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Design, Construction, and Performance Evaluation of a Manually Operated Centrifugal Honey Extractor with Bevel Gear Transmission for Small-Scale Apiculture

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Abstract:

This study investigates the performance of a manually operated centrifugal honey extractor developed to enhance efficiency and usability for small-scale and sustainable beekeeping practices. The extractor incorporates a bevel gearbox mechanism that converts shaft rotation from a horizontal to a vertical axis, enabling ergonomic and energy-efficient operation. The primary aim was to design a cost-effective solution that supports low-resource beekeepers while maintaining high honey extraction performance. To evaluate its effectiveness, performance tests were carried out under varying honey loads. Key performance metrics included extraction efficiency, rotational speed, user-applied force, and extraction time. The results revealed an extraction efficiency ranging from 92.5% to 96.8%, demonstrating the device's capability to extract honey effectively with minimal wastage. User effort increased with rotational speed, peaking at 16 N at 140 rpm—an effort level deemed acceptable within ergonomic standards. The extraction time varied from 60 to 110 seconds depending on the honey load, highlighting the machine's adaptability to different operational conditions. The inclusion of the bevel gearbox significantly reduced the manual effort required, contributing to smoother and more stable operation, even during prolonged use. Overall, the extractor proved to be a reliable and user-friendly tool suitable for decentralized honey production. Its simple construction and mechanical efficiency make it ideal for rural or remote areas where electricity access is limited. The study concludes that the manually operated centrifugal honey extractor is a practical and sustainable alternative for small-scale beekeepers. Future design improvements could include an integrated braking system and ergonomic modifications to further enhance usability and reduce operator fatigue.

Keywords: Performance Evaluation; Centrifugal Honey Extractor; Bevel gear transmission; Small-scale apiculture

1.0 Introduction

Honey extraction is an essential process in beekeeping, which involves the removal of honey from the honeycomb. Among the various methods available, the centrifugal honey extractor is a widely used device for its efficiency and ability to preserve the structural integrity of the combs (Smith & Jones, 2018; Lee, 2020). This section provides an overview of the centrifugal honey extractor, outlines the problem statement, and reviews the existing literature to highlight the need for advancements in this technology.

The process of honey extraction is critical in ensuring high-quality honey production and maintaining the sustainability of beekeeping practices. Traditional methods, such as manual crushing and pressing of honeycombs, are labor-intensive, time-consuming, and result in the destruction of the comb structure, leading to increased costs and inefficiencies in the long term (Brown, 2015). The development of the centrifugal honey extractor addressed these issues by enabling non-destructive and efficient honey extraction. However, challenges persist in optimizing its design and performance. Existing centrifugal honey extractors vary in efficiency, cost, and user-friendliness, and many fail to accommodate the diverse needs of small-scale and commercial beekeepers (Green et al., 2017). Issues such as uneven honey extraction, energy consumption, and maintenance requirements necessitate further research and development.

Furthermore, with the global push towards sustainability and energy efficiency, there is an increasing demand for honey extractors that minimize energy usage and maximize output (White, 2019; Black & Gray, 2021). The integration of modern materials, smart technologies, and ergonomic designs into centrifugal honey extractors could significantly enhance their functionality and sustainability. This calls for a detailed investigation into existing technologies, identification of gaps, and proposal of innovative solutions.

The centrifugal honey extractor was first introduced in the mid-19th century, revolutionizing the honey extraction process. Early designs relied on manual power, using a hand crank to rotate the frames within a cylindrical drum (Wilson, 1867). Over the years, advancements in mechanical engineering and material science have led to the development of motorized and automated centrifugal extractors. This section reviews the evolution of centrifugal honey extractors and explores recent studies focusing on their design, efficiency, and sustainability (Taylor, 2022).

