

Article

Optimized Enzymatic Bioconversion of Palm Kernel Meal to a Mannose-Rich Syrup

Kathya Wainwright , Jade Schlamb, Roberta Targino Hoskin, Fabio Gonçalves Macêdo de Medeiros and Marvin Moncada * 

Department of Food, Bioprocessing and Nutrition Sciences, Plants for Human Health Institute, North Carolina State University, 600 Laureate Way, Kannapolis, NC 28081, USA; kwainwr2@ncsu.edu (K.W.); jmschlam@ncsu.edu (J.S.); rtcorrei@ncsu.edu (R.T.H.); fabiio Macedo1@gmail.com (F.G.M.d.M.)

* Correspondence: mlmoncad@ncsu.edu; Tel.: +1-(301)-655-1022

Abstract

Palm kernel cake (PKC), a byproduct of palm kernel oil extraction, is processed into palm kernel meal (PKM), which contains hemicellulose rich in mannose, a versatile sugar with applications in the pharmaceutical and food industries. However, its association within the lignin–cellulose matrix is a challenge for industrial extraction. This study proposes an optimized enzymatic hydrolysis method utilizing mannanase to maximize the mannose content from PKM powder to produce palm kernel mannose syrup. A 3^3 Box–Behnken design within a response surface methodology coupled with a desirability function method was used to optimize hydrolysis parameters to maximize mannose and solids content while minimizing enzyme concentration and hydrolysis time. The optimal conditions for enzymatic hydrolysis were established as a reaction time of 16 h, 5% (w/v) solids, and 5% (w/w) enzyme, resulting in 4.325 g/L of mannose and a mannose yield of $24.33 \pm 0.5\%$. The palm kernel mannose syrup was evaluated, resulting in a moisture content of $15.85 \pm 0.07\%$, water activity of 0.6918 ± 0.003 , and a pH of 4.05 ± 0.282 , demonstrating shelf-life stability. These findings demonstrate the technical feasibility of valorizing PKC and PKM into a stable, mannose-rich syrup, offering a sustainable and scalable pathway for converting agro-industrial waste into high-value ingredients for multiple value-added applications.

Keywords: *Elaeis guineensis*; palm kernel cake; enzymatic hydrolysis; sugar



Academic Editors: Chao Gai, Diana-Nicoleta Raba, Despina-Maria Bordean and Mariana-Atena Poiana

Received: 11 March 2026

Revised: 11 April 2026

Accepted: 25 April 2026

Published: 28 April 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The African oil palm (*Elaeis guineensis*), native to West Africa, is traditionally considered an important palm species for human use primarily as a source of oil, in addition to wine, building materials, medicine, and various rituals [1,2]. As a result, this crop has grown globally in the last 50 years, gaining popularity in several regions due to its high yield and adaptability. Now, oil palm production is economically crucial in many countries, such as Indonesia and Malaysia, which account for approximately 85% of global palm oil production and exportation of palm oil, meal, and other derivatives [3,4].

Palm oil extraction yields two end products: palm oil, derived from the mesocarp for human consumption, and palm kernel oil, obtained from the kernels mainly used by the oleochemical industry [5–7]. Consequently, the palm oil sector produces various by-products, some considered agro-industrial waste, such as the fiber-rich biomass residue generated after the oil extraction process of palm kernels known as palm kernel cake (PKC) [8,9]. Additionally, PKC can be further processed to produce palm kernel meal

(PKM). The global production of PKC was estimated at 8 million tons in 2020 [9], while Malaysia alone produced over 2.3 million metric tons by the end of 2024 [10]. PKC consists of approximately 30 to 35% β -mannan, which accounts for 75% of its degradable non-starch polysaccharides, qualifying PKC as a source of mannose [9]. Furthermore, the composition of PKC presents a challenge due to its 50.3% carbohydrate content, which includes 11.6% cellulose and 61.5% hemicellulose [11,12]. Cellulose is strongly associated with hemicellulose and lignin in PKC, leading to significant challenges for mannose isolation [13].

Mannose ($C_6H_{12}O_6$) is a hexose sugar, mainly seen in the plant cell wall as a component of the complex polysaccharide mannan [14]. Mannan consists of β -1,4-linked mannose (linear mannan) or glucose (glucomannan), along with alternating side chains of α -1,6-linked galactose residues (galactomannan/galactoglucomannan) [15]. The functional sugar mannose has been widely used in the pharmaceutical, animal feed, and food industries, including as an alternative to sucrose or as an important dietary supplement [14,16]. Various methods have been utilized to produce mannose from plants, including enzymatic hydrolysis (EH) due to its mild conditions, high efficiency, and ecofriendliness, which are major environmental challenges when managing excess PKC waste [9,14]. Additionally, mannose can be further processed to produce a mannose-rich syrup that can serve as a functional ingredient in the food industry [16]. Opposingly, compared to other sugars and their potential use as food syrups, more studies have reported the therapeutic utilization of mannose in limiting the recurrence of urinary tract infections or suppressing inflammatory diseases [17,18]. Furthermore, given the growing interest in sustainable mannose production from plant-derived mannan, agro-industrial residues, such as palm kernel meal, provide a promising and abundant raw material for valorization.

