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Design and Performance Evaluation of a Multi-Fruit Juice Extraction Machine

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ABSTRACT

This study focuses on the design, development, and performance evaluation of a motorized multi-fruit juice extraction machine constructed using locally available materials. The machine comprises two major sections: a chopping unit and an extraction unit, along with additional components such as feed hoppers, an auger conveyor housed in a cylindrical barrel, a juice sieve, and a waste outlet. It is powered by a 1.5 hp electric motor and was constructed at a cost of N170,520. During the performance tests on pineapple, orange, and cashew fruits, statistical analyses using split-plot and Nested experimental designs revealed that extraction speed and feed rate significantly influenced juice yield, with p-values of 0.0148 and 0.0018, respectively. Moreover, the extraction speed had a pronounced effect on extraction efficiency (p-value = 0.0080), while the type of fruit had minimal influence. The model validation using ANOVA and diagnostic plots confirmed the assumptions of normality, the absence of outliers, and constant variance. This affordable, locally fabricated machine offers a practical solution for small- to medium-scale fruit juice extraction, reducing the need for costly imported equipment and enhancing juice production efficiency in local communities.

INTRODUCTION

Agriculture is the backbone of many developing economies, particularly countries in sub-Saharan Africa, where a significant proportion of the population relies on farming for their livelihoods (Giller *et al.*, 2021), and Nigeria happens to be one of them. In Nigeria, agriculture remains a critical sector, contributing significantly to the Gross Domestic Product (GDP) and providing employment to millions of people. Within the agricultural sector, fruit production is a vital component, with fruits such as oranges, mangoes, pineapples, and bananas being cultivated across the country. However, despite the abundance of fruit production in Nigeria, the sector faces numerous challenges that hinder its full potential in contributing to food security, income generation, and industrial development (Asaleye *et al.*, 2023). A key issue is the high level of post-harvest losses caused by inadequate processing, storage, and preservation facilities. These losses are particularly pronounced in the fruit juice industry, where traditional and inefficient methods of extraction are still widely used. This study focuses on addressing these challenges by developing a motorized fruit juice extraction machine that leverages locally available materials to improve juice extraction efficiency, reduce post-harvest losses, and promote local manufacturing.

Nigeria's fruit production potential is enormous, with a diverse range of tropical and sub-tropical fruits grown across different agro-ecological zones. Fruits are an essential source of vitamins, minerals, and other nutrients, making them a critical component of the human diet. However, due to their high perishability, fruits are prone to significant post-harvest losses if not processed or preserved properly. The lack of effective processing technologies is a major factor contributing to these losses, as many small to medium-scale farmers and processors still rely on traditional labor-intensive, time-consuming methods, and yielding low quantities of juice (Bamigbade, 2002). Traditional juice extraction methods, such as manual squeezing and hand pressing, not only result in significant wastage of juice but also pose serious health and hygiene risks due to the use of unhygienic tools and environments. These methods are often characterized by poor extraction efficiency, where a large percentage of the juice remains trapped in the pulp, leading to substantial losses. To address the challenges associated with traditional juice extraction methods, there have been efforts to develop mechanical fruit juice extractors. However, many of these machines are imported and come with high costs, making them unaffordable for local farmers and processors. Additionally, imported machines often require specialized skills for operation and maintenance, which are not readily available in rural areas. The high cost of imported machines and the lack of technical know-how to operate them have resulted in limited adoption of these technologies in Nigeria. Consequently, there is a growing need for locally fabricated juice extraction machines that are not only affordable but also easy to operate and maintain. The development of such machines would enable small to medium-scale farmers and processors to enhance their productivity, reduce post-harvest losses, and improve the quality of their products, thereby increasing their income and contributing to the overall economic development of the country (Jongbo, 2021). In recent years, the Nigerian government has made concerted efforts to

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promote the local fabrication of agricultural equipment as part of its broader strategy to reduce dependence on imports and stimulate industrial development. These efforts include providing support to research institutions, universities, and private enterprises engaged in the design and development of agricultural machinery. The focus has been on developing cost-effective and user-friendly technologies that can be easily adopted by local farmers and processors (Nnanna *et al.*, 2023). However, despite these efforts, the availability of locally fabricated fruit juice extraction machines remains limited, and most existing machines still rely on outdated designs and technologies. This study seeks to bridge this gap by developing a motorized fruit juice extraction machine that is tailored to meet the specific needs of local farmers and processors in Nigeria. The machine is designed to be cost-effective, efficient, and easy to operate, making it accessible to a wide range of users.

The machine developed in this study consists of two main compartments: the chopping compartment and the juice extracting compartment. The chopping compartment is designed to slice or chop the fruits introduced through the hopper, while the juice extracting compartment uses an auger conveyor to crush, press, and squeeze the fruits to extract juice. The machine also includes other essential components such as a juice sieve, a juice collector, a waste outlet, a transmission chain, sprockets, and bearings, all of which are made from locally available materials. The use of locally sourced materials not only reduces the cost of production but also ensures that the machine is durable and easy to maintain. Moreover, the machine is powered by a 1.5hp electric motor, which enhances its efficiency and makes it suitable for medium to large-scale operations. The design of the machine takes into consideration the specific needs and challenges faced by local farmers and processors, including the need for a machine that is easy to use, maintain, and repair. Performance evaluation of the machine was conducted using a split design approach and a Nested experimental design to assess the effect of various operational parameters on juice extraction efficiency.