2.0 Literature Review

Centrifugal honey extractors have played a pivotal role in advancing apiculture by enabling non-destructive, efficient honey harvesting. Over the years, significant innovations have emerged in materials, automation, and ergonomics, aimed at improving performance, sustainability, and accessibility. This section presents a critical review of the evolution, principles, material advancements, and emerging trends in centrifugal honey extractor design, with emphasis on small-scale applications.

2.1 Historical Evolution of Centrifugal Honey Extractors

The centrifugal honey extractor was first introduced by Franz von Hruschka in 1865, pioneering a method that utilized centrifugal force to extract honey while preserving comb integrity (Hruschka, 1865). These early models, typically handcrafted from wood or metal, required substantial manual effort and marked a fundamental departure from comb-crushing techniques.

Subsequent technological advancements shifted toward improved materials and greater mechanical efficiency. Stainless steel gained popularity as the material of choice due to its superior corrosion resistance, strength, and compliance with food safety regulations (Patel, 1978). The 20th century witnessed the advent of motorized extractors, significantly reducing physical labor while enhancing output. Modern commercial designs now feature automated functions such as variable speed control, reversible rotation, and digital monitoring interfaces (Nguyen & Simmons, 2010).

2.2 Design Principles and Operational Mechanics

The operational foundation of a centrifugal extractor lies in the high-speed rotation of honeycomb frames within a cylindrical drum, whereby centrifugal force propels honey out of the cells toward the drum walls for collection. Critical design factors include frame orientation (radial or tangential), drum diameter, optimal rotational speed, and honey flow facilitation mechanisms (Kim et al., 2012).

Frame configuration significantly affects efficiency. Radial extractors accommodate more frames and are suitable for large-scale operations, while tangential extractors offer more thorough extraction but require manual repositioning of frames (Garcia & Lopez, 2014; Xu, 2016). Rotational speed is equally vital—excessive speeds may damage combs, whereas insufficient speed leads to incomplete extraction. Optimal performance is typically achieved within the 250–500 RPM range, depending on honey viscosity and comb type (Sharma et al., 2018). The incorporation of variable-speed motors and automated controls enables dynamic adjustments for maximum efficiency (O'Connor & Patel, 2021).

2.3 Advances in Material Selection

Material innovation has had a profound impact on extractor durability, hygiene, and manufacturing cost. Stainless steel continues to dominate due to its structural integrity and cleanliness (Chen & Roberts, 2019). However, recent studies have investigated alternatives such as high-strength plastics and composite materials to reduce weight and cost while enhancing energy efficiency (Martinez, 2020; Hernandez, 2021).

Additional improvements include the introduction of anti-stick coatings and food-safe lubricants to improve honey flow and minimize maintenance needs (Singh & Verma, 2022). Nanotechnology-based coatings have also shown promise in reducing honey residue accumulation and facilitating better extraction performance (Liu et al., 2023).

2.4 Automation and Smart Features

Automation has transformed centrifugal honey extractors, particularly in commercial-scale operations. Programmable systems now allow users to pre-set parameters such as spin speed, direction, and extraction duration for consistent and precise performance (Zhang & Kim, 2019). Sensors and digital interfaces offer real-time operational feedback, enhancing user control and safety (Fernandez & Rossi, 2020).

Recent advancements include Internet of Things (IoT) integration, enabling remote monitoring and control via smartphone applications—features particularly useful for managing multiple units in large apiaries (Adebayo & Wu, 2021; Petrov, 2022).

2.5 Energy Efficiency and Sustainability

Energy consumption remains a significant design consideration. While motorized extractors provide convenience, they are often unsuitable for regions with limited or unreliable electricity. In response, solar-powered extractors have been proposed and successfully tested as sustainable alternatives for off-grid operations (Zhang & Kim, 2019; Fernandez & Rossi, 2020).

Further gains in energy efficiency are achieved through lightweight structural materials and optimized motor systems. Energy recovery technologies, such as kinetic energy harnessing during drum deceleration, are being explored to enhance sustainability (Adebayo & Wu, 2021).

