

Original Research Article

Techno-Economic Feasibility of Winged Bean Seed Oil and Protein Meal Production

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Abstract: The rising demand for plant-based protein and oil, coupled with Malaysia's heavy reliance on imported soybeans, has underscored the need for alternative local crops, especially winged bean (*Psophocarpus tetragonolobus*). This study evaluates the nutritional potential and processing feasibility of winged bean seeds (WBS) as a substitute for soybean, focusing on proximate composition, process simulation, and techno-economic viability. Proximate analysis revealed that WBS are rich in protein (~36.05–41.13%) and oil (11.07–16.02%), comparable to commercial soybeans, supporting their potential for conventional oil extraction and protein-rich meal production. A process simulation was developed to assess oil and protein meal production, followed by a techno-economic analysis. The results showed strong economic indicators, including a short payback period (3.17 years), an internal rate of return (IRR) exceeding 45%, and a positive net present value (NPV), highlighting the commercial promise of WBS processing. Sensitivity analysis identified WBS price, product prices, and oil content as key economic drivers, while higher processing capacities improved financial performance. This study positions WBS as a sustainable and economically viable crop for enhancing national food and feed security while reducing dependence on soybean imports. Future work should focus on agronomic optimisation and integration into existing agro-industrial frameworks.

Keywords: Winged bean seed; edible oil; crude protein; techno-economic analysis

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1. Introduction

The winged bean (*Psophocarpus tetragonolobus*), locally known as 'kacang botol', is often referred to as the "soybean of the tropics" due to its exceptional nutritional profile. Well-suited to humid tropical climates, it thrives in countries such as Malaysia, Indonesia, Thailand, and Bangladesh (Sriwichai *et al.*, 2021). This versatile plant is highly valued because nearly all its parts, such as leaves, pods, seeds, and tubers, are edible and nutritionally

beneficial. In particular, the young pods are rich in total phenolics, flavonoids and exhibit strong antioxidant activity (Singh *et al.*, 2019).

The seeds, which are currently underutilised in Malaysia, contain 27–45% protein (Bepary *et al.*, 2023), placing them among the most protein-rich legumes, second only to soybeans (Yea *et al.*, 2014). In addition to protein, seeds are abundant in carbohydrates, with a well-balanced amino acid composition that enhances their potential as a plant-based protein source. The seeds of winged beans also possess oil, which can be extracted and used as a source of edible oil. The oil content of winged bean seeds varies between 15% and 23% (Bepary *et al.*, 2023). The oil may contain a high concentration of unsaturated fatty acids, such as linoleic acid and oleic acid, which have positive effects on cardiovascular well-being (Mohanty *et al.*, 2021). The fatty acid profile of winged bean oil (WBO) closely resembles that of soybean oil, indicating its potential as a viable alternative. Furthermore, winged bean oil is rich in tocopherols, which are inherent antioxidants that aid in safeguarding against oxidative harm (Bepary *et al.*, 2023).

The winged bean plant is considered a dual-purpose crop, as both its seeds and tubers hold economic and nutritional value (Sriwichai *et al.*, 2021). The tuber is particularly notable for its high carbohydrate content, primarily in the form of starch, comprising approximately 60–70% of its dry weight. The tropical conditions in Malaysia, characterised by consistent rainfall and well-drained soils, are ideal for its cultivation. Flowering typically begins 50 to 60 days after planting, with the crops reaching full maturity in about 3 to 4 months. Yields of 2 to 4 tons per hectare have been reported (Bahari & Azid, 2019), which is comparable to average soybean yields of around 3.4 tons per hectare in USA (USDA, 2025).

Despite its high nutritional potential, dedicated research and large-scale utilisation of winged bean in Malaysia remain limited, highlighting the need for further exploration and promotion of this crop. This study aims to fill this gap by characterising the proximate composition and evaluating their process compatibility using standard oil extraction and protein recovery methods. In response to safety and environmental concerns associated with hexane-based solvent extraction, this study proposes an alternative oil extraction route for WBS that integrates screw extrusion and mechanical pressing (Cheng & Rosentrater, 2019). A process simulation model was developed to estimate product yields and resource consumption, followed by a techno-economic analysis to assess capital expenditure (CAPEX) and operating expense (OPEX), profitability metrics, and scale-up potential. The findings offer critical insights into the feasibility of WBS as a soybean substitute and

contribute to broader strategies for enhancing local food and feed resilience through sustainable crop utilisation.

2. Materials and Methods

2.1. Winged Bean Seeds (WBS) Characterisations

Three different commercial sources of WBS and soybean (control) were purchased in Malaysia. All seeds were cleaned, dried, and ground to a uniform particle size using a laboratory mill. Analyses were carried out in triplicate. Standard methods were used to determine the proximate composition, methods described by Oladeji *et al.* (2016) and Adegboyega *et al.* (2019), such as moisture, ash, crude protein, crude oil/fat, crude fibre, and carbohydrate contents.

2.2. Process Flowsheet Development

The process design for WBS oil extraction was developed using SuperPro Designer v12 (Intelligen, Inc.), referencing a typical soybean oil processing flowsheet. The process flow consists of sequential unit operations, starting from raw material cleaning to final product packaging, as shown in Figure 1, developed as an overall process flowsheet by the software. The simulation emphasises energy integration, mass balances, and performance parameters for each unit operation.

2.2.1. Seed cleaning and drying

The raw WBS undergoes an initial cleaning step, where foreign materials such as stones, glass, and other debris are removed using a mechanical separator. This ensures that only clean seeds proceed to downstream processing. The cleaned WBS was then subjected to rotary drying to reduce its moisture content to 8% (wet basis). This was achieved by introducing preheated air (916 m³ per MT of WBS) at 125°C. The dried seeds exited the dryer at approximately 70°C, a temperature that supports efficient subsequent cracking (Mariani *et al.*, 2014).

2.2.2. Cracking

After drying, the WBS were fed into a cracking mill, where they were mechanically broken into smaller pieces. Unlike soybeans, WBS have a thin hull that adheres tightly to the kernel, making it difficult to separate. This strong adhesion makes conventional dehulling methods, such as those used for soybeans (Demarco & Gibon, 2020), where the hull separates

easily from the kernel, which was ineffective for WBS. Therefore, the cracked WBS was directly transferred to a holding hopper for the next step, extrusion, without a dehulling stage.