In this study, the two main objectives were to (1) establish an optimized methodology to produce and maximize the mannose content (g/L) from palm kernel meal powder (PKMP) and (2) to further process the optimized treatment sample into a palm kernel mannose syrup (PKMS) for physicochemical analysis (total soluble solids, pH, moisture content, water activity, and color analysis). To accomplish our goals, a response surface methodology (RSM) framework was applied to optimize the enzymatic hydrolysis of PKMP coupled with a desirability function to maximize the mannose content, thus leading to the production of palm kernel mannose syrup (PKMS). To the best of our knowledge, our study is the first to couple a desirability function method with this type of experimental design in order to maximize or minimize specific factors that consequently lead to the final production of a novel PKMS whose physical and chemical properties we then analyzed. Furthermore, our optimized mannose extraction protocol capitalizes on the opportunity to implement an environmentally friendly and cost-effective industrial process to produce a final marketable food product from revalorized palm kernel meal.

2. Materials and Methods

2.1. Materials

Palm kernel cake (PKC) is a byproduct obtained from the mechanical extraction of oil from palm kernel [19]. The palm kernel cake used in this study was donated by Palmas del Ixcan (Guatemala and UUMBAL AgroIndustrial, Palenque, Chiapas, Mexico), and it was received in the form of flour. For the EH, the enzymes Laccase Y120 (Laccase; 108,000 POU/g; CAS No. 80498-15-3; Amano Enzyme Inc., Elgin, IL, USA), AromaseTM H2 (Beta-glucosidase; 80 U/g; CAS No. 9001-22-3; Amano Enzyme Inc., Elgin, IL, USA), and Mannanase BGM “Amano” 10 (Mannanase; 10,000 U/g; CAS No. 37288-54-3; Amano Enzyme Inc., Elgin, IL, USA) were used. All other chemicals and reagents were analytical grade (Sigma Aldrich, Saint Louis, MO, USA) unless otherwise specified. All analytical instruments were submitted to routine calibration.

2.2. Palm Kernel Meal Powder Preparation

The PKC was pulverized using a high-speed multifunction grinder (HC-2000, Goldenwall, Glendale, CA, USA) and sieved (80 mesh), and then mixed to form a single batch of flour. This mesh size was used as a standard proxy to ensure uniformity of the biomass fraction. Although it was not directly measured and may be considered in future studies, the approximate particle size was $\sim 180\ \mu\text{m}$. Next, the sample was defatted by combining hexane (25 *w/v*; 200 mL of hexane to 50 g palm kernel cake flour) with palm kernel cake flour and subjected to ultrasonication (YUCHENGTECH Ultrasonic Homogenizer Sonicator, 20 kHz, 900 W; Shenzhen, China) for 30 min (50% power with the automatic temperature shut off set to 45 °C). After, the sample was agitated at room temperature with a 5-inch LED magnetic stirrer at 800 rpm for one hour. Then, the produced palm kernel meal solids were separated from the supernatant by centrifugation (Thermo Scientific™ Sorvall™ X4R Pro-MD; Osterode, Germany) at 3488 RCF (4000 rpm) for 30 min. The solvent (n-hexane) was evaporated through rotary evaporation (Büchi Rotavapor® R-300; Büchi Labortechnik AG, Meierseggestrasse 40, Flawil, Switzerland), and the defatted palm kernel meal solids were collected and left to air-dry in a fume hood for at least 24 h until a dry flour was produced.

The delignification of the palm kernel meal solids was performed using the Wise method described by [20] with modifications. For this, 20 g of palm kernel meal solids and 500 mL of double-deionized water (DDI) were combined in a 1000 mL Erlenmeyer flask. Subsequently, 4 mL of acetic acid and 6.66 g of sodium chlorite were added to the solution, covered, and stirred in a water bath at 70 °C for 2 h. This process was carried out two more times, where every two hours the same amount of acetic acid and sodium chlorite was added, for a total delignification duration of 6 h under the same conditions. After centrifugation at 3488 RCF (4000 rpm) for 15 min, the supernatant was discarded, and the palm kernel meal solids pellet was rinsed with DDI until pH 7 was reached. Afterward, the solids were dried in a vacuum oven (Isotemp 285A vacuum oven, Fisher Scientific, Hampton, NH, USA) at 50 °C for approximately 24 h. Lastly, the delignified palm kernel meal was ground using a high-speed multifunction grinder and sieved (80 mesh) to form a single batch and will be referred to as palm kernel meal powder (PKMP) herein (Figure 1).

2.3. Optimization of Enzymatic Hydrolysis of Palm Kernel Meal Powder

A 3³ Box–Behnken design (BBD) within a response surface methodology (RSM) framework was applied to optimize the enzymatic hydrolysis (EH) of palm kernel meal powder (PKMP). To maximize the dependent variable mannose concentration (g/L), three independent factors were evaluated at three levels: (A) hydrolysis time (16, 32, and 48 h), (B) solids content (5, 10, and 15%), and (C) enzyme concentration (5, 7.5, and 10%), yielding 15 trial treatments (Table 1). Optimal hydrolysis conditions were then identified using a desirability function to maximize the mannose content, leading to the production of palm kernel mannose syrup (PKMS).