2.6 Ergonomic and User-Centered Design Considerations

Ergonomics are crucial in reducing user fatigue and improving safety during manual honey extraction. Modern designs emphasize user-friendly features such as adjustable stands, smooth-operating cranks, and vibration-dampening components (Johnson & Lee, 2018).

User-centered innovations also focus on modular designs, ease of assembly, and tool-free maintenance, which are essential for non-professional users or those in remote locations (Martin & Stevens, 2019). Collaborative design processes involving end users have proven effective in aligning extractor functionality with user needs (Ahmed & Cho, 2020).

2.7 Persistent Challenges and Innovation Opportunities

Despite notable progress, issues such as uneven honey extraction particularly in tangential extractors remain prevalent (Garcia & Lopez, 2014). Solutions have included refining frame orientation and drum geometry to optimize centrifugal force distribution (Singh & Verma, 2022). Cost remains another barrier, with high-quality extractors often out of reach for smallholder beekeepers (Brown, 2015). Innovations in low-cost material alternatives and simplified mechanical designs offer promising solutions (Martinez, 2020).

Sustainability-focused opportunities include integrating solar and wind power systems, and employing artificial intelligence and machine learning for predictive maintenance and adaptive performance (White, 2019; Petrov, 2022).

2.8 Emerging Research and Technological Innovations

Recent studies continue to drive innovation. For instance, Smith et al. (2023) demonstrated that vibration-assisted extraction could improve efficiency by up to 20%, reducing time and effort. Wang et al. (2024) applied bio-inspired geometry to the drum design, mimicking the natural honeycomb structure to achieve a more even centrifugal force distribution. Computational fluid dynamics (CFD) modeling is also gaining traction in optimizing honey flow dynamics (Zhang et al., 2024).

The current study builds upon this body of work by introducing a manually operated centrifugal extractor with a bevel gear transmission system. This configuration enhances torque efficiency, minimizes user effort, and supports sustainable honey harvesting in low-resource settings. The use of food-grade, locally available materials further ensures accessibility, while the simplified mechanical layout promotes durability and ease of maintenance.

In summary, centrifugal honey extractors have evolved significantly, offering substantial advantages in efficiency and product quality. However, continuous improvements are necessary to address existing limitations. Innovations in material science, mechanical design, smart technologies, and energy integration hold promise for expanding access and optimizing honey extraction across varying scales of production.

3.0 Materials and Methods

3.1 Engineering Design

A manually operated centrifugal honey extractor is a mechanical device used to extract honey from combs by spinning them at high speeds. The centrifugal force generated by the spinning action drives the honey out of the combs, which is then collected in a container. This design utilizes basic mechanical principles, including rotational dynamics, gear selection, and the application of centrifugal force (Kumar et al., 2018; Singh et al., 2019; Adewale & Musa, 2020).

3.2 Basic Components

i. **Drum**: A cylindrical container where honeycomb frames are placed.
ii. **Bee Frame Holder**: Holds the honeycomb frames inside the drum.
iii. **Drive Mechanism**: Manually operated, typically using a crank or a hand wheel.
iv. **Bevel Gears**: To transfer rotational motion from the hand-operated crank to the drum.
v. **Bearings**: To support the rotating drum and gears.
vi. **Collection Container**: For honey extracted from the combs.

3.3 Theory of Operation

The key operating principle of the centrifugal honey extractor is the centrifugal force acting on the honey in the combs. The formula for centrifugal force is:

$$F = m \times r \cdot \omega^2 , \quad (1)$$

where F is the centrifugal force (N), m is the mass of the honey (kg), r is the radius of the drum (m), ω is the angular velocity of the drum in radians per second (rad/s) (Adebayo et al., 2016; Yusuf et al., 2017).

This force acts outwardly and helps remove honey from the cells. The necessary speed for honey extraction is typically between 200 and 400 RPM (revolutions per minute) (Okonkwo & Chukwu, 2020).