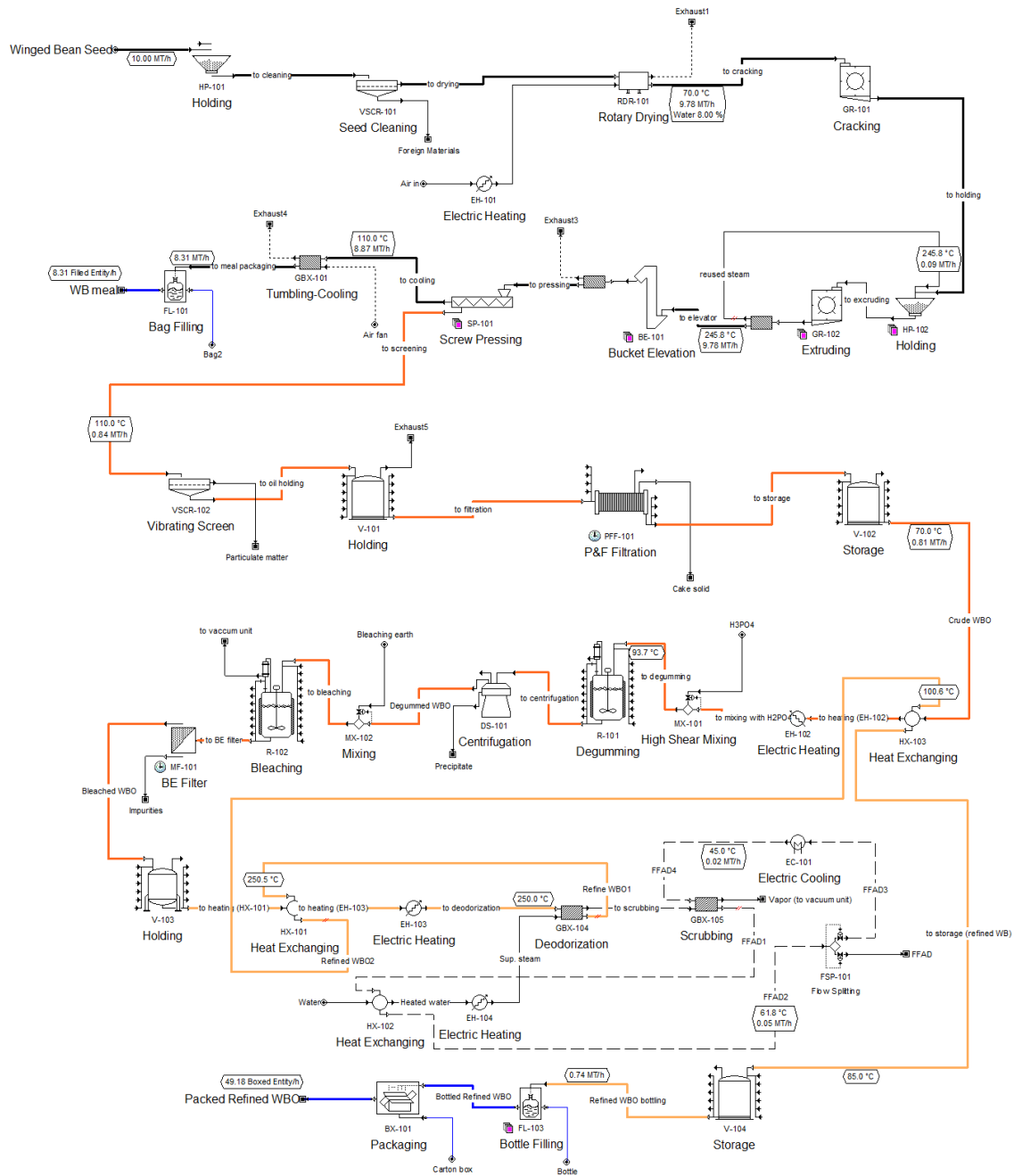


Figure 1. Process flowsheet of overall winged bean processing using SuperPro Designer

2.2.3. Extrusion and thermal conditioning

In the extrusion stage, the cracked WBS was processed under high mechanical shear and pressure using a screw extruder (Cheng & Rosentrater, 2019). The extruder was designed to generate the temperature of the material at 153°C, with an electric power input of 320 kW

per unit, of which 90% energy was assumed to be transferred to the material. This high-temperature processing improves oil yield by disrupting cell walls and releasing bound oil. A vapour recycling system was included to recover heat from the outgoing vapours, which was then redirected via a blower system to preheat the incoming WBS feed in the holding hopper as described in Figure 1, enhancing energy efficiency.

2.2.4. Cooling, pressing, and crude oil collection

After extrusion, the WBS was allowed to cool naturally via a bucket elevator, reducing the temperature to 110°C before entering the screw press (Patil & Ali, 2006). In the pressing stage, crude WBO was extracted, and the solid residue was separated as press cake. The press was set with a power input of 50 kW per unit, and a solids concentration of 94% in the cake, with an overall solid recovery efficiency of 99.7%. The press cake was then directed to a tumbling cooler, where it was cooled down to below 60°C before being packed in 1 MT bags for sale as animal meals.

2.2.5. Crude oil clarification and storage

The extracted crude WBO flows through a vibrating screen to remove coarse particulate residues. It was temporarily stored in a holding tank before undergoing press filtration, which removes fine suspended solids. The clarified WBO was then transferred to a storage tank before entering the refining stage, degumming-bleaching-deodorising.

2.2.6. Degumming and bleaching

The clarified WBO was initially heated to 94°C using an integrated heat recovery system. The heating process involved two stages (as shown in Figure 1): (i) heat integration with the hot refined oil stream exiting the deodoriser, and (ii) further heating to the target temperature using an independent electrical heater. The process is based on a physical refining process for vegetable oil (Gupta, 2017). Subsequently, approximately 0.33% w/w of 80% phosphoric acid was introduced into the heated WBO stream using high shear mixing to ensure proper emulsification and reaction with phospholipids. The acidified oil was then transferred into a degumming tank designed for a residence time of 20 min, allowing the formation of hydrated gums. Degumming precipitate can be further separated by centrifugation.

