
14	5	90	20
15	5	90	20

As illustrated in Fig.3, the process began with the preparation of pineapple leaves through chemical treatment to obtain semi-dry fibers suitable for forming. These fibers were fabricated into paper-like sheets measuring 28 × 28 cm at weights of 3 g, 5 g, and 7 g, with the weights precisely measured using a digital scale (PR224/E, OHAUS), according to the experimental design. Subsequently, pre-vulcanized natural rubber latex (MM Prevulcanized latex) was prepared at a volume of 70 mL for each run. The latex was then poured into aluminum trays of the same dimensions (28 × 28 cm) and processed using a MEMMERT UF 30 oven under specified experimental conditions. After completing the forming process according to the experimental design table, the samples were tested to evaluate the three properties: Y_1, Y_2, and Y_3.

In this study, experiments were conducted to determine the optimal conditions for fabricating bio-based composite materials by employing an experimental design approach, which is one of the techniques of Response Surface Methodology (RSM). This method is widely recognized in engineering and materials science research because it effectively reduces the number of experimental runs without compromising the accuracy of the results. Moreover, it allows for a clear analysis of the interactions between variables. In this experimental design, three independent variables were considered. And the molding process was carried out along with temperature monitoring. The molding was performed using a hydraulic press (TOYO 30 tron) with precise timing control, as shown in Fig.4, while the preparation procedure of the artificial leather is illustrated in Fig. 5.

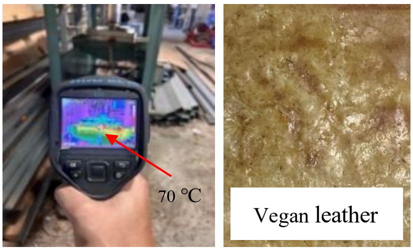


Fig. 4. The molding was performed using a hydraulic press under controlled temperature conditions.

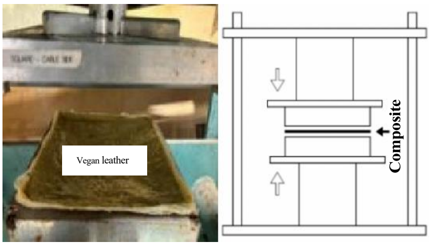
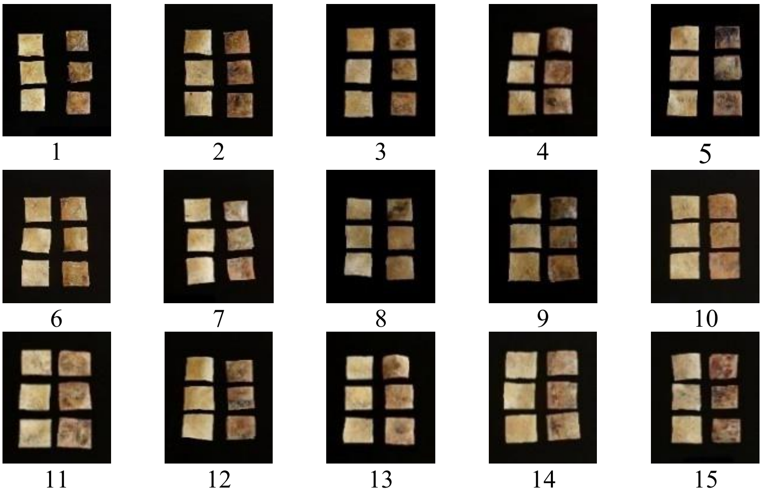


Fig. 5. Preparation procedure of the vegan leather

A. Biodegradation

The results were analyzed following the ASTM G160 standard. Specimens were cut into dimensions of 2 cm × 2 cm and dried at 60 °C for 24 hours [15]. Each specimen was weighed prior to testing, then buried in soil at a depth of 2 cm [16] for a duration of 14 days. After the burial period, the samples were retrieved, cleaned, dried again, and reweighed to determine the weight loss. A comparison of the specimens before and after 14 days of biodegradation testing is shown in Fig. 6.