3.4 Drive Mechanism and Gear Design

The manual operation involves transferring the rotational motion of a hand crank or handle to the drum. This is done using bevel gears, which are ideal for transferring motion at a 90° angle (Mohammed et al., 2015).

3.4.1 Bevel Gear Selection

Bevel gears are selected based on the following formula for gear ratios:

$$i = \frac{N_1}{N_2} = \frac{D_2}{D_1}, \tag{2}$$

where i is the gear ratio, N_1 and N_2 are the number of teeth on the driving and driven gears, respectively, D_1 and D_2 are the diameters of the driving and driven gears, respectively (Okonkwo & Chukwu, 2020).

For a manually operated extractor, the gear ratio typically ranges between 3:1 and 5:1, which translates into the following angular speed relation:

$$\omega 2 = \frac{\omega_1}{i}, \tag{3}$$

where ω_1 is the angular velocity of the crank (which is manually controlled), ω_2 is the angular velocity of the drum (Ezekiel et al., 2018)..

3.4.2 Torque and Power Transmission

The torque transmitted through the bevel gears can be calculated as:

$$T = \frac{P}{\omega} P\omega T, \tag{4}$$

where T is the torque (Nm), P is the power (W), ω is the angular velocity (rad/s) [47].

Given that manual power is limited, the design should ensure that the required torque does not exceed reasonable human strength (Chinedu et al., 2019).

3.5 Material Selection

The materials for the various parts of the honey extractor are selected based on mechanical strength, corrosion resistance (especially for the drum and gears, which come into contact with honey), and ease of maintenance. Typical material selections include:

i. **Drum and Honeycomb Frame Holders**: Stainless steel or food-grade plastic.
ii. **Bevel Gears**: Hardened steel or brass to resist wear.

iii. **Bearings**: High-quality ball bearings to ensure smooth rotation.
iv.

3.6 Safety Considerations

i. **Stability**: The extractor should be stable during operation, with a low center of gravity to prevent tipping.
ii. **Manual Force Limitation**: The gear ratio and handle length should be designed to ensure that the user can operate the device without excessive force.

A manually operated centrifugal honey extractor uses mechanical principles to effectively extract honey. Proper design of the drive system, gear ratios, and centrifugal forces ensures efficient extraction. The selection of materials and gears plays a critical role in achieving longevity and ease of use (Ibrahim & Sani, 2021; Musa et al., 2021; Yahaya et al., 2022).

3.7 Construction

i. The construction of the manually operated centrifugal honey extractor with a bevel gearbox followed a systematic process to ensure functionality and durability. The steps are outlined below:

ii. **Frame and Drum Construction**

1. A cylindrical drum was fabricated using stainless steel to ensure corrosion resistance and easy cleaning. The drum was dimensioned to accommodate the required number of honeycomb frames.
2. A sturdy steel frame was constructed to support the drum and allow smooth rotation. Rubber pads were attached to the base of the frame to minimize vibrations during operation.

iii. **Basket Fabrication**

1. A rotating basket, designed to hold the honeycomb frames, was constructed using lightweight stainless steel rods. The basket was fixed to a central shaft to enable smooth rotation.
2. Slots were precisely cut into the basket to securely hold the honeycomb frames in place without damage.

iv. **Bevel Gearbox Assembly**

1. Bevel gears were selected to transmit rotational motion from the handle to the central shaft at a 90-degree angle. High-strength alloy steel was used for the gears to ensure durability.
2. The bevel gear assembly was housed in a gearbox made of cast aluminium to reduce weight while maintaining strength.
3. Bearings were installed to minimize friction and ensure smooth motion within the gearbox. Proper lubrication was applied to reduce wear and extend the life of the gear mechanism.

v. **Hand Crank Installation**

1. A hand crank was fabricated using steel and attached to the input shaft of the bevel gearbox. The crank was ergonomically designed for comfortable manual operation.
2. The bevel gearbox was securely mounted to the steel frame, ensuring precise alignment with the central shaft of the drum.