The 15 test trials were prepared in 50 mL centrifuge tubes using 3 g of PKMP and different volumes of DDI to prepare the various treatments (Table 1). The pH of each solution was adjusted to 4.0. using an HCl solution and a pH meter (model Orion Star A211, Thermo Fisher Scientific, Waltham, MA, USA) due to the optimal condition ranging between pH 4–5 for these enzymes. That said, the EH was conducted using the methodology described by [21,22] with modifications. For this, samples were pretreated with Laccase Y120 (10% *w/w*) and Aromase™ H2 (10% *w/w*) enzymes and were then placed in an incubator shaker at 50 °C under constant mixing (200 rpm) for 6 h. Subsequently, the mannanase enzyme was added in different percentages and incubated for each of the previously established times (Table 1). Finally, samples were placed in a water bath at 90 °C for 7 min to deactivate the enzymes. Samples were centrifuged at 4415 RCF (4500 rpm)

for 10 min, and the supernatant was kept in cold storage ($-20\text{ }^{\circ}\text{C}$) until the mannose content was measured. For the optimized treatment sample, a similar EH procedure was conducted under optimized conditions (16 h, 5% solids (w/v) and enzyme % (w/w)). Then, the mannose content (g/L) was measured, followed by the mannose yield (%), and a palm kernel mannose syrup (PKMS) was produced for further characterization (Figure 1).

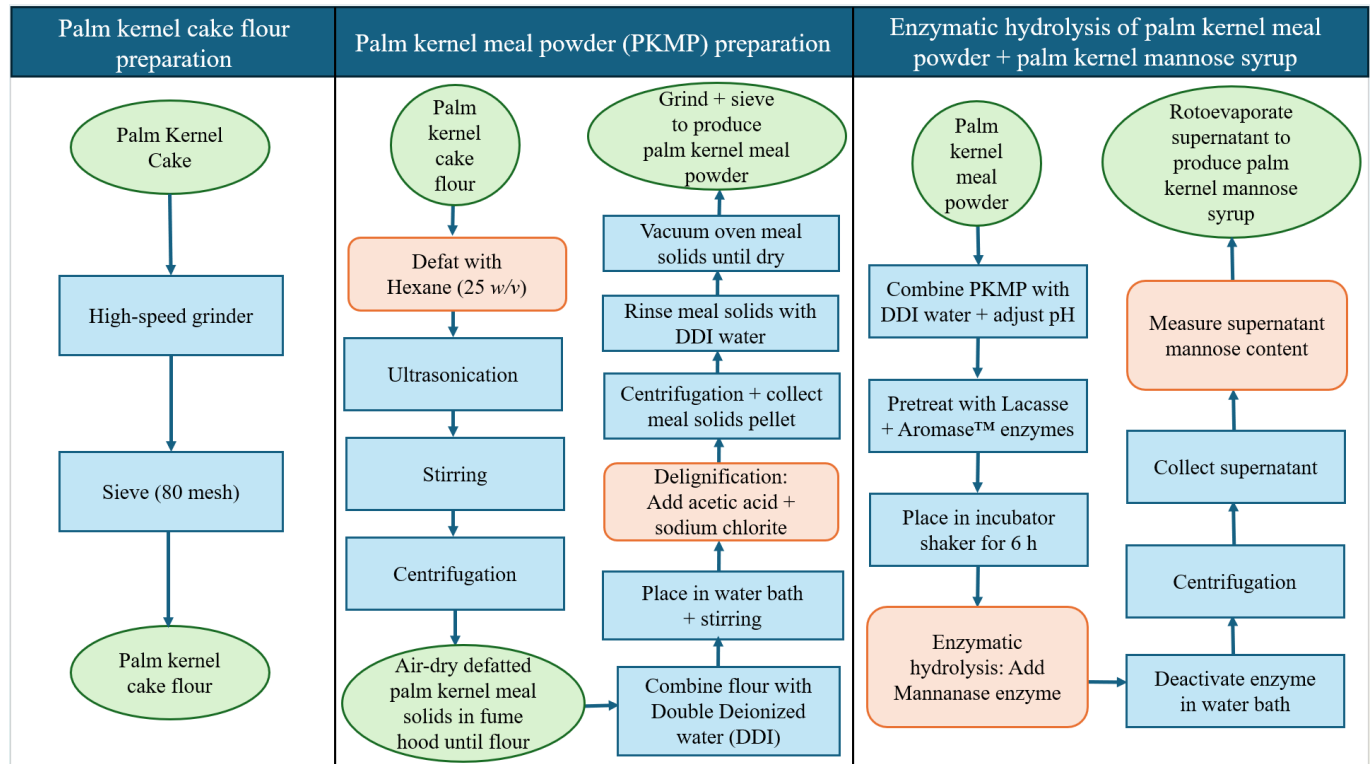


Figure 1. A flow diagram of the process of the palm kernel cake flour preparation, palm kernel meal powder (PKMP) preparation via defatting and delignification, and the enzymatic hydrolysis optimization of palm kernel meal powder and the subsequent production of palm kernel mannose syrup (PKMS).

