



Optimization of Preparation Conditions for Jackfruit Seed Starch-Based Biofilms Using the Taguchi Method

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Abstract

This study aimed to enhance the tensile strength of a biofilm prepared from jackfruit seed starch by optimizing the preparation conditions using the Taguchi method. The results demonstrated that the starch and glycerol contents considerably affected the tensile strength of the biofilm. The optimal formulation was found to be 5% starch, 1% glycerol, 0.5% cooking oil, and 2% acetic acid. The biofilm exhibited a tensile strength of $1.62 \pm 0.27 \text{ N/cm}^2$. In addition, the results indicated that the biofilm prepared from jackfruit seed starch exhibited higher tensile strength than biofilms prepared from cassava starch and wheat flour. Furthermore, this study evaluated the application of the biofilm in instant noodle seasoning packaging, demonstrating its potential to replace traditional plastic packaging and thereby reduce environmental pollution. Overall, these findings validate the feasibility of biofilms derived from jackfruit seed starch and support further research in sustainable packaging solutions.

Keywords: Biofilms, Jackfruit seed, Starch, Taguchi method

1. Introduction

The global increase in plastic and nonbiodegradable waste impacts all ecosystems, including rivers, seas, land, and the atmosphere. Approximately 275 million tons of plastic waste are produced worldwide each year, with 8 million tons entering the oceans, adversely affecting the environment and public health [1]. Meanwhile, nonbiodegradable plastic products are becoming increasingly prevalent, and conventional disposal methods, such as landfills and incinerators, are reaching their limits. In particular, the availability of landfills is decreasing, while investment costs for incinerators continue to rise [2]. Consequently, it is more critical than ever to develop renewable and biodegradable biomaterials as sustainable alternatives to conventional plastics [3,4].

Starch, a common renewable plant material, is emerging as a viable option for biofilm production. Starch is widely available in nature, cost-effective, and fully biodegradable [5]. Among starch sources, jackfruit seeds (*Artocarpus heterophyllus*) are abundant in tropical countries such as Vietnam [6]. Depending on cultivar and fruit maturity, each jackfruit may contain 100–500 seeds, accounting for 10%–15% of the fruit's total weight [7]. Global jackfruit production reaches several million tons annually [8], resulting in large quantities of jackfruit seeds that remain underutilized. Jackfruit seeds contain approximately 60%–70% starch [9], making them a potential source for biofilm preparation. In addition, utilizing jackfruit seeds, a by-product of the food industry, not only reduces agricultural waste but also increases their economic value [10]. However, starch-based biofilms often exhibit poor mechanical properties and limited water resistance due to the hydrophilic nature of starch. To address these limitations, plasticizers such as glycerol have been shown to substantially improve film flexibility, durability, and water resistance [5]. They increase toughness and improve film structure by reducing the interaction forces between starch molecules. The interaction between hydrogen ions and starch increases film uniformity in the presence of acetic acid [11]. Furthermore, some studies have added oil to reduce water absorption and extend the film shelf life under humid conditions [12,13]. For example, the addition of 2% sunflower oil has been reported to improve the properties of starch-based films [14]. Therefore, optimizing the components of

starch-based biofilms—including starch, plasticizer, acetic acid, and oil—to enhance their physical properties is of considerable research interest.

The Taguchi method is a powerful statistical method for optimizing production processes. It employs signal-to-noise (S/N) ratios to transform data and simultaneously optimize the mean and variance [15]. The signal represents the desired response, whereas the noise represents the undesired variation caused by uncontrollable factors. However, the use of this method in optimizing biofilm production conditions is limited. In a previous study, the Taguchi method was successfully applied to optimize the formulation of starch-based bioplastic films prepared from corn and potato starches combined with calcium carbonate and glycerol–sorbitol [16]. Therefore, the present study employed the Taguchi method to determine the optimal combination of factors—such as the levels of starch, glycerol, acetic acid, and cooking oil—to prepare jackfruit seed starch-based biofilms with enhanced tensile strength. This study addresses the reduction of plastic waste and optimizes the use of natural resources, thereby supporting the development of more sustainable materials. However, starch-based biofilms are limited by their low tensile strength [17]. Therefore, they are more suitable for applications requiring lower mechanical performance, such as food packaging. Currently, instant noodle seasoning packets are often derived from plastic materials. These materials exhibit high preservation properties, preventing air, moisture, and light from penetrating, thereby maintaining seasoning quality and flavor. They also provide convenient packaging, are easy to open and use, and meet food safety standards. However, these materials also exhibit some disadvantages; for example, they are difficult to decompose and contribute to plastic waste that is harmful to the environment. Therefore, the development of food packaging from jackfruit seed starch offers both economic and environmental advantages, supporting ecosystem protection and meeting the demand for sustainable materials.