Following degumming, 0.8% w/w of bleaching earth was added to the oil. The mixture was introduced into a bleaching tank with a residence time of 40 min (under vacuum

pressure, e.g., 0.033 bar) to adsorb residual phospholipids, pigments, trace metals, and other impurities. After the bleaching stage, the oil-adsorbent mixture was directed to a bleaching earth (BE) filter unit to separate the spent bleaching earth and associated impurities. The filtrate (bleached oil) was then collected in a holding tank for further processing.

2.2.7. Deodorisation

The deodorisation stage involved vacuum steam distillation at 250°C and under vacuum pressure (0.002 bar), integrated with scrubbing to remove free fatty acid (FFA) and volatile compounds. Before deodorisation, the bleached oil was subjected to a two-stage heating process:

- Heat exchange with the hot refined WBO stream exiting the deodoriser.
- Further heating using an independent electrical heater to reach the deodorisation target temperature of 250°C.

Simultaneously, superheated steam at 375°C was prepared for the stripping process. The steam heating was also designed as a two-stage process: initially pre-heated using the hot FFAD-containing stream (from the scrubbing condensate), followed by further heating with an independent electrical heater (boiler) to reach superheated conditions, as shown in Figure 1. The deodoriser was integrated with a scrubbing system to recover and condense FFAD (free fatty acid distillate). The scrubbing stream was cooled using an independent electrical chiller to facilitate effective condensation and recirculation.

2.2.8. Post-deodorisation, packaging, and storage

The refined WBO exiting the deodorisation unit was further cooled to ambient conditions through heat recovery (exchanging heat with incoming crude WBO) and passed into a storage tank. The final product was filled into 1-L bottles, packed into carton boxes containing 15 bottles each, and prepared for distribution.

2.3. Mass and Energy Balance

The process model for the extraction of crude WBO and residual solids (animal meal) was developed using SuperPro Designer v12. The model simulates a continuous oil extraction facility with a capacity of 10 MT/h of WBS input as base capacity. Key unit operations were based on Section 2.2.

Each unit was parameterised using literature data (especially soybean-based systems) and experimental assumptions for WBS. The simulation performed steady-state mass and

energy balances across all units. Moisture, oil, and solids distributions were tracked across processing steps.

Recovered heat streams, particularly from extruder vapours and press outlet solids, were modelled to assess potential for heat integration and energy savings. It was also done for refining units (critically for the deodorisation step) to obtain refined WBO.

2.4. Techno-economic Analysis

The techno-economic analysis was conducted to evaluate the economic feasibility of the refined WBO and meal production process. Base capacity of the processing was set as 10 MT/h of WBS with an annual operating time (AOT) of 4350 h.

2.4.1. CAPEX estimation

Equipment cost data were derived from SuperPro Designer v12's internal cost library, scaled for the plant capacity using the six-tenths rule as shown in Equation 1:

$$C_2 = C_1 \left(\frac{Q_2}{Q_1} \right)^{0.6} \quad (1)$$

Direct costs (equipment, installation, piping & instruments, auxiliary facilities, etc.) and indirect costs (engineering, contingency, and building) were added to determine CAPEX based on multiplier factors described in (Mokhtar, 2022). Table S1 presents the equipment list and purchasing costs (PC), while Table S2 summarises the direct fixed capital (DFC). The total CAPEX was estimated as the sum of the DFC, working capital (WC), and start-up & validation cost (SC). The WC was assumed to cover 30 days of operation, while the SC was set at 5% of the DFC (Heinzle *et al.*, 2006).

2.4.2. OPEX estimation

The annual operating costs comprised several components, including inlet materials such as WBS and packaging bags; facility-dependent expenses such as maintenance, insurance, and general factory overhead; labour-dependent costs; and laboratory and quality control, which were estimated at 15% of the total labour cost. Utilities, including electricity and water, were calculated based on prevailing local industrial rates, for example, USD 0.10/kWh for electricity. Based on the range of global soybean prices reported by FRED (2025), a conservative base-case WBS price of USD 405/MT was assumed. Labour costs were referenced from the study by Mokhtar (2022).

2.4.3. Revenue estimation

In the base case scenario, refined WBO was priced at USD 45 per carton box, each containing fifteen 1-L bottles, while the WBS meal by-product was valued at USD 500/MT (per bag) based on the minimum expected market rates of soybean meal (Cheng & Rosentrater, 2019). Additionally, FFAD was considered as a revenue stream at an assumed selling price of USD 900/MT, with its potential utilisation as an alternative boiler fuel (Siyal *et al.*, 2021). For degumming precipitate and spent bleaching earth obtained from degumming and bleaching, respectively, they can be sold at a minimum price of USD 20/MT each.

2.4.4. Financial metrics

The financial performance of the project was evaluated using key indicators, including net present value (NPV) at a 10% discount rate, internal rate of return (IRR), payback time (PT), and return on investment (ROI). These metrics were calculated based on a 15-year project lifespan, employing straight-line depreciation over 10 years, and assuming a salvage value equivalent to 5% of the DFC. An income tax rate of 24% was applied, in line with local regulations (Mokhtar, 2022). The financing structure assumed 70% debt financing of the DFC, with a loan term of 10 years at an interest rate of 5%.

2.5. Sensitivity Analysis and Different Process Throughputs

A parametric sensitivity analysis was performed to identify the most influential variables affecting economic performance indicators, including NPV, IRR, PT, and ROI. Key parameters, such as the WBS buying price, selling prices of WBO and meal, electricity price, AOT, and DFC, were individually varied by $\pm 25\%$ from their baseline values.

Additional sensitivity analyses were conducted by independently varying the oil and protein contents by $\pm 25\%$ from their respective base-case values. For each variation, the remaining compositional components were proportionally adjusted while maintaining their relative ratios to ensure that the total seed composition remained at 100%. The resulting effects on CAPEX, OPEX, revenues, ROI, IRR, NPV, and PT were subsequently evaluated.

Furthermore, process capacity was varied by using 10 MT/h of WBS as the base case, and then simulating throughput changes by increasing to 20 and 30 MT/h and decreasing to 5 and 2.5 MT/h. The impacts of these capacity adjustments on CAPEX, OPEX, revenues, ROI, IRR, NPV, and PT were analysed.

