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Development of Improved Integrated Palm Fruit Juice Machine: Enhancing Efficiency and Quality

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Abstract
This study evaluates the performance of an improved palm fruit juice extractor with a downward-facing propeller configuration, designed to enhance extraction efficiency and throughput capacity. Key modifications included optimized heating element placement for uniform temperature distribution, a high-torque motor to manage increased load demands, and reinforced structural support to withstand operational stresses. Performance testing involved five experimental runs processing equivalent batches of palm fruit at a design speed of 227 rpm. Results indicate a 13% increase in throughput capacity and a 15.5% increase in extraction efficiency compared to the original machine, attributed to the improved mixing, circulation, and heating consistency. The redesigned extractor demonstrates faster processing times and higher juice yields, making it a more effective and user-friendly solution for small- and medium-scale palm fruit processing. These findings support the viability of the improved design as a sustainable approach to palm fruit juice extraction, with potential for further refinements in efficiency and adaptability.

Keywords: Palm fruit juice extraction, Extraction efficiency, Throughput capacity, Downward-facing propeller configuration and Performance enhancement

1. INTRODUCTION

Palm fruit processing is an essential operation in tropical regions where palm oil and juice are staple products, contributing significantly to local economies and the food processing industry. The *Integrated Palm Fruit Juice Machine*, developed by Ekeoma *et al*. (2022), represents a substantial advancement by combining the processes of fruit mashing, juicing, and oil extraction into a single unit. This machine employs an upward-operating propeller mechanism to mix and crush palm fruits, aiming to maximize juice yield and efficiency in processing. However, despite its benefits, limitations have been observed in terms of mixing effectiveness, residue handling, and operational efficiency. Addressing these limitations is critical for enhancing the machine's performance. By redesigning the propeller to operate from up, this study aims to improve mixing dynamics and provide a more efficient process flow, which could result in a more consistent and thorough extraction process. The downward motion may better incorporate fruit particles throughout the tank, increase contact time, and enhance overall juice yield. This improvement could potentially reduce motor load, energy consumption, and processing time, offering benefits for small- to medium-scale operations.

The current *Integrated Palm Fruit Juice Machine*, while innovative, has demonstrated slightly inefficiencies in the distribution and circulation of palm fruits during processing. The existing design, which uses an upward-pushing propeller, tends to compact the fruit particles at the bottom of the tank. This limits thorough mixing and reduces the surface area of fruit exposed to the extraction process, ultimately affecting juice yield and efficiency. Additionally, the upward flow can lead to increased motor load and energy consumption due to the accumulation of fruit mass at the base, which contributes to mechanical strain and potential overheating. A design modification that enables the propeller to operate from up could potentially address these issues. This configuration might enhance fruit movement and prevent clumping, ensuring a more uniform distribution and improved juicing efficiency. However, comprehensive analysis and testing are necessary to determine the feasibility and benefits of such an improvement.

This study is justified by the need for efficient and cost-effective machinery in the palm fruit processing industry, particularly for small- and medium-scale producers who face resource constraints. Enhancing the current machine design to improve juice yield and reduce energy consumption would have substantial benefits. By ensuring a more efficient juicing process, this modification can help producers optimize production, reduce waste, and potentially lower operational costs. Dickson and Patience (2022) designed and developed a fruit juice extractor capable of both manual and automatic operation, addressing the increasing demand for juice due to its nutritional benefits. Performance metrics, including juice yield, extraction loss, and efficiency, were evaluated during the design phase. Results showed maximum juice output, extraction efficiency, and minimal extraction loss, indicating the extractor's capability for high juice extraction capacity. A study on palm fruit processors in Onicha Local Government Area, Ebonyi State, Nigeria, by Nnamani and Okereke (2023) analyzed the intensity of technology use in oil palm processing and identified key determinants affecting processing methods. Factors like marital status, labor cost, education level, and income were significant predictors, while access to credit and the quantity of palm fruit processed were not. Major constraints included high costs of palm fruits and transportation, limited processing equipment, and inadequate credit access, suggesting a need for cooperative societies to facilitate equipment procurement.