2. Materials and methods

2.1 Materials

Jackfruit seeds were obtained from markets in Buon Ma Thuot City, Vietnam. The seeds were cleaned, blended with water, and filtered to extract the juice. The juice extracted from the pulp was allowed to settle until the upper layer was transparent, while a fine powder accumulated at the bottom, after which the water was decanted. Subsequently, clean water was introduced and mixed well to dissolve all sediment, followed by prolonged settling. This process was performed approximately 5–6 times to obtain jackfruit seed starch. Finally, the starch was transferred to a tray and dried in an oven at 60 °C for 24 h. Acetic acid and glycerol were purchased from Xilong Chemical Co. (China), while cooking oil (soybean oil), wheat flour, and cassava starch were purchased from Meizan Co. (Vietnam).

2.2 Preparation of starch-based biofilm

Jackfruit seed starch was mixed with water and subsequently combined with acetic acid. The starch–acetic acid mixture was gelatinized at 90 °C for 20 min [18]. The resulting mixture was then added to glycerol and cooking oil to produce the final formulation. To form the film, 20 mL of the starch mixture was evenly poured onto a 120-mm-diameter petri dish and subsequently dried at 28 °C for 5 d. The proportions of starch (%), acetic acid (%), glycerol (%), and cooking oil (%) used for biofilm formation were determined using the Taguchi method.

In the confirmation experiment, films were prepared using the optimized formulation determined by the Taguchi method. Starch sources—including jackfruit seed starch, wheat flour, and cassava starch—were combined with the other components according to the optimal composition: 5% (w/v) starch, 1% (v/v) glycerol, 0.5% (v/v) cooking oil, and 2% (v/v) acetic acid. To create the films, 20 mL of the starch mixture was evenly poured onto a 120-mm-diameter petri dish and dried at 28 °C for 5 d.

2.3 Taguchi design

The Taguchi method was employed to optimize the levels of starch (3%–5%), acetic acid (1%–3%), glycerol (1%–3%), and cooking oil (0.5%–2%). The factor levels were determined based on preliminary experiments and previous reports [19]. Each factor was evaluated at three levels, as presented in Table 1.

Table 1 Factors and their levels.

Factor	Level 1	Level 2	Level 3
Starch (%)	3	4	5
Acetic acid (%)	1	2	3
Glycerol (%)	1	2	3
Cooking oil (%)	0.5	1	2

The selected output factor was tensile strength (N/cm²). The experiment was designed according to a Taguchi L9 orthogonal array, as illustrated in Table 2. The S/N ratio was selected according to the larger-is-better criterion [20]. The S/N ratio was calculated using the following equation:

$$\frac{S}{N} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^n \frac{1}{y_i^2}\right),$$

where n denotes the number of observations, and y_i denotes the tensile strength value of the i -th experiment.

Table 2 Taguchi L9 design.

Run	Starch (%)	Acetic acid (%)	Glycerol (%)	Cooking oil (%)
1	3	1	1	0.5
2	3	2	2	1
3	3	3	3	2
4	4	1	2	2
5	4	2	3	0.5
6	4	3	1	1
7	5	1	3	1
8	5	2	1	2
9	5	3	2	0.5

2.4 Tensile strength assay

The tensile strength of the films was assessed by cutting the films into uniform pieces (60 mm × 10 mm). Each film was clamped with a gauge length of 50 mm. Tensile strength was defined as the force required to stretch the film until breakage and was measured using a handheld digital force gauge (ALIYIQI SF-5).

