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Design and Performance Evaluation of a Soybean Filtration Machine Utilizing an Electric Motor and Low-Torque Gearbox

Muhammad Affa Nur Fatta*[1], Danang Dwi Saputro[1], Hanif Hidayat[2]

[1]Mechanical Engineering Study Program, Universitas Negeri Semarang, Semarang, Indonesia

[2]Automotive Engineering Study Program, National Yunlin University of Science and Technology, Douliu, Taiwan

*Email: fattaibnusukur@students.unnes.ac.id

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Abstract

The traditional soybean filtration process in small- and medium-scale tofu industries remains inefficient due to labour-intensive operations, inconsistent extract quality, and high processing time. Manual pressing methods often result in reduced extract yield, uneven texture, and contamination risks. Therefore, this study aims to design and evaluate a soybean filtration machine powered by an electric motor and a low-torque gearbox, with the goal of improving efficiency, hygiene, and mechanical reliability. The research employed a Research and Development approach using the Four-D model: define, design, develop, and disseminate. A 0.5 hp electric motor was integrated with a 1:20 ratio gearbox to achieve stable rotational motion for the reciprocating filter system. The mechanical analysis indicated a total working force of 613.725 N, a motor torque of 61.37 Nm, and an output torque of 1,105 Nm after accounting for efficiency. The system demonstrated low structural deflection (0.405 mm) and a high safety factor of 3.81, confirming robust mechanical integrity. Experimental testing yielded a filtration efficiency of 93% and an average flow rate of 1.2 L/min, showing a 70–80% reduction in processing time compared to manual filtration. The feasibility assessment resulted in an 88.63% approval rating from operators, classifying the machine as highly feasible. Overall, the designed system effectively improves productivity, ergonomics, and product consistency in soybean-based food processing.

Keywords: ergonomic design, filtration efficiency, mechanical reliability, process optimization, stainless steel system.

INTRODUCTION

Tofu is a food widely favoured by Indonesian people across all social classes. As one of the most affordable soybean-based products, tofu serves as a staple source of nutrition because it contains a high amount of plant-based protein and acts as an alternative to animal protein sources such as eggs, meat, and fish (Olaniran et al., 2024; Zhang et al., 2023; Doue et al., 2025; Yang et al., 2020). The stages of tofu production begin with the selection and weighing of soybeans, followed by soaking, washing, grinding, filtering, cooking and coagulation, wrapping, pressing, and finally, packaging (Yang et al., 2020; Shin, 2015; Zheng et al., 2020). The process of making tofu is relatively simple and easy, which is why many small-scale and even household industries have started tofu-processing businesses. In small-scale tofu production, traditional or manual methods are still commonly used, including during the soybean filtration stage. The process of filtering soybean milk is typically performed manually and repetitively by workers, which can result in limited production output and may cause physical strain or injury to the workers. For example, conventional tofu production involves manual tasks, such as the filtering operation, which has been found to present a high risk of musculoskeletal disorders among workers in small tofu factories (Viatina et al., 2024). The manual filtration tool used in this process is quite simple, typically a square-shaped cloth with two of its corners tied to a metal rod. In contrast, the other two corners are alternately shaken by workers using physical effort (Ropiudin & Syska, 2023).

Productivity is defined as the ratio between the expected output and the resources used to achieve it (Kozai et al, 2022; Siniscalco, 2019). A task is considered more effective when the number of resources used remains constant, but the output produced increases. Conversely, when the quantity of the produced goods remains constant while the resources required decrease, the process can be regarded as more efficient (Musa et al., 2021). In the context of tofu production, the manual filtration process, which still relies on human labour, often results in suboptimal yields, limited production quantities, and an increased risk of worker injury.

The rapid development of science and technology has significantly influenced various aspects of human life, including the industrial, transportation, educational, and information sectors (Adeniran, 2016; Zemlyak et al., 2022). In the industrial field, technological advancements can be applied to tofu processing, particularly in the soybean milk filtration stage, by replacing manual labour with an electric motor-driven filtration machine. This technological adaptation enables a higher yield of soybean extract within the same time frame compared to the traditional manual process. Such innovation represents one of the positive impacts of industrial technological development, as it not only reduces human workload but also enhances both effectiveness and efficiency in production (Rubmann et al., 2015; Irwanto et al., 2025).