3. Results

3.1. Chemical Compositions

Table 1 presents the experimental results for the composition of WBS, highlighting their potential as a viable alternative to commercial soybeans. The oil and protein contents of WBS were found to range from 11.07% to 16.02% and 36.05% to 41.13%, respectively, demonstrating values that are comparable to previous study by Bepary *et al.* (2023). In addition to these key macronutrients, the proximate analysis also revealed that the moisture content, crude fibre, ash, and carbohydrate levels of WBS are comparable to those of soybean, indicating that WBS possess a well-balanced nutritional profile. These findings support the potential of WBS as a promising local legume source for food and feed applications, particularly in regions aiming to reduce dependency on imported soy-based products.

Table 1. Chemical compositions of several sources of winged bean seed (WBS) and soybean (control)

Composition (%)	Soybean	WBS1	WBS2	WBS3
Moisture content	11.63 ± 0.09	9.64 ± 0.10	9.72 ± 0.09	10.42 ± 0.05
Oil	15.83 ± 0.83	11.07 ± 0.31	16.02 ± 0.48	13.23 ± 0.17
Protein	39.93 ± 0.76	41.13 ± 0.84	37.77 ± 0.85	36.05 ± 0.45
Fiber	12.17 ± 0.78	12.37 ± 0.26	16.34 ± 0.30	13.57 ± 0.38
Ash	5.40 ± 0.58	3.18 ± 0.62	5.55 ± 0.62	4.45 ± 0.40
Carbohydrate*	15.04	22.61	14.60	22.28

*Carbohydrate (%) = 100 – (Moisture + Ash + Crude Protein + Crude Fibre + Crude Fat)

3.2. Material Balances (Model-Predicted Values)

Table 2 presents a detailed simulation of the mass flow and composition across selected different processing stages of a 10 MT/h WBS processing system. Initially, the feedstock was set as 90% WBS dry matter with 9.9% moisture and a remaining amount of foreign material and was dried to reach a moisture content of 8%. Following screw extruding, the stream flow slightly reduces to 9.70 MT/h mainly due to moisture evaporation before mechanical pressing. It releases crude protein (39.45%), crude oil (13.84%), and other contents, which represent cell disruption. Following mechanical pressing, the extracted crude WBO stream (0.84 MT/h) exhibits high crude oil content (97.05%) with only minor contamination from carbohydrates, proteins, and water. Meanwhile, the press cake was subjected to tumbling cooling, during which approximately 0.55 MT/h of moisture was removed. The resulting WBS meal retained 45.95% protein, 23.78% carbohydrates and 16.90% fiber. Further downstream, the crude WBO underwent physical refining, including degumming and bleaching, resulting in 0.76 MT/h of degummed and bleached WBO containing 96.87% oil and 3.13% FFA. Final refining produces 0.74 MT/h of high-purity

WBO (99.94%) with lower FFA content (0.06%), comparable to the FFA level reported for refined soybean oil (Syed *et al.*, 2019).

Table 2. Selected streams and their chemical compositions generated by SPD simulation for a processing capacity of 10 MT/h (4350 h/year)

Stream & composition	MT/h	Mass composition (%)
1) Feedstock (WBS)	10	
Foreign Material		0.10
Moisture		9.90
WBS Dry Matter		90.00
2) After screw extruding (before pressing)	9.70	
Ash		4.52
Carbohydrates		20.42
Crude Oil		13.84
Fiber		14.51
Proteins		39.45
Moisture		7.26
3) WBS meal	8.31	
Ash		5.27
Carbohydrates		23.78
Crude Oil		6.41
Fiber		16.90
Proteins		45.95
Moisture		1.69
4) After pressing (extract crude oil)	0.84	
Ash		0.16
Carbohydrates		0.71
Crude Oil		97.05
Fiber		0.46
Proteins		1.37
Moisture		0.25
5) Degummed & bleached WBO	0.76	
FFA		3.13
Oil		96.87
6) Refined WBO	0.74	
FFA		0.06
Oil		99.94

3.3. Techno-economic Analysis

Table 3 outlines the CAPEX, OPEX, and projected revenue for the WBS processing facility with a capacity of 10 MT/h, operating 4,350 h annually. The total CAPEX amounts

to USD 19.09 mil, with DFC being the largest component at USD 15.21 mil (79.67%), followed by working capital (16.35%), and start-up & validation costs. The details of DFC are summarised in Table S2.

Table 3. CAPEX, OPEX, and revenue generated by SPD simulation for a WBS processing capacity of 10 MT/h (AOT 4350 h/year)

Project summary	Value
CAPEX	USD
Equipment purchase cost (PC)	2,296,000
Direct fixed capital (DFC)	15,208,000 (79.67%)
Working capital (WC)	3,121,000 (16.35%)
Start-up & validation cost (SC)	760,000 (3.98%)
Total (DFC+WC+SC)	19,089,000
OPEX	USD/year
Materials (WBS, bag, carton box, etc.)	17,676,000 (81.22%)
Facility-dependent	2,839,000 (13.05%)
Labor-dependent	424,000 (1.95%)
Laboratory/QC/QA	64,000 (0.29%)
Consumable (BE filter)	5,000 (0.02%)
Utilities (electricity)	755,000 (3.47%)
Total	21,763,000
Revenues	USD/year
WBS meal	18,067,000 (65.01%)
Refined WBO	9,628,000 (34.64%)
FFAD	91,000 (0.33%)
Degumming precipitate	2,000 (~0.01%)
Spent bleaching earth	3,000 (~0.01%)
Total	27,791,000
Project indices	
ROI	31.57%
PT	3.17 years
IRR (after tax)	45.39%
NPV (10%)	USD 21,355,000

The annual OPEX is projected at USD 21.76 mil, with raw materials (WBS, bags, packaging, *etc.*) making up the bulk at 81.22%. Facility-dependent costs contribute 13.05%, while other expenditures, such as utilities, labour, quality control, and consumables remained minimal. This trend was almost comparable with the previous study performed by Cheng & Rosentrater (2019). The total annual revenue was projected at USD 27.79 mil, with the majority generated from WBS meal (65.01%) and refined WBO (34.64%). In contrast, contributions from FFAD were marginal, while those from degummed precipitate and spent bleaching earth were almost negligible.