Table 1. Experimental 3^3 Box–Behnken design matrix and the mannose content results for 15 test trials to optimize the enzymatic hydrolysis conditions for palm kernel meal powder (PKMP) to maximize the mannose content using the Mannanase BGM “Amano” 10 enzyme.

Test	Time (h)	Solid (% w/v)	Enzyme (% w/w)	Mannose Content (g/L)
1	16	5	7.5	4.33
2	48	5	7.5	4.87
3	16	15	7.5	1.02
4	48	15	7.5	3.34
5	16	10	5	1.51
6	48	10	5	2.41
7	16	10	10	1.75
8	48	10	10	4.08
9	32	5	5	4.53
10	32	15	5	1.30
11	32	5	10	4.98

Table 1. Cont.

Test	Time (h)	Solid (% w/v)	Enzyme (% w/w)	Mannose Content (g/L)
12	32	15	10	2.48
13 *	32	10	7.5	1.98
14 *	32	10	7.5	1.80
15 *	32	10	7.5	2.21

Legend: * central points.

2.4. Quantifying Mannose Content (g/L) and Mannose Yield (%)

To measure the mannose content from the 15 test trials, the EH supernatant was analyzed following the manufacturer's instructions for D-Mannose, D-Fructose, D-Glucose Assay kit (K-MANGL) (Megazyme International, Wicklow, Ireland). For this, D-mannose was measured using an enzymatic spectrophotometric method at 340 nm. Each test sample was mixed with a buffer and NADP⁺ / ATP, and the initial absorbance was recorded. The reaction was started by adding the specific enzymes provided in the kit, and the change in absorbance was measured after each step. Additional enzymes were added subsequently to quantify the mannose specifically. The sugar concentration was calculated by measuring the change in absorbance at each reaction step. Each change in absorbance corresponded to glucose, fructose, or mannose.

Subsequently, to measure the mannose yield (%) for the optimized experimental treatment sample, the following calculation was used (Equation (1); [23]):

$$\text{Mannose yield (\%)} = \frac{(C_{\text{mannose}} - C_{\text{mannose}}^0) \times 0.9}{\left(\frac{W_{\text{PKM}}}{V^0}\right) \times F_{\text{mannan}}} \times 100 \quad (1)$$

C_{mannose} : The mannose content concentration in the hydrolysate (g/L);

C_{mannose}^0 : The initial mannose concentration (g/L);

W_{PKM} : The dry weight of PKMP used for the extraction (g);

V^0 : The initial liquid volume (L);

F_{mannan} : The mannan fraction in the PKMP.

2.5. Production and Physicochemical Analysis of the Palm Kernel Mannose Syrup (PKMS)

The PKMS was produced using optimized conditions, followed by the evaporation of the obtained EH supernatant in a rotary evaporator at 55 °C until a syrup was produced.

Total Soluble Solids (°Brix), pH, Moisture Content, Water Activity (a_w), and Color Analysis

Using a digital refractometer (model MA871, Milwaukee, WI, USA), the total soluble solids (°Brix) were measured. To measure the pH of the syrup, a pH meter (model Orion Star A211, Thermo Fisher Scientific, Waltham, MA, USA) was used. A moisture analyzer (Mettler Toledo HE53, Columbus, OH, USA) was used to measure the moisture content, and the water activity (a_w) was measured using an Aqualab water activity meter (model 4TE, Meter, Palo Alto, CA, USA). A colorimeter (CR-5; Konica Minolta, Tokyo, Japan), previously calibrated with white and black standards, was used for color analysis. CIELAB L* (lightness), a* (redness–greenness), and b* (yellowness–blueness) parameters were recorded.

3. Statistical Analysis

The software DesignExpert (version 13; Stat-Ease, Minneapolis, MN, USA) was used for the establishment of the experimental design and the BBD data analysis. The regression

model was adjusted to experimental data, and the response surfaces were elaborated. To maximize the mannose content response and generate optimized EH conditions, a desirability function method was used. Experimental replicates were performed in triplicate, and the characterization replicates were performed in duplicate. The statistical data analysis for characterization was performed by analysis of variance (ANOVA).

4. Results and Discussion

4.1. Optimization of Enzymatic Hydrolysis Conditions to Maximize Mannose Content

Using results from Table 1, an independent regression model was constructed for the mannose content (g/L). The coded factors were (A) hydrolysis time (h), (B) solids content (% w/v), and (C) enzyme concentration (% w/w) (Equation (2)):

$$\text{Mannose content (g/L)} = 2.00 + 0.7620A - 1.32B + 0.4490C + 0.4467AB + 0.3583AC + 1.14B^2 \quad (2)$$

The mannose content was influenced by (A) hydrolysis time (h), (B) solids content (% w/v), and (C) enzyme concentration (% w/w), in addition to the linear interaction between AB and AC. The negative impact of the loading of solids (B) is linked to mass transfer limitations, such as an increase in viscosity, limiting effective enzyme–substrate interactions. A higher amount of solids could also lead to particle aggregation, reducing the accessible surface area and limiting the hydration of the mannan. The downward curvature observed in the 3D response surface images (Figure 2) is dictated by the quadratic term B^2 , indicating that factor B influenced mannose production in a non-linear manner. The resulting downward curvature demonstrated that there was an optimal region where the mannose content maximized before diffusional constraints or inhibition became significant.