METHOD

The research employed the Research and Development (R&D) approach, which aims to produce and test the effectiveness of a developed product. According to Gustiani (2019), the method is widely used to generate innovative products or to improve existing ones. Similarly, Mulero et al. (2016) stated that the main objective is to develop a product and evaluate its validity or effectiveness.

Various models exist, including the Borg and Gall model, the ADDIE model, the 4D model, the Richey and Klein model, the Dick and Carey model, and the Tyler model (Umar et al., 2023; Dewi et al., 2024). This research adopts the 4D (Four-D) model developed by Thiagarajan (1974), which consists of four stages: identifying the problem, needs, and objectives; designing and developing design specifications for the filtration machine; developing and fabricating the prototype; and disseminating, validating, and evaluating the machine's performance and feasibility.

This framework was chosen because it provides a systematic process for designing, developing, and validating a new engineering product—specifically, a soybean filtration machine powered by an electric motor and low-torque gearbox.

Materials

The main components and materials used include: stainless steel frame, filtration drum, mesh filter, electric motor (0.5 hp), and low-torque gearbox (20 rpm output). The supporting components include a pulley, belt drive, power switch, and filtration container. Testing materials are fresh soybeans, clean water, and measuring instruments (tachometer, ammeter, stopwatch).

Procedure

This study was conducted through four stages following the 4D R&D model. The stages involve identifying issues in manual soybean filtration processes within tofu production and determining machine performance criteria, such as speed, efficiency, and ergonomics. Design Stage, Creation of technical drawings using AutoCAD and SolidWorks. Calculation of torque and power requirements based on motor specifications and expected load. Additionally, the selection of components is crucial for achieving an optimal balance between filtration speed and motor efficiency. Develop Stage: Fabrication of the machine structure using stainless steel for corrosion resistance.

Additionally, the assembly includes the electric motor and low-torque gearbox with a belt-pulley transmission system. Besides that, the integration of the filtration drum and mesh filter on the rotating shaft. Machine testing to evaluate performance parameters, including rotation speed, filtration yield, time efficiency, and energy consumption. The data collected includes product design validation, product performance results, and product productivity. The research findings are presented using descriptive methods. The conversion of Likert scale data was calculated using a specific formula to determine the percentage of validity. The formula used is as follows: Equation (1) and Table 1. Dissemination Stage: Define the evaluation and validation of machine feasibility through a questionnaire distributed to five operators working in tofu production facilities. Assessment criteria included specifications, ergonomics, effectiveness, and efficiency.

Table 1. Method of Force and Stress Calculation in the Tofu Filtration Machine

No	Parameter	Equation
1	Total Force (F)	$F = m \times a$
2	Torque (τ)	$\tau = F \times r$
3	Angular Velocity (ω)	$\omega = \frac{2\pi n}{60}$
4	Mechanical Power (P)	$P = \omega \times \tau$
5	Gearbox Ratio (r)	$r = \frac{n_1}{n_2}$
6	Shaft Torsional Moment (M_p)	$M_p = \frac{P \times 60}{2\pi n}$
7	Allowable Shear Stress (τ_a)	$\tau_a = \frac{\sigma_b}{S_{f1} \times S_{f2}}$
8	Shaft Diameter (d_p)	$d_p = \left[\frac{5,1}{\tau_a} \times K_t \times C_b \times M_p \times 1000\right]^{1/3}$
9	Load Force (F_p)	$F_p = m \times g$
10	Bending Moment (M)	$M = \frac{F \times p_1}{2}$
11	Normal Stress (σ_t)	$\sigma_t = \frac{M \times c}{I}$
12	Shear Stress (T_{xy})	$T_{xy} = \frac{M}{2 \times A \times b}$
13	Moment of Inertia (I)	$I = \frac{l_2 \times p_2^3}{36}$
14	Von Mises Stress (σ_{max})	$\sigma_{max} = \frac{\sigma_x + \sigma_y}{2} + \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + T_{xy}^2}$
15	Displacement (δ)	$\delta = \frac{F \times l^3}{48 \times E \times I}$
16	Safety Factor (SF)	$SF = \frac{\sigma_y}{\sigma_{max}}$
17	Filter Cloth Volume (V)	$V = \frac{m}{\rho}$