LITERATURE REVIEW

The exploration of fruit juice extractors reveals a wide range of designs and improvements over time, which have addressed various aspects of efficiency, capacity, and operational mechanisms of the machine.

Adewumi focused on citrus fruits, designing a juice extractor powered by a 1.17kW electric motor running at 1420 rpm. This machine demonstrated notable performance with an average juice extraction capacity of 5.11kg/hr for oranges and 2.79kg/hr for grapes. The extraction efficiency was 78.78% for oranges and 75.66% for grapes. The extractor's performance was significantly enhanced by modifying the tapered auger to a straight one, resulting in increased extraction efficiency from 78.9% to 89.2% and capacity from 5.1 to 15.8 kg/h for oranges. This improvement was further analyzed with various fruit sizes and shaft speeds, establishing strong quadratic relationships for extraction efficiency and capacity, and optimizing operational speeds for peak performance (Adewumi, 1998). In a similar vein, Badmus and Adeyemi designed a small-scale pineapple juice extractor featuring beater blades and a powered screw-pressing mechanism. Their machine successfully processed 12kg of ripe pineapple into 8liters of juice. This design emphasized practical processing capabilities and highlighted the machine's efficiency in handling pineapple, a challenging fruit due to its fibrous nature (Badmus & Adeyemi, 2004). Ishiwu and Oluka developed an extractor specifically for oranges, incorporating a screw jack, frame, connecting screw rod, pressing mechanism, and other components. Their performance evaluation revealed a juice yield of 76%, extraction efficiency of 83%, and an extraction loss of 3%. The extractor demonstrated significant time and cost savings compared to manual methods, with reductions of 96.6% and 89.6%, respectively. This design underscored the potential for mechanical extractors to enhance productivity and reduce labor in juice extraction (Ishiwu & Oluka, 2004).

Hebbar *et al.* (2008) advanced the field with a multi-fruit juice extractor capable of processing pineapple, orange, and melon. The machine utilized a screw conveying system and was evaluated for various performance indicators. Results showed that fruit type and peel condition significantly impacted performance, with peeled fruits yielding higher percentages of juice compared to unpeeled ones. The extractor achieved juice yields of 79.1% for pineapple, 77% for orange, and 89.5% for melon, with extraction efficiencies of 96.9%, 94.3%, and 96.6%, respectively. This study emphasized the importance of considering fruit characteristics in extractor design (Umesh *et al.*, 2008). Ogunsina and Lucas developed a manually operated cashew juice extractor based on the screw press principle. The machine, designed for cashew apples, had a juice output of 1.02 liters per hour and an extraction efficiency of 85.38%. This design demonstrated the adaptability of extraction principles to different fruit types and the potential for achieving high efficiency with manual operation (Ogunsina & Lucas, 2008). Furthermore, Samaila *et al.* (2008) designed a fruit juice extractor with an outer stainless steel cylindrical vessel and an inner perforated cylindrical vessel. The extractor was evaluated using orange, tomato, and watermelon, revealing differences in juice yield and extraction efficiency. The extractor achieved a maximum yield of 54.33% for watermelon, compared to 48.49% for orange and 32.77% for tomato. The study highlighted the influence of fruit type on extraction performance and the need for tailored designs to address specific processing challenges (Samaila *et al.*, 2008). Oyediran introduced a motorized cashew juice extractor featuring a 3 HP electric motor and a tilted feeding hopper. This design achieved an extraction efficiency of 83.9% with a throughput capacity of 0.267g/s. The study demonstrated the benefits of motorization in enhancing extraction efficiency and throughput in cashew juice production (Oyediran, 2010). Additionally, Adewumi and Ukwenya designed an extractor for mango juice with a main frame, hopper, auger, extraction unit, and juice outlet. Their machine, requiring 1.42 horsepower, recorded a maximum juice extraction efficiency of 76% and a capacity of 26.67 liters per hour. The study highlighted the relationships between shaft speed and extraction efficiency, which aided in making informed decisions on operational parameters for optimal performance (Adewumi & Ukwenya, 2012). Aye and Ashwe also created an orange juice extractor with sharpened blades on a rotating shaft, achieving extraction rates of 180-220 oranges per hour. The design combined maceration and extraction, to demonstrate its efficiency in processing large quantities of fruit (Aye & Ashwe, 2012). Olaniyan and Obajemihi developed a combined abrasion-macerating device for mango juice extraction. The machine by the use of a perforated cylindrical drum and a decreasing-pitch screw conveyor, achieved an average juice yield of 34.56% and extraction efficiency of 55.14%. This design highlighted the effectiveness of continuous extraction methods for mango processing (Olaniyan & Oje, 2011). In the studies of Ogola, a modified a hand-operated pineapple juice extractor was built, with a screw conveyor in a cylindrical drum incorporated to enhance juice extraction. The modified machine achieved efficiencies of 83.36% and 85.38%, which highlighted the benefits of design modifications in improving performance (Ogola, 2015).