Tensile strength (N/cm²) was calculated using the following equation [21]:

Tensile strength (N/cm²) = Breaking force (N)/area (cm²)

2.5 Thickness, moisture content, and water solubility

Film thickness was measured following the method described by Shanbhag et al. (2023) using a thickness gauge (Mitutoyo, Japan) [11]. Moisture content and water solubility were determined following the method described by Senarathna et al. (2022) [22].

2.6 Application in instant noodle seasoning packaging

The film was cut into squares of equal size (10 cm × 10 cm), folded in half, and heat-sealed along the bottom and side edges. A measured quantity of instant noodle seasoning (4 g) was then placed inside the film, and the open edge was heat-sealed to enclose the seasoning. The seasoning was obtained from Hào Hào instant noodle packets produced by Acecook Vietnam Co. (Vietnam).

2.7 Dissolution test of seasoning packet

The packet was placed in a bowl together with an instant noodle block. Boiling water (100 °C) was poured into the bowl to completely immerse the noodles and packet. After gentle stirring with chopsticks for several seconds, the packet was visually observed for signs of fragmentation and release of the seasoning into the water.

2.8 Statistical analysis

A Taguchi L9 (3⁴) orthogonal array design was employed, consisting of four factors (starch, acetic acid, glycerol, and cooking oil), each at three levels.

3. Results and discussion

3.1 S/N ratio results

In the Taguchi method, the S/N ratio quantifies both the mean response and its variability. The larger-is-better criterion was applied, where a higher S/N ratio indicates greater and more consistent tensile strength. Therefore, the optimal formulation corresponds to the factor combination yielding the highest S/N ratio. As illustrated in Table 3, higher S/N ratios correspond to improved tensile strength and increased system stability. Run 8 exhibited

the highest S/N ratio (2.71), indicating that the combination of 5% starch, 2% acetic acid, 1% glycerol, and 2% cooking oil resulted in the highest tensile strength. In contrast, Run 3 exhibited the lowest S/N ratio (−18.45), indicating that the combination of 3% starch, 3% acetic acid, 3% glycerol, and 2% cooking oil resulted in the lowest tensile strength.

Table 3 Results of tensile strength and signal-to-noise (S/N) ratio.

Run	Starch (%)	Acetic acid (%)	Glycerol (%)	Cooking oil (%)	Tensile strength (N/cm ²)	S/N ratio
1	3	1	1	0.5	0.70 ± 0.27	−5.68
2	3	2	2	1	0.28 ± 0.04	−11.23
3	3	3	3	2	0.13 ± 0.03	−18.45
4	4	1	2	2	0.39 ± 0.12	−9.31
5	4	2	3	0.5	0.38 ± 0.09	−9.20
6	4	3	1	1	0.60 ± 0.27	−7.28
7	5	1	3	1	0.44 ± 0.15	−8.59
8	5	2	1	2	1.57 ± 0.50	2.71
9	5	3	2	0.5	0.98 ± 0.22	−1.05

Table 4 presents the average S/N analysis results for different factors at each level in the Taguchi experiment. The delta values represent the difference between the largest and smallest S/N ratios for each factor. A larger delta value indicates a stronger influence of the corresponding factor on the response variable. Therefore, factors with larger delta values are considered more influential. The starch factor exhibited a delta value of 9.48 and ranked first, indicating that starch had the greatest influence on tensile strength. Level 3 (5%) of starch exhibited the highest S/N ratio (−2.31), indicating that this was the optimal level. Rahmawati et al. (2022) reported a similar trend, in which a higher starch content led to greater tensile strength in films prepared from jackfruit seed starch combined with carboxymethyl cellulose and glycerol [23]. The delta value of glycerol was 8.66 and ranked second, indicating that glycerol also substantially affected tensile strength. Level 1 (1%) of glycerol exhibited the highest S/N ratio (−3.42), indicating that this was the optimal level for tensile strength. The delta values of cooking oil and acetic acid were 3.72 and 3.02, respectively, indicating a weaker effect on tensile strength. The optimal levels of these two factors were level 1 (0.5% cooking oil) and level 2 (2% acetic acid). Therefore, the optimal factor levels for achieving the highest S/N ratio were 5% starch, 1% glycerol, 0.5% cooking oil, and 2% acetic acid.