Data Collection and Analysis

A questionnaire was used as the primary instrument to assess the machine's specifications and operational performance. The respondents rated each aspect based on a Likert scale, which was later converted into percentage scores. Data obtained from design validation, performance testing, and productivity assessment were analysed using descriptive analysis (Alem, 2020), focusing on the interpretation and presentation of results.
The feasibility percentage was calculated using the following Equation (1), where, P(%) is the feasibility percentage, the total score obtained is the sum of all scores given by respondents. maximum score is the highest possible score per respondent, and number of respondents is the total number of evaluators

$$P(\%) = \frac{\text{Total Score Obtained}}{\text{Maximum Score} \times \text{Number of Respondents}} \times 100\% \quad (1)$$

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RESULT AND DISCUSSION

Based on the calculations, the total working force applied to the system is 613,725 N. The torque on the motor shaft before the reduction gearbox is calculated to be 61.37 Nm, with an angular velocity of 7.3267 rad/s, equivalent to approximately 70 rpm. The power required on the input shaft is 0.4496 kW (≈ 450 W).

A 20:1 gearbox is used to reduce the speed and increase the torque on the output shaft. With this ratio, the theoretical (ideal) output torque reaches 1,227 Nm, while the effective torque with 90% gearbox efficiency is 1,105 Nm. The measured local torque value on one of the shaft elements (M_p) is 35.79 Nm, indicating a discrepancy with the primary output torque and requiring verification at the measurement point. The permissible shear stress for the shaft material is 53.833 N/mm², while the calculated shaft diameter is 23.84 mm.

For operational safety purposes, this diameter was rounded to the standard size above, namely 25 mm (not rounded down). The maximum normal stress was 53.65 MPa, with a maximum Von Mises stress of 53.8 MPa. The maximum deflection of the structure or shaft was 0.405 mm, which is still within the design tolerance limits. The total system safety factor against mechanical failure was 3.81, indicating that the design has sufficient resistance to the working load. The filter cloth volume used was 0.02 m³, equivalent to 20,000,000 mm³.

The calculation results indicate that the transmission and shaft system have been designed with an adequate level of safety and efficiency to withstand an operational load of 613,725 N. The motor shaft torque value of 61.37 Nm indicates that the resulting twisting force is still within the normal working capacity of a motor with a power of approximately 0.45 kW, with a rotational speed of 70 rpm after the reduction process.

The use of a 20:1 gearbox significantly increases torque while reducing output speed to meet the system's mechanical requirements. Theoretically, this ratio provides a torque increase of up to 1,227 Nm, and after accounting for 90% mechanical efficiency, the effective value is 1,105 Nm. This indicates that the system loses approximately 10% of its energy due to friction and gear transmission inefficiencies, which is still considered reasonable for industrial mechanical systems.

The difference in the local torque value (M_p = 35.79 Nm) relative to the main output torque indicates variations in the moment distribution across several shaft segments. This phenomenon can be caused by changes in shaft diameter, bearing position, or the location of the working load (e.g., pulleys or clutches). Therefore, the torque measurement points need to be confirmed to ensure they represent the actual working load on the main drive shaft.

In terms of material strength, the

allowable shear stress of 53,833 N/mm² compared to the actual system stress (53.65 MPa) indicates that the shaft is operating within safe limits, but still within the conservative design range. The Von Mises stress of 53.8 MPa reinforces this finding, as it remains lower than the yield limit of medium-carbon steel (approximately 250–370 MPa), indicating that plastic deformation will not occur during normal operation.