Financially, the project demonstrates strong viability. Key performance indicators include an ROI of 31.57%, an IRR of 45.39% (after tax), and a PT of just 3.17 years. The

NPV, discounted at 10%, stands at USD 21.36 mil, confirming the project's potential for profitable returns and long-term sustainability.

3.4. Sensitivity Analysis

The sensitivity analysis of WBS processing into refined WBO and solid meal highlights the economic impact of six key parameters: WBS price, refined WBO selling price, WBS meal price, electricity cost, AOT, and DFC. Each parameter was varied by $\pm 25\%$ to assess its influence on four economic indicators: ROI, PT, IRR, and NPV. The results clearly show which factors most significantly affect the viability of the project (Figure 2).

Among all parameters, the price of WBS is the most sensitive (Figure 2 a). A 25% increase in WBS price reduces ROI, IRR, and NPV by 57.2%, 73.0%, and 94.1%, respectively, relative to the base case, while increasing PT by approximately 133%. Conversely, a 25% decrease in WBS price notably boosts project performance, increasing ROI, IRR, and NPV by more than approximately 60% relative to the base case. These changes highlight the critical importance of securing low-cost raw materials to ensure economic success.

The refined WBO selling price also plays a vital role (Figure 2b). A 25% increase in the refined WBO selling price increases ROI and IRR by more than 30% relative to the base case, whereas a 25% decrease reduces both indicators by more than 30%. Similarly, the selling price of WBS meal (Figure 2c), a key co-product, greatly influences outcomes. A price drop of 25% leads to a substantial decrease in all performance metrics, while a 25% increase raises ROI by nearly 57% and NPV by approximately 93% relative to the base case. These results showed that both refined WBO and meal must be marketed at competitive prices to sustain profitability.

In contrast, electricity cost exhibits minimal influence (Figure 2d). Even with a 25% increase or decrease, ROI and IRR vary by only around ± 2.5 – 3.1% , and NPV shifts slightly close to $\pm 4\%$. This indicates that while energy cost matters operationally, it is not a major driver of financial viability in this process.

The AOT has a moderate impact (Figure 2e). More hours of operation (a 25% increase) improve ROI, IRR, and NPV by about 28.7%, 31.0 %, and 46.9% change, respectively, reflecting better asset utilisation. Reducing operating time leads to noticeable financial decline, emphasising the need for efficient scheduling and minimal downtime. Similarly, DFC has a moderate influence on project economics (Figure 2f). A 25% increase

in DFC reduces IRR and NPV by 25.6% and 26.2%, respectively, whereas a 25% reduction improves the profitability indicators.

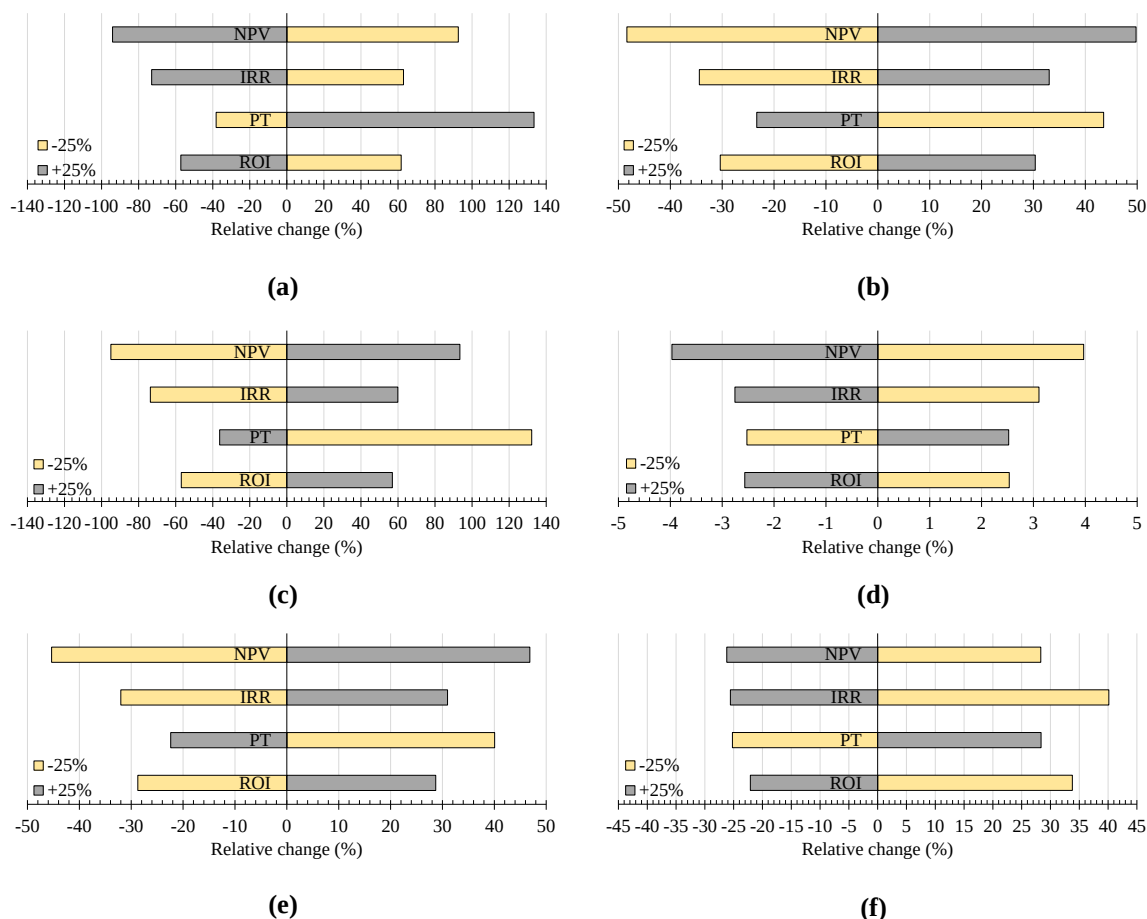
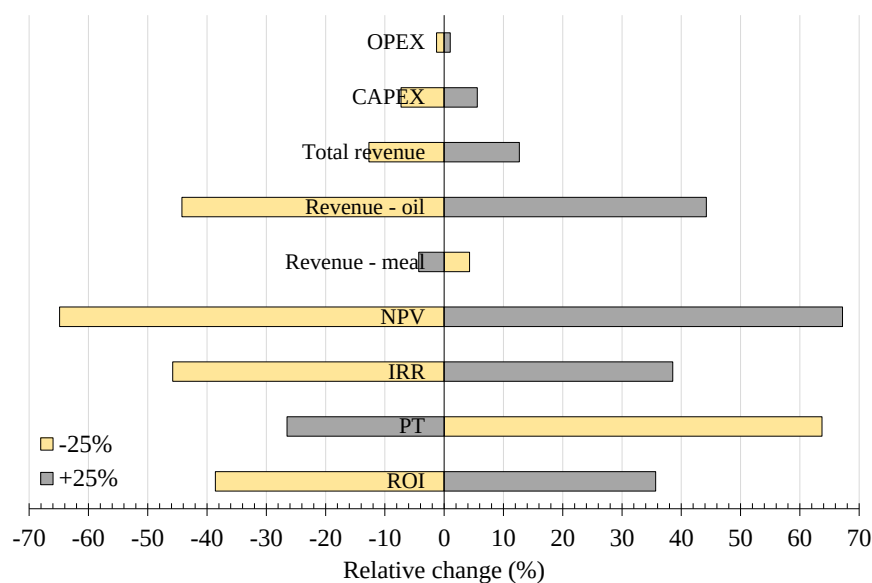
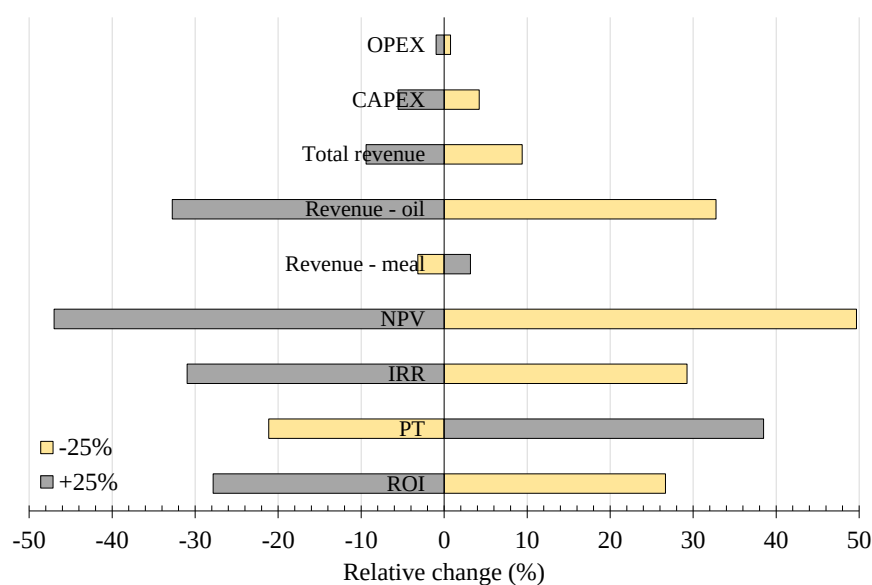