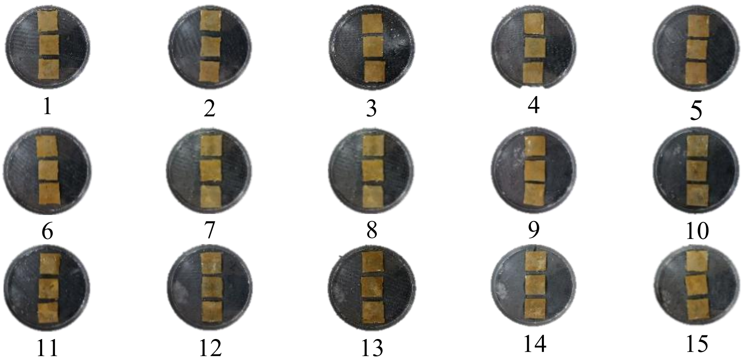


🟨 🟫 1
🟨 🟫 2 All experiments were conducted in triplicate to ensure the reproducibility of the results
🟨 🟫 3

Fig. 6. Comparison of samples before and after biodegradation testing at 14 days. (The experiments were repeated three times to verify the consistency of the results)

B. Water absorption

The experimental results were analyzed using specimens measuring 2 cm × 2 cm in accordance with ASTM D570. Each specimen was weighed prior to testing, then dried at 60 °C for 24 hours. The samples were subsequently immersed in 10 mL of DI water for 24 hours. Excess water was removed using absorbent paper, and the specimens were weighed again [17], as illustrated in Fig. 7.



🟫 1 All experiments were conducted in triplicate to ensure the
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Fig. 7. The samples were tested for water absorption over a 24 hr. period

C. *Tensile strength*

The test specimens were analyzed according to ASTMD412 and ISO 37 standards, with the samples cut into a dumbbell shape (Type C). Tensile testing was performed at a constant crosshead speed of 100 mm/min with a load of 1 kg [18]. The tests were conducted at room temperature using a Universal Testing Machine, as illustrated in Fig. 8.

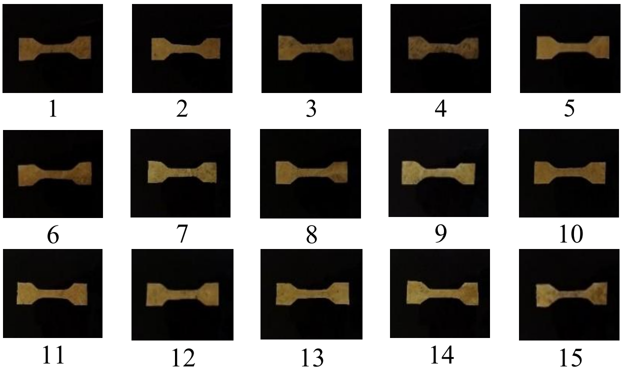
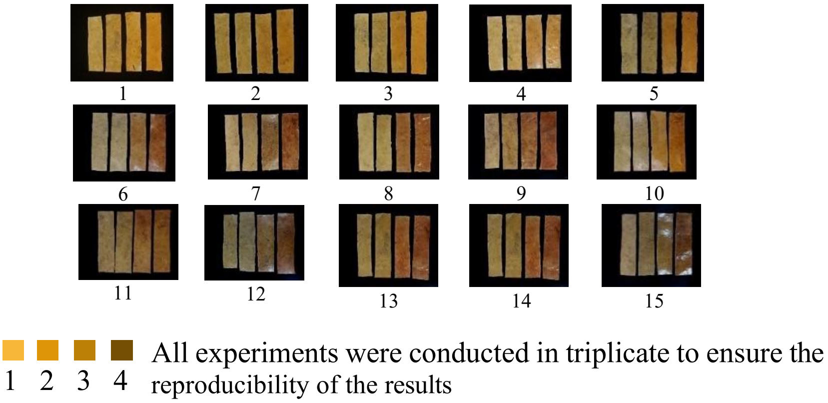


Fig. 8. Type C sample before tensile strength testing.

D. *UV aging*

The analysis focused on the degradation of materials when exposed to ultraviolet (UV) radiation from sunlight over extended periods. This is one of the critical factors contributing to the deterioration of various materials, particularly plastics, rubber, and polymers, which may experience a loss of properties. The analysis involved observing color fading, discoloration, or changes in surface appearance, such as embrittlement or surface cracking. The exposure tests were conducted for durations of 24 hours, 48 hours, and 72 hours [19], as illustrated in Fig. 9.



All experiments were conducted in triplicate to ensure the reproducibility of the results

Fig. 9. Visual comparison of the sample before UV testing and after 24, 48, and 72 hours of UV exposure.