Table 4 Taguchi signal-to-noise ratio response.

Level	Starch	Acetic acid	Glycerol	Cooking oil
1	−11.79	−7.86	−3.42	−5.31
2	−8.60	−5.90	−7.20	−9.03
3	−2.31	−8.92	−12.08	−8.35
Delta	9.48	3.02	8.66	3.72
Ranking	1	4	2	3

3.2 ANOVA results

The ANOVA results for the S/N ratio are presented in Table 5. The F-values for starch and glycerol were high (19.62 and 16.39, respectively), indicating that these factors had a significant influence. A factor is considered statistically significant when $p < 0.05$. Accordingly, starch and glycerol, with p -values of 0.011 and 0.016, respectively, had a significant influence. In contrast, acetic acid and cooking oil exhibited no significant influence. A higher sum of squares (SS) value indicates a greater contribution of a factor to the variation in S/N ratio. According to Table 5, starch had an SS value of 134.76, contributing the most to the variation, followed by glycerol, which had an SS value of 112.58. In contrast, acetic acid and cooking oil had low SS values, indicating a smaller contribution to the variation. Similarly, the %SS of starch and glycerol were high (46.41% and 38.77%, respectively), indicating that the majority of the variation in the data was explained by these two factors. In summary, the ANOVA results are in good agreement with the Taguchi method results, indicating that starch and glycerol were the most influential factors. Based on the ANOVA results, the optimal levels of starch and glycerol were 5% and 1%, respectively.

Table 5 ANOVA results.

	DF	SS	MS	F-value	p -value	%SS
Starch	1	134.76	134.76	19.62	0.011	46.41
Acetic acid	1	1.69	1.69	0.25	0.646	0.58
Glycerol	1	112.58	112.58	16.39	0.016	38.77
Cooking oil	1	13.88	13.88	2.02	0.228	4.78
Error	4	27.48	6.87			
Total	8	290.39	36.30			

DF, degree of freedom; SS, sum of squares; MS, mean square.

3.3 Validation of results

Experiments were conducted to validate the results obtained under the optimal conditions determined by the Taguchi method. The results demonstrated that the biofilm prepared with 5% starch, 1% glycerol, 0.5% cooking oil, and 2% acetic acid achieved a tensile strength of 1.62 ± 0.27 N/cm² (Figure 1). These results are in good agreement with the results predicted by the Taguchi method, confirming its effectiveness and reliability in optimizing the preparation conditions of jackfruit seed starch-based biofilms. The tensile strength obtained in this study was higher than the values reported for jackfruit seed starch-based biofilms by Rahmawati et al. (2022), which were 8.35×10^{-5} N/mm² and 2.56×10^{-4} N/mm² [23]. However, it was lower than that of gelatin films supplemented with carboxymethyl cellulose derived from pineapple core (0.23 – 0.37 kg·cm⁻²) [4]. Other studies have reported tensile strength values for starch-based films ranging from 0.36 to 20.64 MPa, which are higher than those obtained in the present study [11]. Therefore, the low tensile strength represents a limitation of starch-based films for food-packaging applications requiring high mechanical resistance. Nevertheless, Żółek-Tryznowska and Kałuża (2021) suggested that starch-based films with lower tensile strength may still be suitable for single-use packaging [24], such as instant noodle seasoning packets. The present study also included films prepared from cassava starch and wheat flour. The results indicated that films prepared from jackfruit seed starch exhibited higher tensile strength than those prepared from cassava starch (0.22 ± 0.03 N/cm²) and wheat flour (0.74 ± 0.09 N/cm²), indicating the potential of jackfruit seed starch as a promising alternative to cassava starch or wheat flour for biofilm preparation.