Figure 2. Sensitivity analysis on NPV, IRR, PT, and ROI by changing $\pm 25\%$ of (a) WBS price; (b) Selling price of refined WBO; (c) Selling price of WBS meal; (d) Electricity price; (e) AOT; (f) DFC

In this study, sensitivity analysis based on the impact of WBO content variations on the economic performance of the processing system was also done in which reveals that oil content is a highly influential parameter (Figure 3a). When the oil content increases by 25%, key financial indicators improve greatly: ROI (+36.7% change), IRR (+38.6% change), and NPV (+ 67.2% change). Conversely, a 25% decrease in oil content severely undermines project viability. This indicates that oil content is a highly influential compositional parameter, as a 25% increase in oil content results in a 44.2% increase in oil-related revenue. The effect on total revenue is also substantial ($\pm 12.7\%$), while CAPEX and OPEX exhibit minor fluctuations. These results indicate that ensuring high oil content in WBS is critical to achieving financial success in oil extraction-based operations.



(a)



(b)

Figure 3. Sensitivity analysis to OPEX, CAPEX, revenues, NPV, IRR, PT, and ROI by changing $\pm 25\%$ of (a) oil content; (b) Protein content of WBS

In contrast, increasing the WBS protein content by 25% reduced ROI, IRR, and NPV by 27.8%, 31.0%, and 47.0%, respectively. In the compositional sensitivity analysis, increasing protein content required proportional reductions in the remaining seed components to maintain a total composition of 100%, including a reduction in oil content. Consequently, revenue from refined WBO decreased by 32.8%, outweighing the modest increase in meal revenue (+3.2%). Conversely, decreasing protein content increased the relative proportion of

the remaining components, including oil, resulting in improved economic performance. These findings indicate that process profitability is particularly sensitive to changes in oil content because of the comparatively high unit value of refined WBO.

3.5. Throughput Analysis

The throughput analysis of WBS processing, which targets the production of refined WBO and protein-rich meal, highlights how plant scale significantly influences economic performance, as shown in Figure 4. Using a base capacity of 10 MT/h, the analysis compares both smaller and larger capacities to assess their relative feasibility and profitability. Based on the results, it indicates that a 10 MT/h capacity offers a balanced and financially attractive scale for commercial implementation.