4 RESULT AND DISCUSSION

This study, the objective was to determine the optimal conditions for fabricating artificial leather combined with natural rubber. The experimental design was based on the Response Surface Methodology (RSM) using Minitab 21 software, investigating three factors at three levels: Y_1, Y_2, and Y_3. The fabricated samples were then subjected to property testing to evaluate their performance and the efficiency results are presented in Table 3.

The fabricated specimens were subjected to comprehensive property evaluations to assess their overall performance. The experimental results were subsequently analyzed using statistical modeling to derive regression equations describing the influence of each variable on the responses. The analysis encompassed the estimation of regression coefficients to quantify factor effects, lack-of-fit testing to verify model adequacy, determination of coefficients of determination (R^2) and adjusted R^2 to evaluate model fit, and predictive indicators to assess the model's forecasting capability. Finally, numerical optimization was performed to identify the most suitable combination of variables, achieving optimal material properties while minimizing experimental cost. The results of the experiment were divided as follows

Table 3. The efficiency results

	Factors			Response Variables		
No.	X_1(g)	X_2(°C)	X_3(min)	Y_1(%)	Y_2(%)	Y_3(MPa)
1	3	70	20	19.70	15.79	1.12
2	3	110	20	11.41	16.97	1.58
3	7	70	20	11.36	18.23	2.35
4	7	110	20	7.86	12.50	3.44
5	3	90	10	17.41	17.48	1.48
6	3	90	30	4.21	19.64	1.82
7	7	90	10	12.15	21.82	2.93
8	7	90	30	9.05	14.68	3.46
9	5	70	10	14.51	13.33	1.45
10	5	70	30	10.20	11.37	1.86
11	5	110	10	19.35	12.85	2.79
12	5	110	30	13.12	12.84	3.11
13	5	90	20	14.86	10.90	2.44
14	5	90	20	12.88	12.96	2.46
15	5	90	20	10.88	16.94	2.51

A. Analysis of Variance - ANOVA of biodegradation.

From the study, the biodegradation test results were collected after 14 days, as shown in Fig.6, comparing the samples before and after the test, with three replications. In addition, SEM images were taken before and after the test at magnifications of 400X and 20X to observe the surface morphology of the artificial leather and to evaluate the biodegradation efficiency after soil burial, Subsequently, a response surface regression analysis was performed to determine the relationship among the factors, based on statistical probability values (P-values) at a 95% confidence level. If the P-value was less than or equal to 0.05, the variable was considered statistically significant in the model for biodegradation testing. The results indicated that the significant factors were the X_1 with a P-value of 0.004 and X_2 with a P-value of 0.010, while X_3 had a P-value of 0.241, indicating no significant effect.

Furthermore, the lack-of-fit value was found to be 0.553, indicating that the model adequately fits the data. When considering the coefficient of determination (R^2) of 92.24% and the adjusted of 78.27%, it suggests that the model could explain a substantial proportion of the variability in the response and the ANOVA results are presented in Table 4.

After considering the P-value, a multiple regression equation was created, as shown in Eq.1 Biodegradation (%) = $74.6 - 2.12\,X_1 - 0.984\,X_2 - 0.232\,X_3 - 0.485X_1^2 + 0.00412X_2^2 - 0.0023X_3^2 + 0.2991X_2 + 0.1263\,X_1\,X_3 - 0.00240X_2X_3$

B. Analysis of Variance - ANOVA of water absorption.

Water absorption reflects the ability of artificial leather to absorb moisture or liquid from the surrounding environment, particularly in plant-fiber-based materials with a porous structure. The results were analyzed from water absorption tests conducted over a 24-hour period to evaluate the material's performance in maintaining its integrity when exposed to water. Type sizes for final papers. The analysis focused on the variation of the model and examined the relationship between factors. Statistical significance was determined using the P-value, where a P-value less than or equal to 0.05 indicates that the variable is accepted in the model and has a statistically significant effect on water absorption.

From the analysis of variance (ANOVA), it was found that X_1 had a P-value of 0.146, X_2 had a P-value of 0.503, and X_3 had a P-value of 0.949. The lack-of-fit value was 0.998, indicating that the experimental data were highly suitable for the model. Furthermore, the quadratic term of X_1^2 had a P-value of 0.011, showing statistical significance. The coefficient of determination (R^2) was 86.73%, which indicates that the model explains a high proportion of the variation in the data. From the results, the independent variable explained 13.27% of the variation, indicating limited control. The R-sq (adj) was 62.85% suggesting that the model could explain a substantial portion of the variance in the data. However, the R-sq (pred) was 0.00%, showing that the model had no predictive ability for water absorption. This may be due to the unclear relationship with tensile strength or an insufficient amount of data and the ANOVA results are presented in Table 4.