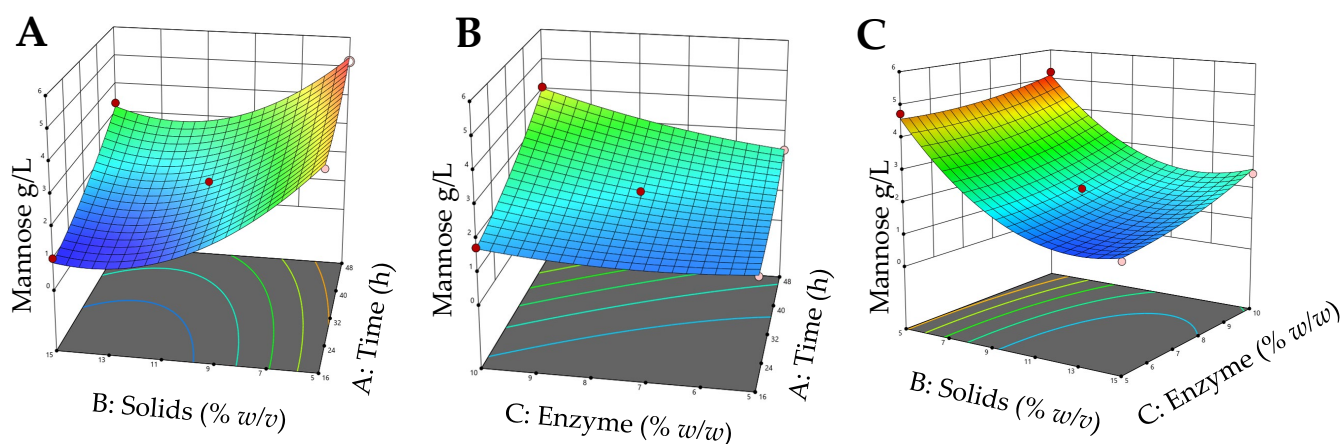


Figure 2. The three-dimensional response surfaces obtained to optimize the palm kernel meal powders' (PKMP) mannose content (g/L). (A): B, solids content (% w/v) by A, hydrolysis time (h); (B): C, enzyme concentration (% w/w) by A, hydrolysis time (h); and (C): B, solid content (% w/v) by C, enzyme concentration (% w/w).

The ANOVA results of the BBD model (Table 2) show that the mannose content model is predictive, with an F-value of 68.26 and a p -value of 0.0001. The model sum of the squares ($SS = 26.57$) accounts for almost all the overall variability ($SS = 26.78$), suggesting that the model predicts mannose content with accuracy. The lack-of-fit (LoF) test is non-significant ($p = 0.5375$), indicating that the model fits the data. The high coefficient R^2 of 0.9919 indicates that the model correctly captures the variability of the observed variable (mannose content).

Table 2. The analysis of variance (ANOVA) of the BBD model to maximize the mannose content.

Factor	SS	df	MS	F-Value	p-Value
Mannose content (g/L)					
Model	26.57	9	2.95	68.26	0.0001
Residual	0.2162	5	0.0432		
LoF	0.1293	3	0.0431	0.9920	0.5375
PE	0.0869	2	0.0435		
Total	26.78	14			
R ²	0.9919				

Legend: SS: Sum of squares, df: degree of freedom, MS: mean square, LoF: lack of fit, PE: pure error, and R²: correlation coefficient.

As seen in Table 1, the highest mannose content (4.98 g/L) was achieved after 32 h, 5% *w/v* solids content, and 10% *w/w* enzyme concentration, resulting in a mannose yield of 27.67%. This is similar to the results found by [24], which reported a 30% yield by applying EH to extract mannose from PKC using a 10% (*v/w*) mannanase enzyme and a 5% solids content. Additionally, ref. [23] recovered 98.6% of the mannose from açai seeds. For this, they pretreated the sample with sulfuric acid at 121 °C, then used mannanase for EH. The PKC is more resistant to EH due to its unique refractory lignocellulosic structure, which suggests that the enzyme has less accessibility to mannans than it does to other biomass products [22]. This implies that an improved lignin removal procedure should be applied to increase the overall mannose content and subsequently the mannose yield.

That said, the PKC sample underwent defatting and delignification to produce the PKMP, prepping the sample for enzymatic hydrolysis to improve the extraction of mannose. However, residual lignin and or phenolic inhibitors may still be present in the sample, hindering the efficiency of the mannose extraction. Because of this, mannanase alone may be limited in accessing mannan, so a pretreatment was applied. Laccase Y120 is a phenol-oxidizing enzyme that further degrades residual lignin, helping to expose mannan chains by making them more accessible during hydrolysis. In addition, Aromase™ H2 complements laccase by further removing residual lignin or phenolic inhibitors, helping Laccase with opening the plant cell wall, consequently improving substrate accessibility. Together, these enzymes ensure a more complete delignification; however, neither of these enzymes hydrolyze mannan into mannose. Mannanase BGM “Amano” 10 is responsible for generating mannose by cleaving β-1,4-mannosidic linkages in linear mannan or gluco-mannan, thus converting polysaccharides into manno-oligosaccharides and free mannose. Altogether, the combination of these enzymes improves the mannose extraction efficiency and the subsequent mannose yield.