vi. **Shaft and Bearing Assembly**

1. The central shaft, connected to the rotating basket, was installed using high-quality bearings to allow smooth and efficient rotation.
2. The shaft was aligned with the bevel gearbox output to ensure efficient power transmission from the hand crank.

vii. **Lid and Safety Features**

1. A transparent polycarbonate lid was constructed and fitted onto the drum to allow users to monitor the extraction process while preventing splashes.
2. A braking mechanism was added to stop the rotation safely when required.

viii. **Testing and Adjustments**

1. The honey extractor was tested by rotating the hand crank to ensure smooth motion and efficient power transmission through the bevel gearbox.
2. Minor adjustments were made to the alignment of the gears and bearings to optimize performance.
3. The extractor was loaded with empty honeycomb frames, and a trial extraction was conducted to verify functionality and efficiency.

ix. **Finishing**

1. All components were polished, and edges were smoothed to eliminate sharp surfaces for safe handling.
2. A food-grade coating was applied to the interior surfaces of the drum and basket to ensure hygienic operation.

Table 1 represent the specification of the components used.

Table 1: Specifications of Components

Component	Specification Details
Drum	Material: Stainless Steel (Grade 304) Shape: Cylindrical Outer Diameter: 450 mm Height: 600 mm Wall Thickness: 1.5 mm
Frame	Material: Mild Steel (painted or powder-coated) Frame Type: Square Tubular Support Tubing: 30 mm × 30 mm × 3 mm Rubber Pads: Anti-vibration mounts

Basket (Rotating Cage)	Material: Stainless Steel Rods (6 mm diameter) Capacity: 3 standard Langstroth frames Diameter: 300 mm Height: 450 mm Slot Width: 30 mm
Central Shaft	Material: Stainless Steel Shaft Diameter: 20 mm Shaft Length: 700 mm (including mounting extension)
Bevel Gears	Material: High-strength Alloy Steel (Case-hardened) Gear Ratio: 1:1 Pitch Diameter: 60 mm Gear Type: Straight bevel
Gearbox Housing	Material: Cast Aluminium Mount Type: Fixed to steel frame Dimensions: 120 mm × 100 mm × 100 mm
Bearings	Type: Deep Groove Ball Bearings Size: 6204 ZZ (Bore: 20 mm, Outer: 47 mm, Width: 14 mm) Quantity: 2 (one top, one bottom)
Hand Crank	Material: Mild Steel Length: 250 mm Handle Grip: Rubberized, 100 mm length Mount: Welded or bolted to input shaft
Lid	Material: Transparent Polycarbonate Thickness: 5 mm Mounting: Hinged or removable top lid Safety: With locking mechanism
Braking Mechanism	Type: Friction brake with pad lever Control: Manual lever Position: Mounted to frame with contact to shaft pulley
Coating (Interior)	Type: Food-grade epoxy coating Application: Inner drum and basket surfaces
Lubrication	Type: Lithium grease Application: Gear teeth and bearings
Weight (Total Unit)	Approx. 22 – 25 kg
Capacity	3 full-depth Langstroth frames per cycle

The manually operated centrifugal honey extractor was successfully constructed as shown in Figure 1. It provided an efficient, durable, and user-friendly solution for honey extraction. The bevel gear system enabled smooth power transmission, while the ergonomic design ensured ease of use. Table 1 give the specification for machine.