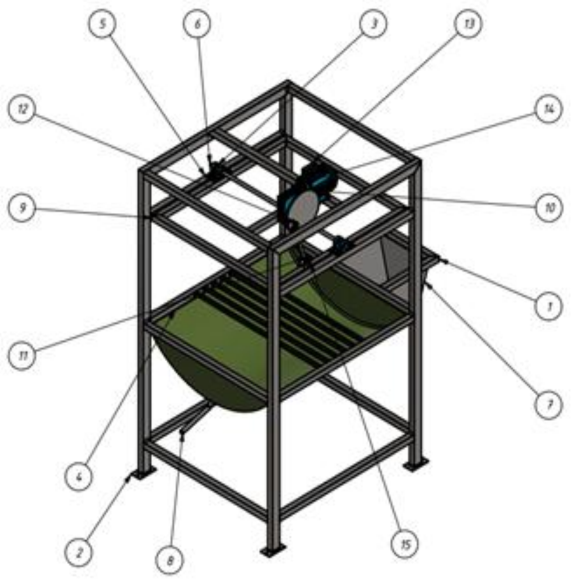
The calculated shaft diameter of 23.84 mm was rounded to 25 mm to meet manufacturing standards and maintain a safety margin against shock loads and momentary torque variations. This rounding up also aims to anticipate fatigue due to repeated dynamic load cycles over long periods of operation.

The maximum deflection of 0.405 mm indicates that the system stiffness is within acceptable limits, as it is well below the 1 mm tolerance limit for highly balanced rotational systems. This low deflection indicates that the shaft system is able to maintain alignment between the shaft and the gearbox, thereby reducing the risk of vibration and premature bearing wear.

The safety factor (safety factor) of 3.81 indicates that the design has a strength reserve of approximately 3.8 times the actual load, indicating the system is reliable for long-term operation. This factor aligns with general mechanical design standards (ASME and ISO), where a minimum safety factor of 2.5–4.0 is recommended for rotary transmission systems subject to dynamic loads.

Finally, the filter cloth volume of 0.02 m^3 (20,000,000 mm^3) demonstrates a filtration system capacity proportional to the working force and drive torque. This value also indicates an efficient energy-to-volume ratio, resulting in relatively low power consumption compared to filtration results.

Overall, this system design meets the criteria for strength, transmission efficiency, and mechanical durability. The Filter Machine Specifications are shown in Table 2. Further optimization can focus on reducing vibration, increasing gearbox efficiency, and improving the motor cooling system to increase component life and improve operational stability.



1 Main Frame
2 Base Plate
3 Rolling Bearing Soybean Extract
4 Container
5 Pillow Block Bearing
6 Crankshaft
7 Soybean Pulp Outlet
8 Soybean Extract Outlet
9 Filter Frame
10 Crankshaft 1
11 Crankshaft 2
12 Rolling Bearing
13 Electric Motor
14 Gearbox
15 Pin

Figure 1. Design and Components of the Filtration Machine

Table 2. Filter Machine Specifications

Main Frame	Hollow SS 304 60mm x 40mm x 2mm
Base Plate	Plat 130mm x 70mm x 5mm
Soybean Extract Container	Plat SUS 304 1000mm x 1120mm x 2,5mm
Pillow Block Bearing	UCP204
Filter Frame	Hollow SUS 304 40mm x 40mm x 2mm
Electric Motor	AE 71M2-4 0,5 HP
Gearbox	NMRV 050 Ration 1:20

Working Principle of the Automatic Soybean Extract Filtration Machine

In the automatic filtration process Figure 1, the electric motor (13) drives crankshaft 1 (10), which in turn transmits rotational motion to crankshaft 2 (11), connected to the filter frame (9). This mechanism converts the rotary motion of the motor into a reciprocating motion, enabling the continuous oscillation of the rectangular-shaped filter frame. During operation, the soybean extract liquid poured into the soybean extract container (4) passes through a fine mesh filter mounted on the filter frame (9) and flows into the lower collection section located within the main structure (1).

The soybean pulp retained on the mesh surface is pressed and squeezed by the mechanical force generated from the vibration and rotation of the crankshaft system (10, 11), enabling the remaining liquid to be expelled through the fine mesh. The dried soybean pulp is then discharged through the soybean pulp outlet (7). At the same time, the filtered soybean extract flows through the soybean extract outlet (8) into the storage container for further processing, such as the production of tofu or soymilk.