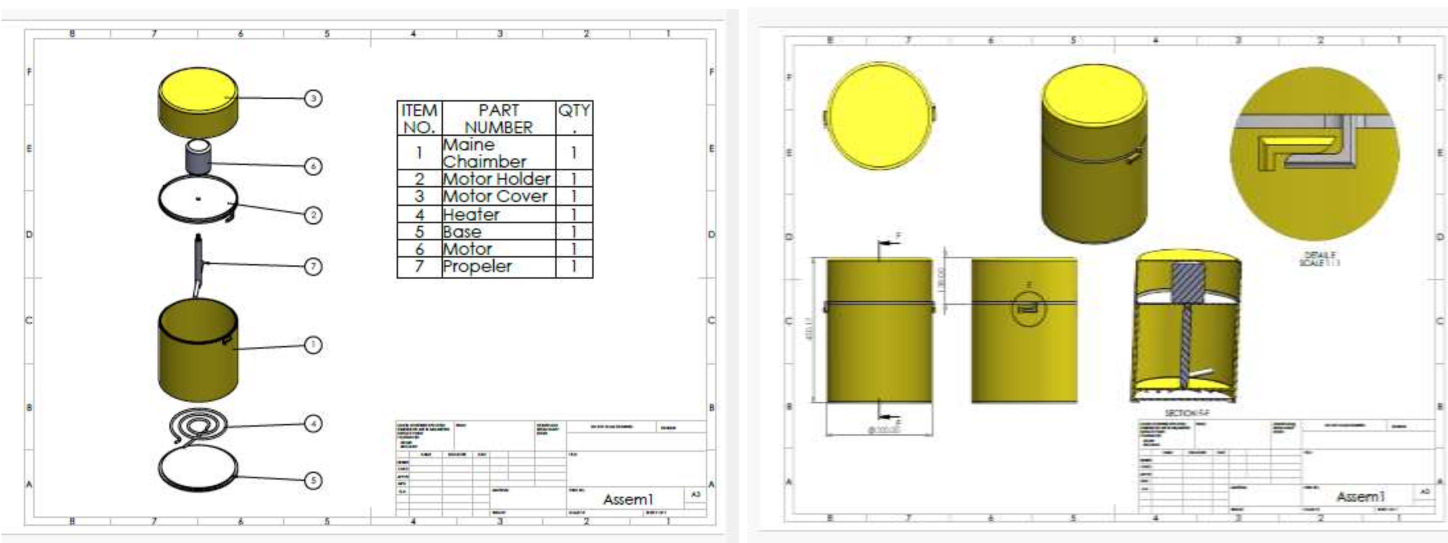
The increased extraction efficiency could contribute to higher profitability for small-scale operators, while promoting sustainability through reduced power requirements and machine wear. The findings from this study could also contribute to the broader field of agricultural machinery design, particularly in the development of processing equipment for other high-fiber fruits and crops. The aim of this study is to improve the efficiency and yield of the *Integrated Palm Fruit Juice Machine* by redesigning its propeller mechanism to operate in a downward motion, enhancing fruit circulation, mixing efficiency, and energy consumption.

2. MATERIALS AND METHODS

2.1 Description of the improved developed Integrated palm fruit juice extractor

The developed integrated palm fruit juice extractor is designed to improve extraction efficiency and product quality. It consists of several major components, including outer pot and inner pot (stainless steel), shaft, pulley, electric motor, belt, bearing, dampers, heater element, control switch and palm fruit agitator, as shown in Fig. 1.

The operation of the palm fruit juice extractor relies on centrifugal and centripetal forces,



facilitated by an electrically controlled system with essential components like an agitator, electric motor, and heating element. To start, thoroughly washed palm fruits are loaded vertically into the machine, and cold water is added to fill the inner pot. Activating the heating element with a control button brings the water to a boil, maintaining a temperature of around 61°C for approximately 12 minutes. Following the heating phase, the electric motor is turned on to rotate the agitator, which presses the palm fruits against the inner drum walls, efficiently separating the exocarp and endocarp.

Once the fruit is sufficiently processed, it is transferred to an external pot equipped with a sieve for filtering the juice, a feature included with the machine. This process can be repeated as needed to achieve optimal juice extraction from the palm fruits.

2.2 Design analysis of the machine

2.2.1 Design Considerations for Improved Palm Fruit Juice Extractor

In developing an improved palm fruit juice extractor, where the propeller operates downwards, the following design considerations were emphasized: The downward-propeller configuration aims to increase the efficiency of fruit movement within the extractor, improving the mixing and circulation patterns to maximize juice yield and reduce processing time. Modifications to the heating element placement and distribution were made to ensure even heating throughout the palm fruit mass. This prevents overcooking at the base and ensures consistent softening of the fruit for more effective extraction.