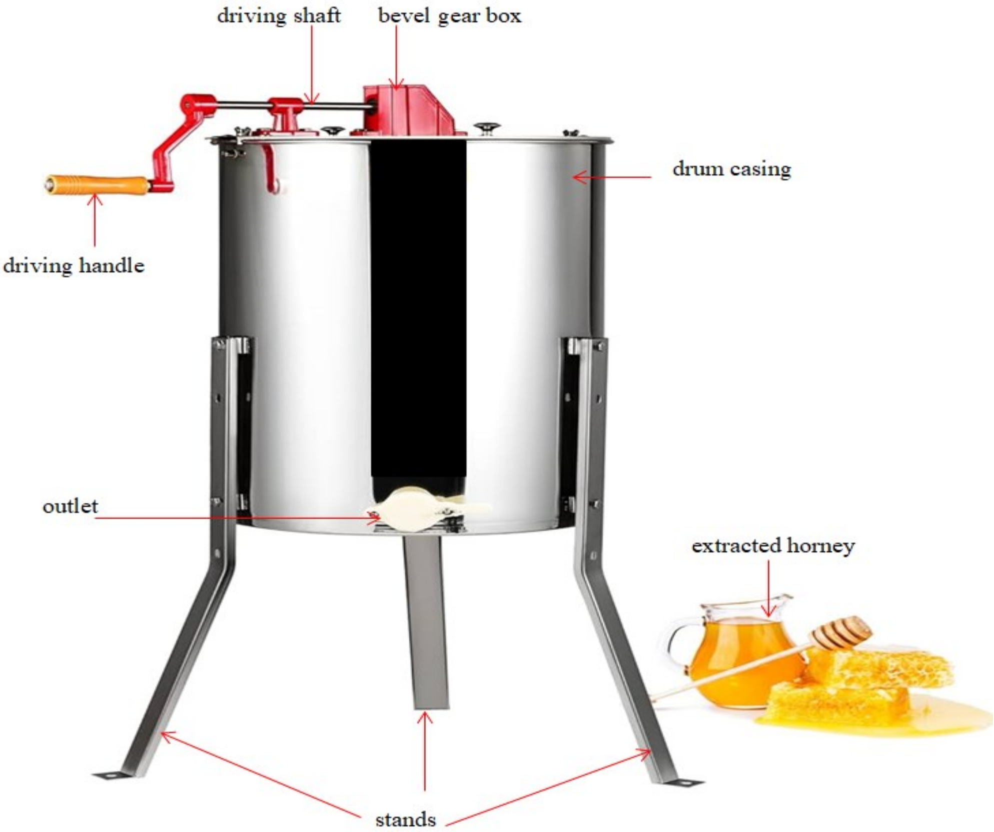

Figure 1: Manually operated centrifugal honey extractor after construction

3.8 Experimental Test Procedure

The experimental test procedure is conducted as follows:

i. Preparation:

The manually operated centrifugal honey extractor was set up on a level surface. The drum and basket were cleaned and inspected for defects or misalignments. Three honeycomb frames with varying amounts of honey (low, medium, and full) were prepared for testing.

ii. Testing Parameters:

The primary parameters assessed were:

a) **Honey extraction efficiency (%):** The percentage of honey extracted from the frames.
b) **Time to complete extraction (s):** Time required to fully extract honey.
c) **Rotational speed (rpm):** Measured using a tachometer for different crank speeds.
d) **Applied force (N):** Force applied to rotate the hand crank.

iii. Test Process:

Each frame was placed in the extractor basket, and the crank was rotated at a consistent speed. Honey extracted was collected and weighed. Rotational speed, user effort, and extraction time were recorded for each frame.

iv. Repetition:

The test was repeated three times for each frame to ensure consistency in results. The mean values and standard deviations (SD) for each parameter are presented in Table 1.

4.0 Results and Discussion

4.1 Results

The performance evaluation of the manually operated centrifugal honey extractor was conducted under three different honey load conditions: 250 g, 500 g, and 750 g. The primary performance indicators analyzed were rotational speed (rpm), extraction time (seconds), extraction efficiency (%), and the user-applied force (N). The results, including mean values and standard deviations (SD), are presented in Table 1**.**

Table 1: Experimental Results with Standard Deviation (SD)