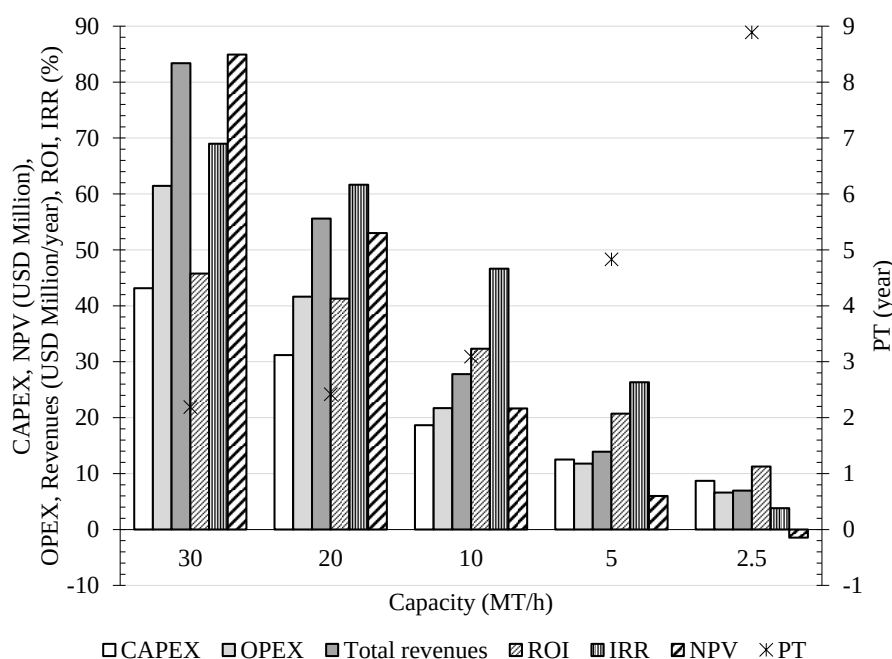


Figure 4. Effect of different process throughputs on techno-economic analysis

When the capacity is scaled down, profitability declines considerably. For instance, a 5 MT/h plant (half the base capacity) shows reduced economic attractiveness despite a proportionally lower CAPEX of USD 13.04 mil and OPEX of USD 11.84 mil/year. Annual revenue drops to USD 13.90 mil, resulting in a lower ROI of 19.89%, IRR of 24.92%, and an NPV of only USD 5.6 mil. The PT extends to 5.03 years, indicating lower economic attractiveness. At the smallest scale of 2.5 MT/h, the process becomes economically unviable, with a negative NPV (-USD 1.40 mil) and an IRR of just 4.14%, while the PT increases to nearly 9 years.

In contrast, scaling up beyond 10 MT/h notably enhances financial performance due to economies of scale. A 20 MT/h plant, for example, achieves nearly double the revenue (USD 55.58 mil) but with less than double the CAPEX and OPEX, resulting in a substantially higher NPV of USD 52.13 mil, ROI of 39.95%, and IRR of 59.61%. The PT improves to 2.5 years, demonstrating the efficiency of larger-scale operations. At the highest evaluated capacity of 30 MT/h, the economic outlook became even more favourable. With an NPV exceeding USD 83 mil, an ROI of 43.82%, an IRR of 66.02%, and a PT of just 2.28 years, this scale yields the highest ROI and shortest PT in this study.

4. Discussions

WBS demonstrates considerable potential as an alternative to commercial soybeans, particularly in regions seeking to reduce reliance on imported soy products. Their lipid and protein contents are comparable to those of soybeans, both in this study and in previously reported data (Yea *et al.*, 2014; Mohanty *et al.*, 2021). In addition, WBS exhibits similar levels of moisture, crude fibre, ash, and carbohydrates, suggesting a well-balanced nutritional profile suitable for both food and feed applications.

Processing simulations for a 10 MT/h WBS system demonstrated the effective extraction of WBO and a protein-rich meal. After processing, the crude oil stream achieved a high purity, while the residual meal retained notable amounts of protein and carbohydrates, making it a potentially suitable protein-rich feed ingredient, subject to evaluation of antinutritional factors, digestibility, and feeding performance (Kari *et al.*, 2023; Pope *et al.*, 2023). Further refining produced model-predicted WBO containing 99.94% oil and 0.06% FFA, with the FFA level comparable to that reported for refined soybean oil by Syed *et al.* (2019).

Nutritionally, WBS are also promising due to their high lysine and threonine contents (Mnembuka & Eggum, 1995), which are important amino acids that are often limited in plant proteins. Recent findings by Bepary *et al.* (2023) further support the analogy between WBS and soybeans in terms of biochemical composition and nutritional quality. However, the full potential of WBS remains underexplored. Therefore, further studies are strongly recommended to better characterise their properties, health benefits, and functional applications.

Economically, the WBS processing facility demonstrates strong viability. With a PT of just over 3 years, the project demonstrates favourable economic performance under the assumptions applied in this study. Sensitivity analysis revealed that economic performance

is highly influenced by raw material costs and product prices. An increase in WBS buying price substantially reduces ROI and IRR, whereas a decrease substantially enhances profitability. Besides the WBS price, sensitivity to the refined WBO selling price is also critical, as fluctuations driven by geography, product grade, or market dynamics can significantly affect overall profitability. Within the compositional sensitivity analysis, increasing protein content proportionally reduced the remaining components, including oil, thereby lowering WBO revenue. While operating time and capital cost moderately influence economics, electricity cost showed relatively insignificant effects.

This study highlights the importance of securing affordable raw materials, optimising product value, and maximising plant utilisation to ensure economic sustainability. Among the factors influencing profitability, oil content plays a dominant role in determining the economic viability of the process, making it a key criterion for raw material selection. Although protein content contributes to the quality and value of the meal, the compositional trade-off imposed in the sensitivity analysis indicates that increasing protein content may reduce oil-related revenue. Given the relatively higher selling price of refined oil compared to the lower value of WBS meal as animal feed, the development of oil-rich WBS varieties is strongly recommended to enhance profitability in co-production systems.

Scaling the processing capacity further impacts profitability. Smaller capacities (e.g., 2.5 MT/h) render the process economically unattractive due to lower efficiencies, while larger capacities (up to 30 MT/h) considerably enhance profitability through economies of scale. Although a 10 MT/h capacity offers a strong and feasible base case for commercial WBS processing, medium- to large-scale operations are more economically attractive due to better capital efficiency and higher profit margins. While smaller plants could serve pilot projects or decentralised processing in rural areas, their financial viability remains limited. To fully realise the economic and nutritional potential of WBO and meal production, investment in medium- to large-scale processing facilities, alongside targeted breeding efforts for oil-rich varieties, is strongly recommended.

5. Conclusions

This study demonstrates the viability of WBS as a promising alternative to commercial soybeans in both nutritional and industrial contexts. Proximate analyses revealed that WBS possess comparable protein and oil contents to soybeans. Process simulation and techno-economic analysis confirmed that WBS can be efficiently processed into high-value WBO and protein-rich meal, yielding favourable financial indicators, including strong ROI,

IRR, and a short PT. Sensitivity analysis identified raw-material price, product prices and oil content as key economic drivers, while throughput analysis demonstrated improved economic performance at larger processing scales. However, the analysis also indicated that a decline in the selling price of refined WBO would substantially reduce profitability, rendering the process less economically attractive due to high unit value of WBO. Collectively, these findings support the strategic utilisation of WBS as a locally sourced, economically viable crop to reduce soybean dependency and enhance food and industrial resilience in regions such as Malaysia. Future work should focus on genetic improvement, agronomic performance, and downstream product development to further unlock the full potential of winged beans in the agri-food and bioeconomy sectors.