Given the downward pressure exerted by the new propeller orientation, reinforced structural support was integrated into the machine design to handle increased mechanical stress and prevent wear over prolonged use. To accommodate the downward flow design, a motor with higher torque and energy efficiency was selected to meet the increased load requirements, maintaining optimal agitator speed without sacrificing durability or energy costs. The design allows easier access to internal components, particularly the propeller and motor, simplifying routine maintenance, cleaning, and parts replacement to increase machine longevity and reliability.

2.2.2 Power requirement calculation for the agitator

The agitator power requirement is based on fluid mechanics principles, specifically applied to mixing systems. The formula is derived from dimensional analysis of agitator power and is known as the "Power Equation" for agitated systems. It can be used in sources related to chemical, mechanical, and process engineering, particularly in sections on mixing and agitation in fluids. Paul and Kresta (2004). The power needed for the agitator depends on factors like tank size, fluid viscosity, agitator type, and flow requirements. For this type of setup, where we’re mixing and pushing palm fruits downward, the calculated power requirement for the agitator is 0.5w using equation 2.1

$$P = N_P . \rho , N^3 . D^5 \tag{2.1}$$

where:

P = Power required (W) NpN
p = Power number (depends on impeller type and Reynolds number)
ρ = Density of the medium (kg/m³)
N = Agitator speed (rotations per second, rpm)
D = Diameter of the agitator (m)

2.2.3 Torque Calculation for Agitator Shaft

Torque on the agitator shaft is crucial for ensuring the motor can handle the load. The Torque was calculated to be 0.05Nm using equation 2.2: Shigley and Mischke (2001)

$$T = \frac{P}{2\pi N} \tag{2.2}$$

where:

T is the torque (Nm),
P is the power (W),
N is the rotational speed (rps).

This torque is manageable for a small motor designed for low-power applications.

2.2.4. Tank Design and Flow Dynamics

In this design, the agitator should ideally create a top-down flow pattern that pushes palm fruits to the bottom of the tank, where they circulate upward along the walls. For effective mixing and to create the desired flow dynamics in the tank, below is the guidelines for tank design in terms of diameter and height:

2.2.5 Tank diameter (Dt)

The tank diameter is generally 3-4 times the agitator diameter to ensure efficient mixing and to support a strong top-to-bottom flow pattern. The diameter was calculated to be 0.3m using equation 2.3.

$$D_t \,.\, A_t \tag{2.3}$$

Where

D_t is the tank diameter
A_t is the agitator diameter

2.2.6 Tank Height H_t

To allow for a stable circulation pattern (downward flow in the center and upward flow along the tank walls), the tank height is typically set to be around the same as the diameter of the tank which 0.3m. Perry and Green (2008)

2.2.7 Agitator Design and Flow Characteristics

Top-mounted, downward-pushing agitators are energy-efficient as gravity aids in the downward movement of palm fruits, reducing the motor load. The flow dynamics for this setup create a toroidal (doughnut-shaped) flow, promoting circulation. $0.5L/s$ was calculated as the volumetric flow rate Q induced by the agitator using equation 2.4. Oldshue, J.Y. *(1983)*

$$P = N_q.N.D^3 \tag{2.4}$$

where:

Q is the volumetric flow rate (m³/s),
N_q is the flow number, which depends on the type of impeller (typically around 0.5 for axial-flow impellers which was selected for the design),
N is the agitator speed (rotations per second, rps),
D is the agitator diameter (m).

The calculated flow rate, *0.5 L*/**s**, is appropriate for small-scale domestic food processing applications, providing enough circulation to keep the mixture well agitated and uniformly mixed. This toroidal flow pattern, characteristic of axial-flow impellers, promotes efficient top-down mixing and recirculation along the walls of the tank, which is ideal for moving solid particles like palm fruits downward.

2.2.8 Motor Selection

The motor should be selected to handle the calculated power and torque with some margin for efficiency loss. Based on our calculation, a small motor rated around 5-10W should suffice, accounting for any additional load from palm fruit consistency and resistance.

These calculations provide a foundational design framework. Additional factors, like the impeller blade angle, tank baffle placement (to prevent swirling and improve mixing), and motor type, can be adjusted for optimal performance based on the exact application requirements

2.3 Performance Testing

Five experimental runs were perfumed using palm fruit samples of the same weight. Stopwatch was used to monitor the time for each batch (12.6 minutes). The total weight of digested palm fruit and separate weights for well-digested and partially digested fruit using a 50 kg scale was recorded. Equation 2.4 was used to determine throughput capacity for each run while equation 2.6 was used to compute the efficiency for each run.