Furthermore, for this study, a desirability function that maximized the mannose content and solids content while minimizing the hydrolysis time and enzyme concentration was used to identify the optimal EH conditions based on the mannose content results of the 15 test trials (Table 1). The determined optimal conditions for the experimental treatment sample were a hydrolysis time of 16 h, 5% solids content (*w/v*), and 5% enzyme concentration (*w/w*). The expected mannose content concentration calculated by the desirability function was 4.682 g/L, and the actual measured experimental value was 4.325 g/L. The measured mannose content value for the experimental treatment was then used to calculate the overall mannose yield ($24.33 \pm 0.5\%$; Equation (3)). After, the experimental treatment sample was further processed into a PKMS for physicochemical characterization.

$$\text{Mannose yield (\%)} = \frac{(4.325 - 0) \times 0.9}{\left(\frac{3}{0.06}\right) \times 0.32} \times 100 \quad (3)$$

C_{mannose} : The mannose content concentration in the hydrolysate (g/L);

C_{mannose}^0 : The initial mannose concentration (g/L);

W_{pkm} : The dry weight of PKMP used for the extraction (g);

V^0 : The initial liquid volume (L);

F_{mannan} : The mannan fraction in the PKMP.

4.2. Economic Assessment of Process Optimization

The present work focuses on developing a tailored pretreatment and enzymatic strategy demonstrating the feasibility and optimization of mannose production from PKM by providing insights into enzyme usage, process efficiency, and scalability. Based on current enzyme and raw material costs, the estimated production cost for mannose under the optimized conditions is ~\$20/kg compared to a higher cost of approximately ~\$30/kg under the maximum-yield conditions due to longer reaction time and higher enzyme usage. Although the pretreatment sequence is multistep, each enzyme targets specific structural barriers to maximize the mannose yield. Moreover, the highest mannose concentration (4.98 g/L at 32 h) corresponds to a productivity of ~0.16 g/L·h, the optimized condition (4.325 g/L at 16 h) reaches ~0.27 g/L·h while reducing the enzyme loading by 50%. This shows that the selected optimum is driven by process efficiency, balancing yield, time, and enzyme cost rather than maximizing concentration alone. Though the reported yields may differ from some earlier works, this study provides a novel understanding of biomass-specific strategies and optimization approaches relevant to cost-effective mannose production. In addition, unit operations are industrially established and can be streamlined during scale-up. Furthermore, these parameters are being systematically captured in ongoing studies to provide a comprehensive basis for process optimization and scale-up evaluation.

4.3. Characterization of Palm Kernel Mannose Syrup (PKMS)

The physicochemical properties (total soluble solids (°Brix), pH, moisture content, water activity (a_w), and color analysis) were analyzed to evaluate the stability and storage suitability of PKMS (Table 3). The optimized treatment had a low moisture content ($15.85 \pm 0.07\%$). Because the moisture content influences the final product's stickiness, stability, and shelf life, it is a crucial factor to consider when making syrups [25]. The PKMS had a limited water availability ($a_w = 0.6918 \pm 0.003$), minimizing the risk of most kinds of microbial growth [26,27]. The water activity is also important because it has a major impact on the sensory qualities of food, such as flavor, texture, and aroma [28,29].

Table 3. The physicochemical properties and color parameters of the palm kernel mannose syrup (PKMS) obtained under the optimized EH conditions.

Parameter	PKMS
Moisture (%)	15.85 ± 0.07
a_w	0.6918 ± 0.003
°Brix	70.1 ± 0.424
pH	4.05 ± 0.282
L^* (Lightness)	47.92 ± 0.198
a^* (Red-Green)	34.35 ± 0.565
b^* (Yellow-Blue)	64.81 ± 0.261

Legend: The results are shown as mean $\pm$ standard deviation (n = 2).

The PKMS had a total soluble solids content of 70.1 ± 0.424 and a pH value of 4.05 ± 0.282 , which indicated that the syrup was acidic. Thus, our results help improve the syrups' shelf-life stability and aid in inhibiting microbial growth. Generally, the food products are divided into two groups: high-acid (pH < 4.6) and low-acid (pH > 4.6). The basis for this distinction is the foodborne pathogen *Clostridium botulinum*'s capacity to proliferate at the lower threshold pH of 4.6 [30]. Furthermore, PKMS is a stable product with a lower chance of spoiling according to its measured physicochemical properties.

Moreover, color is another important characteristic of food products, as it allows them to be used in different food matrices. The CIELAB color space parameters were measured for the optimized treatment sample (Table 3), where the L value (lightness) was 47.92 ± 0.198 , representing a moderate lightness. The a value (34.35 ± 0.565) indicates a tendency toward red, while the b value (64.81 ± 0.261) leans toward a yellow component in the color.