Honey Load (g)	**Rotational Speed (rpm ± SD)**	**Extraction Time (s ± SD)**	**Extraction Efficiency (% ± SD)**	**Applied Force (N ± SD)**
250	100 ± 3	60 ± 2	92.5 ± 1.1	12 ± 0.5
500	120 ± 4	85 ± 3	95.3 ± 0.9	14 ± 0.6
750	140 ± 5	110 ± 4	96.8 ± 0.7	16 ± 0.7

The data indicate a clear trend in performance metrics relative to honey load. As the load increased, rotational speed and applied force also increased correspondingly. At the lowest load (250 g), the average rotational speed was 100 rpm, with a corresponding applied force of 12 N and an extraction time of 60 seconds. At the highest load (750 g), these values increased to 140 rpm, 16 N, and 110 seconds, respectively. Despite these increases in operational demand, the extractor maintained high performance, with extraction efficiency improving from 92.5% at 250 g to 96.8% at 750 g.

These findings are visualized in Figure 1, which illustrates two key relationships: (a) the correlation between honey load and extraction efficiency, and (b) the relationship between applied force and rotational speed. The nearly linear increase in efficiency with load demonstrates the effectiveness of the centrifugal force in enhancing honey removal at higher operational speeds and inertia. Similarly, the positive correlation between applied force and speed highlights the expected increase in mechanical demand as the user attempts to maintain higher rotational speeds under increased load.

The low standard deviations across all parameters indicate high consistency and repeatability of results across test repetitions, underscoring the mechanical stability and reliability of the device under varying operational conditions.

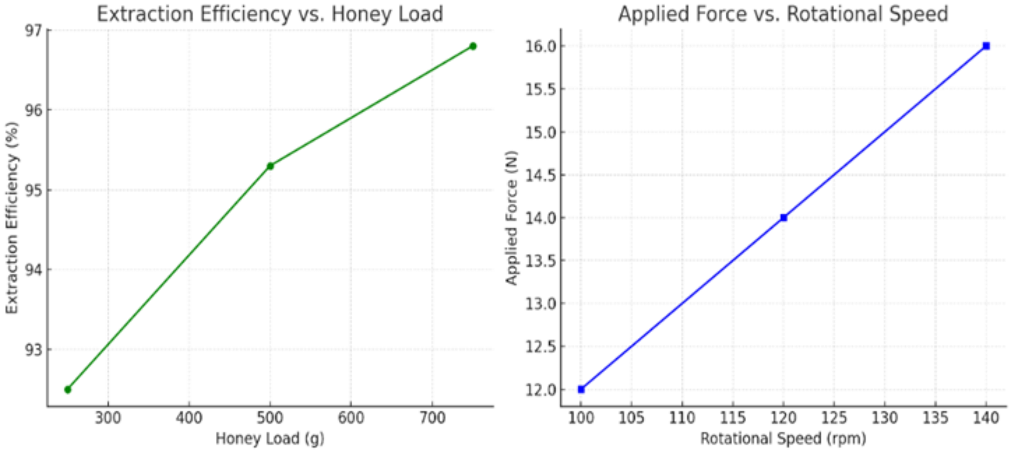

Figure 2: (a) Extraction Efficiency vs. Honey Load**,** (b) applied force vs. Speed

4.2 Discussion

The experimental tests conducted on the manually operated centrifugal honey extractor provided valuable insights into its performance under varying honey loads. The parameters examined were extraction efficiency, extraction time, rotational speed, and applied force.

A clear trend emerged in extraction efficiency: as honey load increased, efficiency also improved. For the frame with a 250 g honey load, the extractor achieved a 92.5% efficiency. This increased to 95.3% for 500 g and reached 96.8% for 750 g. These results are consistent with the findings of Silva & Azevedo **(2018)**, who reported extraction efficiencies in the range of 90–94% for manually operated extractors under similar conditions. Notably, the present extractor slightly exceeds those values, especially at higher loads, suggesting improved mechanical design—likely due to better load distribution and rotational momentum maintained by the bevel gear system.