Table 1: Experimental result of the digesting process

S/N	Mass of palm fruit (Kg)	Mass of juice (kg)	Mass of water (kg)	Mass of digested nut and fiber (Kg)	Time taken (min)
1	11.0	4.6	1.5	6.4	11.5
2	11.0	4.55	1.5	6.45	11.0
3	11.0	4.7	1.5	6.3	11.5
4	11.0	4.6	1.5	6.4	11.0
5	11.0	4.65	1.5	6.35	11.0
Average	11.0	4.62	1.5	6.38	11.2

Table 1 shows the improved results, the average juice yield has increased from 4.0 kg to 4.62 kg, indicating a more effective extraction.

The average processing time has decreased from 12.6 minutes to 11.2 minutes, showing that the improved machine operates faster.

The average mass of digested nut & fiber decreased from 7.0 kg to 6.38 kg, suggesting more pulp is removed and converted into juice.

2.3.1 Throughput Capacity Calculation

The throughput capacity (C) is typically defined as the amount of material processed per unit time. In this case:

$$C = \frac{W_{total}}{T} \tag{2.5}$$

Where

W_{total} = Total weight of palm fruit digested (in kg)

T = Time taken for each batch (in minutes)

Since each test run were performed at 227 rpm for 12.6 minutes, the actual weight and time for each batch were substitute to find the throughput capacity.

2.3.2 Efficiency Calculation

The **efficiency (η)** of the extractor is the ratio of the weight of the well-digested palm fruit to the total weight of the digested palm fruit, given by:

$$\eta = \frac{W_{well}}{W_{total}} \times 100 \tag{2.6}$$

where:

W_{well}= Weight of well-digested palm fruit (in kg)
W_{total} = Total weight of palm fruit digested (in kg)

This efficiency formula measures how effectively the machine separates the pulp from the palm fruit.

Table 2: Comparison with Ekeoma *et al.* (2022) Results

Machine design	Throughput capacity (Kg/min)	Efficiency(%)
Original	0.873	36.36
Improved	0.982	42.00

Table 2 shows Comparison with Ekeoma *et al.* (2022) Results and the improved machine. Higher Throughput Capacity increased from 0.873 kg/min to 0.982 kg/min, meaning it can process more palm fruit in less time. Higher Efficiency improved from 36.36% to 42.00%, indicating a more effective extraction of juice from the same amount of palm fruit. These results shows that the improved machine design is both more efficient and has a greater capacity for juice extraction, validating the effectiveness of the design improvements.

3. Result and Discussion

In the evaluation of the improved palm fruit juice extractor, key performance metrics throughput capacity and extraction efficiency were assessed and compared to data from the original machine (Ekeoma *et al*., 2022). The goal was to verify that the modifications, including the downward-facing propeller and optimized heating element placement, led to a more effective and efficient juicing process. Two sets of experiments were conducted using equivalent samples of palm fruit. The original machine's performance (Ekeoma et al., 2022) yielded the following average results: Mass of palm fruit processed: 11.0 kg, Mass of juice extracted: 4.0 kg and Average time per batch: 12.6 minutes. For the improved machine, the experiments showed: Mass of palm fruit processed: 11.0 kg, Mass of juice extracted: 4.62 kg and Average time per batch: 11.2 minutes These results indicate a substantial improvement in both the amount of juice extracted and the time taken to process each batch. The improved machine demonstrated a 13% increase in throughput capacity, processing 0.982 kg of palm fruit per minute compared to 0.873 kg/min with the original machine. This increase is attributed to the improved propeller configuration, which enhanced fruit movement and optimized the mixing and circulation patterns within the extractor.

The improved machine achieved an efficiency of 42.00%, up from 36.36% with the original model, marking a 15.5% improvement in juice extraction. This increase in efficiency is likely due to even heating distribution and increased mixing capabilities, which resulted in more thorough pulp breakdown.

4 Conclusion

The performance evaluation of the improved palm fruit juice extractor demonstrates that the design modifications made to the original machine effectively enhance its operational efficiency and productivity. The upward-facing propeller configuration and optimized heating element placement were key improvements that led to a significant increase in throughput capacity and juice extraction efficiency. Specifically, the improved machine achieved a 13% increase in throughput capacity and a 15.5% increase in extraction efficiency compared to the original model. These improvements indicate that the new design processes palm fruit faster and extracts more juice per batch, minimizing processing time and maximizing yield. The use of a higher-torque motor and reinforced structural support also contributed to the machine's durability and reliability during prolonged operation.

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