C. Analysis of Variance - ANOVA of tensile strength

The tensile test is a method used to evaluate the ability of a material to resist forces that attempt to stretch it. The results are recorded for subsequent analysis of the material's strength.

From the ANOVA, it was found that X_1 had a P-value of 0.084, compression X_2 had a P-value of 0.019, and X_3 had a P-value of 0.004. The lack-of-fit value was 0.005, indicating that the experimental data were not suitable for the model. The coefficient of determination (R^2) was 89.84%. While, the R-sq (adj) was 71.55% suggesting that the model could explain a substantial portion of the variance in the data. However, the R-sq (pred) was 0.00%, showing that the model had no predictive ability for water absorption. This may be due to the unclear relationship with Tensile strength or an insufficient amount of data.

For the results to be reliable, the experiments should be repeated to obtain more consistent values, and other relevant factors should be considered to accuracy and the ANOVA results are presented in Table 4.

Table 4. ANOVA for response surface methodology on the efficiency results of pineapple leaf fiber-based vegan Leather

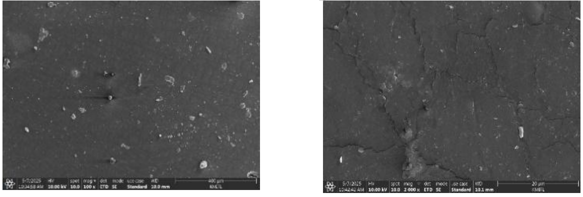
	Y_1[a]					Y_2[b]					Y_3[c]				
Source	DF	Adj SS	Adj MS	F-Value	P- Value	DF	Adj SS	Adj MS	F-Value	P- Value	DF	Adj SS	Adj MS	F-Value	P- Value
Model	9	226.495	25.1661	6.60	0.026	9	125.543	13.9492	3.63	0.085	9	6.96595	0.77399	4.91	0.047
Linear	3	168.254	56.0845	14.72	0.006	3	13.370	4.4566	1.16	0.411	3	6.58890	2.19630	13.94	0.007
X_1	1	98.631	98.6310	25.88	0.004	1	11.353	11.3526	2.96	0.146	1	0.73205	0.73205	4.65	0.084
X_2	1	62.888	62.8881	16.50	0.010	1	2.000	2.0000	0.52	0.503	1	1.82405	1.82405	11.58	0.019
X_3	1	6.734	6.7345	1.77	0.241	1	0.017	0.0171	0.00	0.949	1	4.03280	4.03280	25.59	0.004
Square	3	26.081	8.6938	2.28	0.197	3	77.663	25.8877	6.74	0.033	3	0.26677	0.08892	0.56	0.662
X_1^2	1	13.902	13.9023	3.65	0.114	1	60.264	60.2644	15.69	0.011	1	0.04777	0.04777	0.30	0.606
X_2^2	1	10.047	10.0472	2.64	0.165	1	11.535	11.5350	3.00	0.144	1	0.20174	0.20174	1.28	0.309
X_3^2	1	0.192	0.1918	0.05	0.831	1	2.161	2.1608	0.56	0.487	1	0.01621	0.01621	0.10	0.761
2-Way Interaction	3	32.160	10.7200	2.81	0.147	3	34.510	11.5034	3.00	0.134	3	0.11028	0.03676	0.23	0.870
$X_1 X_2$	1	5.736	5.7360	1.51	0.274	1	11.937	11.9370	3.11	0.138	1	0.09923	0.09923	0.63	0.463
$X_1 X_3$	1	25.502	25.5025	6.69	0.049	1	21.622	21.6225	5.63	0.064	1	0.00902	0.00902	0.06	0.820
$X_2 X_3$	1	0.922	0.9216	0.24	0.644	1	0.951	0.9506	0.25	0.640	1	0.00203	0.00203	0.01	0.914
Error	5	19.055	3.8109			5	19.203	3.8406			5	0.78785	0.15757		
Lack-of Fit	3	11.134	3.7115	0.94	0.553	3	0.348	0.1159	0.01	0.998	3	0.78525	0.26175	201.35	0.005
Pure Error	2	7.920	3.9601			2	18.855	9.4276			2	0.00260	0.00130		
Total	14	245.550				14	144.746				14	7.75380			
S = 1.95216						S = 1.95973					S = 0.396951				