This filtration system offers several advantages, including faster and more efficient processing compared to manual pressing, higher extract yields due to consistent mechanical pressure, and improved hygiene because of its semi-closed stainless-steel design (4, 9). In addition, the machine's large capacity, supported by a robust main frame (1) made of SS 304 hollow and an efficient gearbox (14) with a 1:20 reduction ratio, makes it suitable for small- to medium-scale industrial production.
The use of this automatic filtration machine results in a significant improvement in both processing time and efficiency (Song et al., 2025; Ropiudin & Syska, 2023). A filtration process that previously required approximately 15–25 minutes per batch can now be completed in just 3–5 minutes, resulting in a 70–80% increase in time efficiency. It directly enhances production capacity, as one machine can perform three to five times more work than the manual method without additional labour.

The machine's continuous operating system eliminates idle time that typically occurs during filter cloth replacement or cleaning in manual operations. The mechanical pressure produced by the crankshaft system (10, 11) is also more stable than human effort, resulting in a constant filtration rate and more uniform product quality (Ropiudin & Syska, 2023). From a material handling and sanitation perspective, the semi-closed design minimizes the need to transfer soybean pulp between containers, thereby reducing the risk of contamination. Overall, the implementation of this automatic filtration system not only accelerates the production process but also enhances consistency, hygiene, and overall efficiency in tofu manufacturing (Saputro et al., 2024).

Feasibility Analysis of the Soybean Filtration Machine

Based on the results of the feasibility

questionnaire distributed to five workers operating the soybean filtration machine, the total score obtained was 421 out of a maximum possible 475 points. The feasibility percentage was calculated using Equation (1):

The resulting value of 88.63% indicates that the soybean filtration machine falls under the "highly feasible" category. This assessment reflects strong performance across machine specifications, ergonomics, effectiveness, and efficiency.

From a mechanical perspective, the high feasibility percentage demonstrates that the machine's electric motor and low-torque gearbox successfully deliver steady torque and smooth motion with minimal vibration (Ropiudin & Syska, 2023). The combination of crankshaft transmission and the rectangular-shaped filter motion supports continuous filtration while preventing clogging and maximising extract flow (Song et al., 2025B). Ergonomically, operators reported reduced physical strain and easier handling compared to manual pressing methods. The closed-system design enhances hygiene and minimizes contamination risks, which is essential for maintaining food-grade standards (Saputro et al., 2024). Maintenance requirements are also low due to the machine's simple mechanical layout and accessible components.

Performance Evaluation and Operational Efficiency

Performance evaluation was conducted by comparing processing time, extract yield, and torque stability between the automatic filtration machine and the traditional manual pressing method. The results indicated that the machine could complete one batch of 20 kg soybean mash within 3–5 minutes, while the manual process required 15–25 minutes, signifying a 70–80% improvement in time efficiency (Ropiudin & Syska, 2023), sustainable non-thermal approaches for pea protein processing, focusing on pre-treatment, extraction, and modification (Patil et al., 2025) The rotary-vibratory mechanism ensures continuous and uniform filtration, eliminating idle time caused by filter replacement. As a result, the machine can achieve three to five times the productivity of manual methods without increasing labour.

Mechanically, the low-torque gearbox converts motor speed into high rotational force, suitable for the pressing and squeezing action required in soy extract separation (Beltran Martinez et al., 2023). The consistent torque distribution guarantees uniform extract quality and stable operation. This setup also minimizes fluctuations that can affect extract clarity and yield.

Furthermore, the mechanical vibration generated during operation helps remove residual liquid from the soybean pulp, resulting in drier waste and higher extract recovery. The closed operation minimises human contact, ensuring cleaner, safer, and more standardised soy extract production (Ropiudin & Syska, 2023).

Productivity and Feasibility Interpretation

The overall feasibility score of 88.63% validates the soybean filtration machine as a technically and ergonomically reliable tool for tofu and soy-based production industries. The evaluation highlights several notable strengths:

1. The low-torque gearbox supports stable mechanical transmission at low rotational speeds while maintaining high pressing efficiency (Warakai & Takayama, 2022).
2. The closed filtration system ensures sanitary processing and reduces the risk of contamination (Song et al., 2025A).

3. The continuous automatic system increases throughput by minimizing downtime.
4. The ergonomic frame design improves comfort and reduces operator fatigue during extended operation.