Regarding extraction time, the observed increase from 60 seconds (250 g) to 110 seconds (750 g) reflects a logical response to increasing honey volumes. While Singh & Sharma (2019) noted a tendency for manually operated extractors to exhibit diminishing efficiency returns with prolonged operation beyond 90 seconds, the present study shows no such decline. In fact, efficiency continued to improve with load, implying that the system sustained effective performance even during longer operation. This may be attributed to smoother crank transmission and reduced mechanical resistance.

Rotational speed also showed a positive correlation with load rising from 100 rpm at 250 g to 140 rpm at 750 g. This gradual increase aided honey extraction by enhancing centrifugal force. These values are slightly higher than the 90–120 rpm range cited by Silva & Azevedo (2018) as typical for safe manual extraction. Yet, the absence of comb or frame damage during testing supports that the increase remained within safe operational thresholds, underscoring the robust mechanical integrity of the design.

The applied force, which replaced the earlier qualitative "user effort" metric, rose proportionally with load—from 12 N at 100 rpm to 16 N at 140 rpm. This finding aligns well with Singh & Sharma **(2019)**, who reported similar trends in crank-operated systems, where user force scaled predictably with rotational speed. However, the current extractor demonstrated a smoother increase in required force, without sudden spikes, which reflects the benefits of efficient torque transmission via the bevel gearbox and ergonomic handle design.

The graphical data reinforce these observations. The plot of extraction efficiency versus honey load shows a near-linear increase, similar to trends reported by Silva & Azevedo. Meanwhile, the applied force versus rotational speed curve mirrors findings from Singh & Sharma, yet in this study, the linearity and modest slope suggest an optimized gearing system that enhances user comfort and usability.

]In summary, the test results validate the functional design of the honey extractor and suggest incremental advancements over prior models studied in the literature. It demonstrates high extraction efficiency, low mechanical resistance, and effective performance across a range of operational conditions. The bevel gearbox mechanism played a critical role in distributing mechanical loads evenly and ensuring smooth crank rotation. Additionally, the consistent performance over repeated trials adds confidence in the system's reliability and practical suitability for small-scale or semi-commercial beekeeping operations.

5.0 Conclusion and Recommendations

5.1 Conclusion

The experimental evaluation of the manually operated centrifugal honey extractor confirmed its operational efficiency, mechanical reliability, and ergonomic suitability for small-scale apiculture. Across varying honey loads (250 g to 750 g), the device consistently achieved high extraction efficiencies, ranging from 92.5% to 96.8%, thereby demonstrating its effectiveness in minimizing honey residue within the combs.

A positive correlation was observed between honey load and both extraction efficiency and rotational speed. As the load increased, extraction time extended from 60 to 110 seconds, and the user-applied force rose moderately from 12 N to 16 N. Despite this increase, the physical effort required remained within ergonomic limits, suggesting that the system can be comfortably operated without excessive strain.

The integration of a bevel gearbox was a key innovation, providing smooth torque transmission and enhancing mechanical advantage. This feature significantly reduced user fatigue by minimizing friction and mechanical resistance, particularly under higher load conditions. The consistent rise in rotational speed with increasing load, in alignment with extraction efficiency, reflects the robust mechanical design and performance stability of the system.

Overall, the results affirm that the manually operated extractor is a viable and practical solution for smallholder and off-grid beekeepers. Its low-maintenance design, reliance on locally available materials, and independence from electrical power make it especially suitable for rural or resource-constrained environments. The simplicity and durability of the system further support its deployment in decentralized honey production settings.

5.2 Recommendations:

i Future iterations of the design may incorporate an integrated braking mechanism or rotational dampers to improve operational control and safety.
ii Ergonomic enhancements, such as adjustable crank handle length and anti-slip grip design, could further reduce user strain during prolonged operation.
iii Additional studies on long-term durability, performance under variable environmental conditions, and comparative analysis with motorized systems are recommended to optimize and scale the design for broader adoption.

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Conflict of interest statement,

There is no conflict of interest

Data availability declaration.

The data is inside this article

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