[a]Y_1: Biodegradation , [b]Y_2: Water absorption ,[c]Y_3: tensile strength

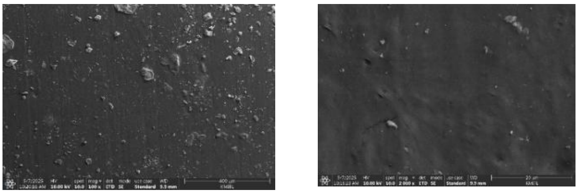
D. Material Analysis

The pineapple leaf fiber (PALF) was examined and analyzed using a scanning electron microscope (SEM) and a light microscope. The results are summarized as follows:

(a) Bio-degradation Analysis: The SEM images (Fig. 10) presented clear microstructural differences between the samples before and after testing



(a)

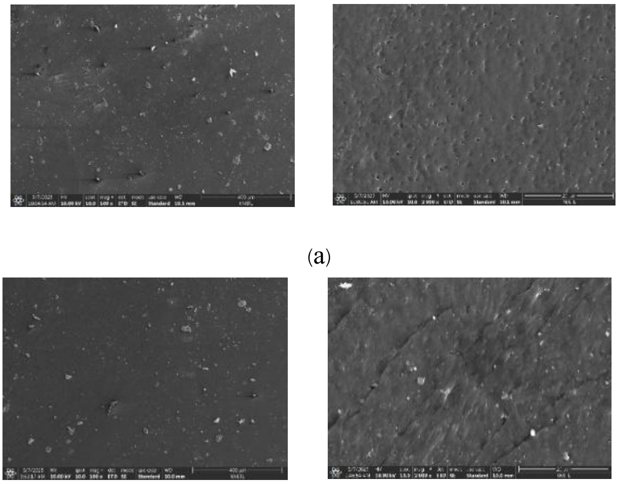


(b)

Fig. 10. Bio degradation (a: before testing (brown) and b: after testing (yellow)

- 100X magnification: The surface showed diffusion of fiber along with the presence of foreign objects. In addition, small cracks and uneven particles were observed surrounding the fiber surface (left).
- 10,000X magnification, the surface structure at the nanoscale appeared relatively smooth with small pores. Some interfacial bonding was observed between the fiber and the rubber matrix at the microstructural level (right)

(b) Water Absorption Analysis: The SEM images (Fig. 11.) revealed distinct microstructural changes in the samples when comparing their conditions before and after testing.



(a)

(b)

Fig. 11. Water absorption brown (a: before testing (brown) and b: after testing (yellow)

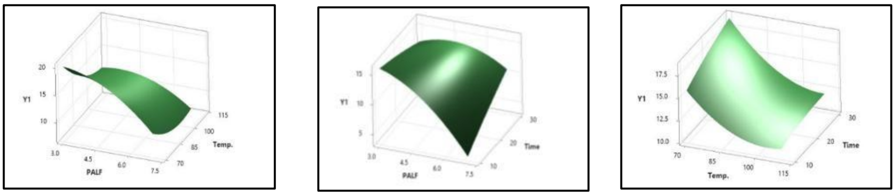
- 100X magnification, the surface appeared diffused and rugged. In addition, small scratches and cracks were observed at certain points.
- 10,000X magnification, numerous holes and cracks were observed distributed across the surface, indicating imperfections in the material at the microstructural level.

E. Optimization of response surface methodology for fabricating artificial leather combined with natural rubber

Based on the analysis of variance (ANOVA), it was found that X_1, X_2, and X_3 influenced the responses Y_1, Y_2, and Y_3. Of these, only Y_1 was further analyzed using Response Surface Methodology (RSM) because it was considered the most relevant for determining the optimal conditions calculated from the ANOVA for fabricating artificial leather combined with natural rubber.