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Supplementary Materials: The following is available at <https://journals.hh-publisher.com/index.php/AAFRJ/article/view/1135/734>. Table S1: List of equipment and purchasing cost (PC), Table S2: Direct fixed capital (DFC) summary for 10 MT/h WBS capacity.

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References

- Adegboyega, T., Abberton, M., Abdelgadir, A., *et al.* (2019). Nutrient and antinutrient composition of winged bean (*Psophocarpus tetragonolobus* (L.) DC.) seeds and tubers. *Journal of Food Quality*, 2019, 3075208. <https://doi.org/10.1155/2019/3075208>
- Bahari, U., & Azid, M. (2019). *Kompendium Sayuran Tradisional (in Malay)*. Serdang: MARDI.
- Bepary, R., Roy, A., Pathak, K., *et al.* (2023). Biochemical composition, bioactivity, processing, and food applications of winged bean (*Psophocarpus tetragonolobus*): A review. *Legume Science*, 5(3), e187. <https://doi.org/10.1002/leg3.187>
- Cheng, M., & Rosentrater, K. (2019). Techno-economic analysis of extruding-expelling of soybeans to produce oil and meal. *Agriculture*, 9(5), 87. <https://doi.org/10.3390/agriculture9050087>
- Demarco, A., & Gibon, V. (2020). Overview of the soybean process in the crushing industry. *OCL*, 27, 60. <https://doi.org/10.1051/ocl/2020047>
- Federal Reserve Economic Data (FRED). (2025, December 1). *Global Price of Soybean*. Retrieved on December 1, 2025, from <https://fred.stlouisfed.org/series/PSOYBUSDQ>
- Gupta, M. (2017). *Practical guide to vegetable oil processing*. London: AOCS Press.

- Heinzle, E., Biwer, A., Cooney, C. (2006). *Development of Sustainable Bioprocesses: Modeling and Assessment*. Chichester: John Wiley & Sons.
- Kari, Z., Mat, K., Kabir, M., *et al.* (2023). Soybean by-product: as an alternative to fish meals as protein sources for aquaculture industry. *Journal of Sustainability Science and Management*, 18(5), 177–200. <https://doi.org/10.46754/jssm.2023.05.013>
- Mariani, V.C., Perussello, C.A., Cancelier, A., *et al.* (2014). Hot-air drying characterization of soybeans and influence of temperature and velocity on kinetic parameters. *Journal of Food Process Engineering*, 37, 619–627. <https://doi.org/10.1111/jfpe.12118>
- Mnembuka, B., Eggum, B. (1995). Comparative nutritive value of winged bean (*Psophocarpus tetragonolobus* (L) DC) and other legumes grown in Tanzania. *Plant Foods for Human Nutrition*, 47, 333–339. <https://doi.org/10.1007/BF01088271>
- Mohanty, C., Syed, N., Kumar, D., *et al.* (2021). Chemical characterization of winged bean (*Psophocarpus tetragonolobus* (L.) DC. seeds and safety evaluation of its fatty oil. *Journal of Food Measurement and Characterization*, 15, 807–816. <https://doi.org/10.1007/s11694-020-00680-1>
- Mokhtar, M.N. (2022). Techno-economic evaluation of a process for the transformation of VitAto sweet potato into value-added products. *Journal of Food Process Engineering*, 45(8), e14043. <https://doi.org/10.1111/jfpe.14043>
- Oladeji, A., Bussie, M., Ibironke, P., *et al.* (2016). Nutritional evaluation and consumer preference of legume fortified maize-meal porridge. *Journal of Food and Nutrition Research*, 4(10), 664–670. <https://doi.org/10.12691/jfnr-4-10-6>
- Patil, R., & Ali, N. (2006). Effect of pre-treatments on mechanical oil expression of soybean using a commercial oil expeller. *International Journal of Food Properties*, 9, 227–236. <https://doi.org/10.1080/10942910600592315>
- Pope, M., Borg, B., Boyd, R. H., *et al.* (2023). Quantifying the value of soybean meal in poultry and swine diets. *Journal of Applied Poultry Research*, 32(2), 100337. <https://doi.org/10.1016/j.japr.2023.100337>
- Singh, M., Dubey, R., Koley, T., *et al.* (2019). Valorization of winged bean (*Psophocarpus tetragonolobus* (L) DC) by evaluation of its antioxidant activity through chemometric analysis. *South African Journal of Botany*, 121, 114–120. <https://doi.org/10.1016/j.sajb.2018.10.026/>
- Siyal, A., Low, A., & Shamsuddin, R. (2021). Fatty acid distillate as an alternative boiler fuel. *Energy Reports*, 7, 8688–8698. <https://doi.org/10.1016/j.egyr.2021.11.141>
- Sriwichai, S., Monkham, T., Sanitchon, J., *et al.* (2021). Dual-purpose of the winged bean (*Psophocarpus tetragonolobus* (L.) DC.), the neglected tropical legume, based on pod and tuber yields. *Plants*, 10(8), 1746. <https://doi.org/10.3390/plants10081746>
- Syed, N., Mahesar, S., Sherazi, S., *et al.* (2019). Quality assessment and safety measurement of different industrial processing stages of soybean oil. *Turkish Journal of Food and Agriculture Sciences*, 1(2), 28–33. <https://doi.org/10.14744/turkjfas.2019.006>

United States Department of Agriculture, Foreign Agricultural Service (USDA). (2025, April 10). *United States Soybean Area, Yield and Production*. Retrieved on April 26, 2025, from <https://ipad.fas.usda.gov/countrysummary/Default.aspx?id=US&crop=Soybean>

Yea, C., Ebrahimpour, A., Hamid, A., *et al.* (2014). Winged bean [*Psophorcarpus tetragonolobus* (L.) DC] seeds as an underutilised plant source of bifunctional proteolysate and biopeptides. *Food & Function*, 5, 1007–1016. <https://doi.org/10.1039/C3FO60667H>



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