5. Conclusions

This research effectively optimized the EH of PKMP by using response surface methodology coupled with a desirability function method, determining the optimal conditions of 5% (*w/v*) solids content, 10% (*w/w*) enzyme concentration, and a hydrolysis time of 16 h. In addition, the subsequent mannose-rich syrup (PKMS) demonstrated low moisture content, reduced water activity, and acidic pH, which are characteristics that improve its shelf stability and offer a wide range of potential uses in different areas of the food industry. This study indicates that palm kernel meal powder represents a strategic source of mannose for diverse applications. Enhancements in extraction efficiency and sensory improvements could lead to the development of high-quality, sustainable ingredients. Furthermore, although part of the scope of this study was to increase the mannose yield from plant-derived mannan, future work will focus on the other components of PKCs and subsequent PKMs, including protein concentration and dietary fiber purification.

Author Contributions: Conceptualization, methodology, resources, writing—review and editing, supervision, project administration, funding acquisition, M.M.; conceptualization, methodology, software, formal analysis, F.G.M.d.M.; conceptualization and writing—review and editing, R.T.H.; visualization, writing—original draft preparation and writing—review and editing, J.S.; methodology, software, formal analysis, investigation, data curation, visualization, writing—original draft preparation and writing—review and editing, K.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: Palm kernel cake (starting raw material) was donated by Palmas del Ixcán (Guatemala and UUMBAL AgroIndustrial, Palenque, Chiapas, México). The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

PKC	Palm kernel cake
PKM	Palm kernel meal
EH	Enzymatic hydrolysis
PKMP	Palm kernel meal powder
PKMS	Palm kernel mannose syrup
RSM	Response surface methodology
DDI	Double-deionized water
BBD	Box–Behnken design
a_w	Water activity
°Brix	Total soluble solids
ANOVA	Analysis of variance

References

1. Carrere, R. *Oil Palm in Africa: Past, Present, and Future Scenarios*; World Rainforest Movement: Montevideo, Uruguay, 2013; p. 15.
2. Gruca, M.; van Andel, T.R.; Balslev, H. Ritual uses of palms in traditional medicine in sub-Saharan Africa: A review. *J. Ethnobiol. Ethnomed.* **2014**, *10*, 60. [\[CrossRef\]](#)
3. Murphy, D.J.; Goggin, K.; Paterson, R.R.M. Oil palm in the 2020s and beyond: Challenges and solutions. *CABI Agric. Biosci.* **2021**, *2*, 39. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Tabe-Ojong, M.P.J.; Molua, E.L.; Nanfouet, M.A.; Mkong, C.J.; Kiven, V.; Ntegang, V.A. Oil palm production, income gains, and off-farm employment among independent producers in Cameroon. *Ecol. Econ.* **2023**, *208*, 107817. [\[CrossRef\]](#)
5. Alhaji, A.M.; Almeida, E.S.; Carneiro, C.R.; da Silva, C.A.S.; Monteiro, S.; Coimbra, J.S.d.R. Palm Oil (*Elaeis guineensis*): A Journey through Sustainability, Processing, and Utilization. *Foods* **2024**, *13*, 2814. [\[CrossRef\]](#)
6. Gibon, V. Palm Oil and Palm Kernel Oil Refining and Fractionation Technology. In *Palm Oil: Production, Processing, Characterization, and Uses*; Academic Press and AOCS Press: Champaign, IL, USA, 2012. [\[CrossRef\]](#)
7. Sundram, K.; Sambanthamurthi, R.; Tan, Y.-A. Palm fruit chemistry and nutrition. *Asia Pac. J. Clin. Nutr.* **2003**, *12*, 355–362. [\[PubMed\]](#)
8. Chieng, B.W.; Lee, S.H.; Ibrahim, N.A.; Then, Y.Y.; Loo, Y.Y. Isolation and characterization of cellulose nanocrystals from oil palm mesocarp fiber. *Polymers* **2017**, *9*, 355. [\[CrossRef\]](#)
9. Dong, W.; Dong, S.; Li, Y.; Lei, Y.; Peng, N.; Liang, Y.; Zhao, S.; Ge, X. Comprehensive utilization of palm kernel cake for producing mannose and manno-oligosaccharide mixture and yeast culture. *Appl. Microbiol. Biotechnol.* **2022**, *106*, 1045–1056. [\[CrossRef\]](#) [\[PubMed\]](#)
10. Malaysian Palm Oil Board. Production of Palm Kernel Cake for the Month of December 2025, January–June 2024 & 2025 (TONNES). 2025. Available online: <https://bepi.mpob.gov.my/index.php/import/1194-production-of-palm-kernel-cake-2025> (accessed on 1 March 2026).
11. Azman, N.F.; Abdeslahian, P.; Kadier, A.; Shukor, H.; Al-Shorgani, N.K.N.; Hamid, A.A.; Kalil, M.S. Utilization of palm kernel cake as a renewable feedstock for fermentative hydrogen production. *Renew. Energy* **2016**, *93*, 700–708. [\[CrossRef\]](#)
12. Baladrán-Quintana, R.R.; Mendoza-Wilson, A.M.; Ramos-Clamont Montfort, G.; Huerta-Ocampo, J.Á. Chapter 4—Plant-Based Proteins. In *Proteins: Sustainable Source, Processing and Applications*; Elsevier: Amsterdam, The Netherlands, 2019.
13. Abolore, R.S.; Jaiswal, S.; Jaiswal, A.K. Green and sustainable pretreatment methods for cellulose extraction from lignocellulosic biomass and its applications: A review. *Carbohydr. Polym. Technol. Appl.* **2024**, *7*, 100396. [\[CrossRef\]](#)
14. Dhanalakshmi, M.; Sruthi, D.; Jinuraj, K.R.; Das, K.; Dave, S.; Andal, N.M.; Das, J. Mannose: A potential saccharide candidate in disease management. *Med. Chem. Res.* **2023**, *32*, 391–408. [\[CrossRef\]](#)
15. Berglund, J.; Azhar, S.; Lawoko, M.; Lindström, M.; Vilaplana, F.; Wohler, J.; Henriksson, G. The structure of galactoglucomannan impacts the degradation under alkaline conditions. *Cellulose* **2019**, *26*, 2155–2175. [\[CrossRef\]](#)
16. Hu, X.; Shi, Y.; Zhang, P.; Miao, M.; Zhang, T.; Jiang, B. d-Mannose: Properties, Production, and Applications: An Overview. *Compr. Rev. Food Sci. Food Saf.* **2016**, *15*, 773–785. [\[CrossRef\]](#)
17. Zhang, W.; Cheng, H.; Gui, Y.; Zhan, Q.; Li, S.; Qiao, W.; Tong, A. Mannose Treatment: A Promising Novel Strategy to Suppress Inflammation. *Front. Immunol.* **2021**, *12*, 756920. [\[CrossRef\]](#)
18. Kyriakides, R.; Jones, P.; Somani, B.K. Role of D-Mannose in the Prevention of Recurrent Urinary Tract Infections: Evidence from a Systematic Review of the Literature. *Eur. Urol. Focus* **2021**, *7*, 1166–1169. [\[CrossRef\]](#)