In the surface plot (Fig. 12) used to identify the equilibrium value, it was observed that the maximum response for Y_1 (a) occurred in the relationship between X_1 and X_2. Specifically, when X_3 was fixed at 20 min, Y_1 showed the highest trend at an X_1 range of 4.5–5.0 g and X_2 between 90–100 °C. Furthermore, the X_1 and X_3 plot, with X_2 fixed at 90 °C, indicated a maximum Y_1 (b) for X_1

between 4.5−5.0 g and X_3 between 20−25 min. Finally, fixing X_1 at 5 g resulted in the highest Y_1 (c) response in the X_2 and X_3 plot, at X_2 between 90−100 °C and X_3 between 20−25 min. These combined observations suggest a highly favorable region for Y_1.



(a) (b) (c)

Fig. 12. Response Surface Plots illustrating the combined effects of X1, X2 and X3 on Y1

Conversely, the established model (Eq. 1) predicted a maximum biodegradability of 20.9946%. This optimal value was achieved under the following specific conditions (Fig. 11). achieved under the conditions of X_1 = 3 g, X_2 = 70 °C, and X_3 = 10 min, as shown in Fig. 13.

Fig. 13. Optimization of response surface methodology on the biodegradation

According to the model in Fig 11, the percentage of biodegradation tended to decrease as X_1 increased, which may be due to the higher fiber content making the material more resistant to degradation. In addition, increasing X2 and X3, which affect the compression of material, leads to higher density, potentially restricting access and thereby slowing the biodegradation process.

F. Perspectives on circular economy and sustainable development

Nowadays, the development of PALF from a traditional waste product into a valuable resource provides an excellent case study for the intersection of the circle economy and sustainable development [20-21]. While Thailand's pineapple cultivation has traditionally resulted in a significant amount of unused biomass [22-23], the emerging PALF industry demonstrates a paradigm shift from the linear take-make-waste model to a more regenerative, circular one [22]. This experiment demonstrates that the lifecycle of a PALF-based product can be extended beyond its initial use by recycling it into new materials at the end of its life, thereby reinforcing the circular model and reducing the need for virgin resources.

Crucially, this research quantifies resource efficiency in alignment with SDG 12 (Responsible Consumption and Production) [24]. The process begins with biomass valorization, where 1 kg of pineapple leaves yields only 20 g of viable PALF for experimental material. Furthermore, the RSM methodology ensures that comprehensive, multi-variable analysis is conducted with minimal material consumption: a total of only 75 g of PALF was required for the 15 experimental runs (approximately 3 kg of leaf pineapple leaves waste total), demonstrating the principles of Green Technology and efficient R&D [25-26]. This rigorous focus on minimizing material consumption supports sustainable industrial processes.

In addition, the development of PALF from Pineapple leaves to the achievement of some of the Sustainable Development Goals (SDG), particularly of SDG 7 (Affordable and Clean Energy), SDGs 9 (Industry, Innovation and Infrastructure) and SDG 12 (Responsible Consumption and Production) [27-28], through the provision of new bio-based products, development of novel and sustainable industrial processes, and boosting of regional and global economic development.

5 CONCLUSION

This research focused on synthetic polymers and single-source natural fibers, using Box– Behnken Design (BBD) and Response Surface Methodology (RSM) to study the effects of key factors (X_1, X_2, and X_3) on material properties (Y_1, Y_2, and Y_3). The results showed that X_1, X_2, and X_3 had a statistically significant effect (P-value) on Y_1, with the highest biodegradability (20.99%) obtained under the conditions of X_1 = 3 g, X_2 = 70 °C, and X_3 = 10 min. In contrast, Y_2 and Y_3 did not show statistically significant effects. However, although the factors did not significantly influence the P-values, the model still indicated trends: the minimum Y_2 was 10.90%, while Y_3 reached the highest value of 3.46 N/mm² under the conditions of X_1 = 3 g, X_2 = 90 °C, and X_3 = 20 min. Nevertheless, no sustainable statistical significance was found in these responses. In contrast, synthetic polymers that have been developed demonstrate potential to support the circular economy model and reduce reliance on virgin resources from the agricultural sector in the future.

Author contributions

Sokjabok S. conceptualized the research idea and prepared the manuscript. Srisang S. revised the manuscript and provided suggestions regarding management. Hutangkoon T., Eiangmee O., and Maikaew T. conducted the experiments, carried out the evaluations, and investigated the system performance. Kunyuan J. and Srisang N. reviewed and approved the final version of the manuscript.

Funding

This work was financially supported by King Mongkut’s Institute of Technology Ladkrabang [KREF186723]

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