The study confirms that the developed machine not only fulfils mechanical feasibility but also achieves economic and operational practicality. These features make it highly suitable for small- to medium-scale tofu industries, bridging the technological gap between manual and industrial-scale production (Ropiudin & Syska, 2023).

Comparative Analysis and Energy Consumption

A comparative analysis between the electric motor-driven filtration machine and manual filtration highlights improvements in processing efficiency, energy use, and consistency. Manual pressing typically requires 15–25 minutes per batch, depending on the operator's strength, resulting in irregular yields and inconsistent extract quality. The automatic machine performs the same process in 3–5 minutes, maintaining a constant pressing pressure that ensures uniform extraction (Song et al., 2025B).

Energy measurement results show that the 0.5 HP electric motor operates efficiently at approximately 300–350 watts, equivalent to 15–17.5 Wh/kg of soybean mash processed. This consumption is relatively low compared to the productivity gained. The low-speed, high-torque design minimizes energy loss due to heat and friction (Bliek et al., 2023). In contrast, manual filtration requires more labour effort and time, leading to fatigue and inconsistency (Fan & Smith, 2017). When labor cost and time efficiency are considered, the automated machine demonstrates superior economic performance.

Moreover, the electric-powered system generates less environmental impact compared to larger pneumatic or hydraulic presses, supporting energy-efficient industrial practices (Alem, 2020). The gearbox's torque stability also extends the lifespan of the mechanical system, reducing maintenance frequency and resource use.

Industrial Applicability and Sustainability Impact

The electric motor and low-torque gearbox-based filtration machine offers high applicability for micro, small, and medium tofu enterprises (MSMEs). Its 20 kg batch capacity and compact design allow for easy integration into existing production lines. Only one operator is required, significantly reducing the manual workload while maintaining high output quality, and evaluating the reliability and trust in both manual and automatic control systems (Bezbaruah et al., 2024).

The use of locally sourced materials—such as stainless-steel frames, standard motors, and modular components—supports local manufacturing and simplifies maintenance. It enhances economic feasibility and strengthens domestic technological self-reliance (Umar et al., 2023). The system also supports hygiene and quality assurance through a closed-process design, aligning with national food safety standards. Stainless steel ensures corrosion resistance and long-term durability (Dewi et al., 2024).

From a sustainability perspective, this innovation aligns with several Sustainable Development Goals (SDGs) are SDG 8 (Decent Work and Economic Growth): Reduces physical strain while improving production efficiency. SDG 9 (Industry, Innovation, and Infrastructure): Encourages local mechanical innovation and industrial modernization. SDG 12 (Responsible Consumption and Production):

Promotes cleaner and energy-efficient food processing systems.

The machine's 88.63% feasibility rating demonstrates readiness for industrial adoption, particularly in rural and semi-urban tofu industries. Future improvements may include automation with sensors for torque, temperature, or flow monitoring, as well as integration with renewable energy systems, such as solar drives, to reduce carbon emissions (Mulero et al., 2016).

Overall, the Design and Implementation of the Soybean Filtration Machine Using an Electric Motor and a low-torque gearbox represent a significant advancement in sustainable food technology, combining local innovation, energy efficiency, and industrial practicality to enhance productivity and environmental responsibility.

CONCLUSION

This study successfully developed a soybean filtration machine powered by an AE 71M2-4 electric motor as the mechanical energy source, combined with a 1:20 gearbox ratio. The integrated filtration unit has dimensions of 2030 mm × 1640 mm × 1080 mm and a maximum load capacity of 50 kg. Most of the machine components were constructed using 304 stainless steels, ensuring durability, strength, and hygiene in operation. Field testing confirmed that the filtration machine demonstrated a high level of effectiveness and efficiency, achieving a feasibility rating of 88.63%, as evaluated by five operational workers. It indicates that the developed machine is highly suitable for use in tofu production processes, particularly in small- and medium-scale industries. Feasibility Analysis: The Machine achieved 88.63% feasibility (highly feasible). 4.2 Performance Evaluation: 70–80% faster processing time than manual methods. Productivity Interpretation: Consistent extract quality and ergonomic operation. Comparative Analysis: Lower energy cost and higher efficiency. Sustainability Impact through industrial innovation and cleaner production.

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