19. Azizi, M.N.; Loh, T.C.; Foo, H.L.; Chung, E.L.T. Is palm kernel cake a suitable alternative feed ingredient for poultry? *Animals* **2021**, *11*, 338. [[CrossRef](#)]
20. Ilyas, R.A.; Sapuan, S.M.; Ishak, M.R.; Zainudin, E.S. Effect of delignification on the physical, thermal, chemical, and structural properties of sugar palm fibre. *Bioresources* **2017**, *12*, 8734–8754. [[CrossRef](#)]
21. Singh, G.; Kumar, S.; Afreen, S.; Bhalla, A.; Khurana, J.; Chandel, S.; Aggarwal, A.; Arya, S.K. Laccase mediated delignification of wasted and non-food agricultural biomass: Recent developments and challenges. *Int. J. Biol. Macromol.* **2023**, *235*, 123840. [[CrossRef](#)] [[PubMed](#)]
22. Shukor, H.; Abdeslahian, P.; Al-Shorgani, N.K.N.; Hamid, A.A.; Rahman, N.A.; Kalil, M.S. Enhanced mannan-derived fermentable sugars of palm kernel cake by mannanase-catalyzed hydrolysis for production of biobutanol. *Bioresour. Technol.* **2016**, *218*, 257–264. [[CrossRef](#)] [[PubMed](#)]
23. Monteiro, A.F.; Miguez, I.S.; Silva, J.P.R.B.; da Silva, A.S. High concentration and yield production of mannose from açai (*Euterpe oleracea* Mart.) seeds via mannanase-catalyzed hydrolysis. *Sci. Rep.* **2019**, *9*, 10939. [[CrossRef](#)]
24. Cerveró, J.M.; Skovgaard, P.A.; Felby, C.; Sørensen, H.R.; Jørgensen, H. Enzymatic hydrolysis and fermentation of palm kernel press cake for production of bioethanol. *Enzym. Microb. Technol.* **2010**, *46*, 177–184. [[CrossRef](#)]
25. Wang, R.; Hartel, R.W. Effects of moisture content and saccharide distribution on the stickiness of syrups. *J. Food Eng.* **2020**, *284*, 110067. [[CrossRef](#)]
26. Peleg, M. Models of the water activity effect on microbial growth rate and initiation. *Appl. Microbiol. Biotechnol.* **2022**, *106*, 1375–1382. [[CrossRef](#)]
27. Schlamb, J.; de Medeiros, F.G.M.; Hoskin, R.T.; Wainwright, K.; Moncada, M. A Novel Approach Coupling Optimized Enzymatic Hydrolysis Conditions with Spray Drying to Produce Functional Acheta domesticus Protein Powder Ingredients. *Appl. Sci.* **2025**, *15*, 9721. [[CrossRef](#)]
28. Maneffa, A.J.; Stenner, R.; Matharu, A.S.; Clark, J.H.; Matubayasi, N.; Shimizu, S. Water activity in liquid food systems: A molecular scale interpretation. *Food Chem.* **2017**, *237*, 1133–1138. [[CrossRef](#)]
29. Rahman, M.S. *Handbook of Food Preservation*, 3rd ed.; CRC Press: Boca Raton, FL, USA, 2016.
30. Rolfe, C.; Daryaei, H. Intrinsic and Extrinsic Factors Affecting Microbial Growth in Food Systems. In *Food Safety Engineering*; Food Engineering Series; Springer: Cham, Switzerland, 2020. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.