The obtained film exhibited a thickness of 0.26 mm, a moisture content of 19.7%, and a water solubility of 32.7%. Compared with edible films prepared from prickly pear peel mucilage and potato husk starch, the jackfruit seed starch film exhibited lower water solubility (32.7% vs. 39%–54%) but higher moisture content (19.7% vs. 10%–12%) [25]. In another study, films derived from pea starch and guar gum exhibited water solubility and moisture content values of 21.04%–42.27% and 9.74%–31.40%, respectively [26]. Similarly, Shanbhag et al. (2023) reported that starch-based films had thicknesses of 0.159–0.384 mm, moisture contents of 6.76%–16.39%, and water solubility values of 3.25%–35.29% [11]. Overall, the thickness and solubility values obtained in the present study fall within the ranges reported for other starch-based biodegradable films. These results suggest that jackfruit seed starch films may be suitable for the biodegradable packaging of dry food products. In addition, starch-based films are generally odorless and tasteless, thereby minimizing the risk of altering the sensory characteristics of packaged foods.

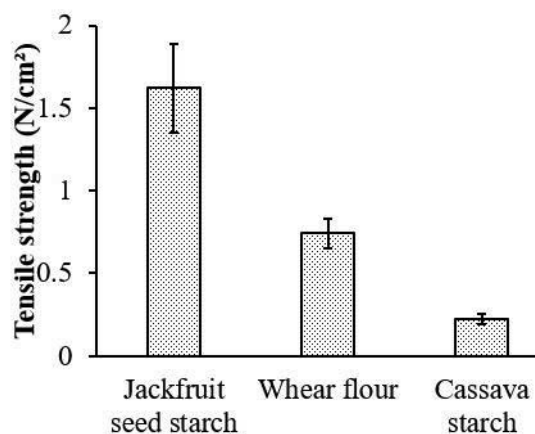


Figure 1 Tensile strength of biofilms prepared from jackfruit seed starch, cassava starch, and wheat flour. Data are presented as mean $\pm$ standard deviation.

3.4 Application of Biofilm in Instant Noodle Seasoning Packaging

This study evaluated films prepared from jackfruit seed starch for use in instant noodle seasoning packaging. Figure 2 displays an instant noodle seasoning packet prepared from jackfruit seed starch-based biofilm. The results demonstrate that it is feasible to use this biofilm in instant noodle seasoning packaging. The seasoning packet dissolves in boiling water within a few seconds. During the dissolution test, it rapidly softened, fragmented, and released the seasoning powder after immersion in water at 100 °C for 5–10 s with gentle stirring. This property allows the packet to be added directly to instant noodle soup without needing to be opened. Similarly, Chen et al. (2021) reported that all flavor packets prepared from starch-based films dissolved in hot water within a few seconds [27].



Figure 2 (A) Biofilm and (B) instant noodle seasoning packet prepared from jackfruit seed starch.

4. Conclusion

This study applied the Taguchi method to optimize the preparation of biofilms from jackfruit seed starch. Based on S/N ratios and ANOVA results, the key factors affecting the tensile strength of the biofilm were identified. Among these factors, starch and glycerol had the most significant influence, with F- and *p*-values revealing statistically significant effects. The optimal formulation for biofilm preparation was 5% starch, 1% glycerol, 0.5% cooking oil, and 2% acetic acid. The developed biofilms demonstrate potential for use in instant noodle seasoning packaging as an alternative to conventional synthetic materials. However, compared with petroleum-based plastics, their water resistance and mechanical strength require further improvement for practical packaging applications.

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6. Author contributions

Conceptualization, C.T.D. and T.N.T.; methodology, C.T.D.; formal analysis, T.P.T.H., C.T.D. and T.N.T.; investigation, T.P.T.H., T.D.D., T.L.N.; resources, C.T.D.; data curation, C.T.D. and T.N.T.; writing—original draft preparation, C.T.D. and T.N.T.; writing—review and editing, C.T.D. and T.N.T.; visualization, C.T.D.; supervision, C.T.D.; project administration, C.T.D. All authors have read and agreed to the published version of the manuscript.

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