A review on these previous designs have shown a rail of improvements made over time in exploring the field of fruit juice extractors, and this study have added more light to aspects of efficiency, capacity, and operational mechanisms.

MATERIALS AND METHODS

We proceed to discuss the conceptualization, design, and construction of the fruit juice extraction machine in line with basic industrial requirements of ease of operation, low production and operational cost, and improved extraction efficiency. Our approach involved mathematical as well as structural design models for the development of the machine making it well suited for processing pineapple, orange, and cashew fruits with simplicity and effectiveness while ensuring replicability. The idea of using readily available materials and components sourced from the local environment was also key to our design decisions. The Analysis of Variance (ANOVA) method was used to analyze the rate of feeding and extraction speed and other performance parameters such as juice yield, juice extraction efficiency, and extraction losses of the machine. During test and operation, the criteria for safe food management in machineries were observed as outlined in ISO 22000.

Working Operation of the Fruit Juice Extraction Machine

The machine operates based on the principles of chopping, crushing, and squeezing the fruit. The process begins with fruit being fed through the trapezoidal-shaped hopper, designed to gradually introduce the produce into the chopping and extraction chambers by gravity. The fruit enters the chopping unit, where blades on a rotating shaft slice the fruit into smaller pieces. Next, the sliced fruit moves into the extraction unit, where the screw conveyor compresses the fruit against the internal surfaces of the cylindrical barrel. As the screw rotates, it generates shear and compressive forces, effectively crushing the fruit and squeezing the juice out. The extracted juice is filtered through perforations in the bottom of the barrel and collected in the juice outlet, while the residual pulp is ejected through the cake outlet. A single-phase 1.5 hp electric motor powers the machine. The motor is connected to the screw conveyor and chopping unit via a system of pulleys and a V-belt, transmitting rotational energy to drive the juice extraction process. The motor speed can be adjusted using the gearbox to optimize the crushing and squeezing operations.

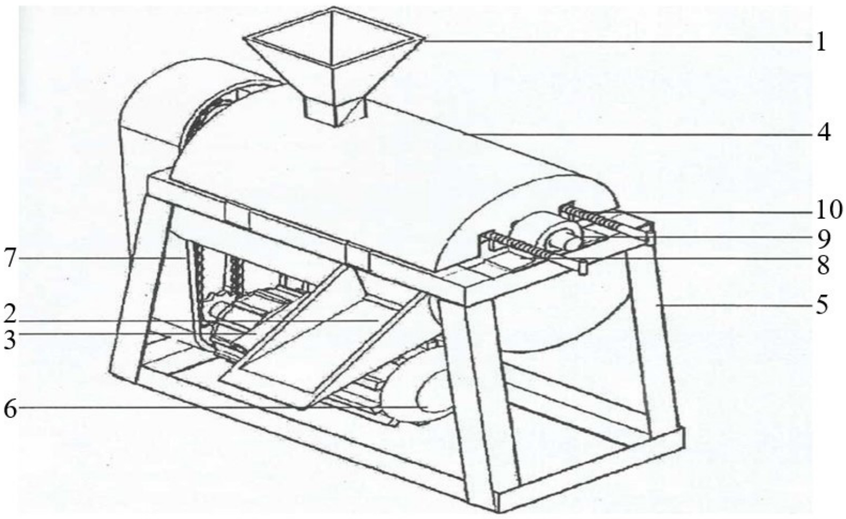

Figure 1: Designed and Fabricated Fruit Juice Extraction Machine

The design and fabrication process of the juice extraction machine were guided by specific material and operational requirements. Stainless steel was primarily selected for components in contact with juice, such as the hopper, screw conveyor, and cylindrical barrel, to ensure corrosion resistance and food safety. The frame was constructed from angle iron to provide rigidity and support. The machine components were carefully selected for durability, ease of maintenance, and cost-effectiveness.

Table 1: Materials Used in the Design and Construction

SN	Item	Description	Quantity
1	Hopper	Stainless steel (2 mm)	1
2	Chopping Unit outlet	Stainless steel (blades and shaft)	1
3	Screw Conveyor	Stainless steel (tapered)	1
4	Cylindrical Barrel	Stainless steel (4 mm)	1
5	Frame	Angle iron (5 mm)	1
6	Electric Motor	1.5 hp single-phase	1
7	V-Belt housing	Mild Steel	1
8	Bearings	Steel	2
9	Shaft	Stainless steel	1
10	Bolts	Mild Steel	1

Design Considerations

The design process took several key operational factors into account, including juice output, fruit type, machine stability, and hygiene. The juice extraction machine was designed to handle a capacity of 60 liters per hour for pineapples, 50 liters per hour for oranges, and 40 liters per hour for cashews, ensuring high throughput. Stainless steel was selected for components that would come in direct contact with juice to prevent corrosion and contamination, ensuring that the machine meets industrial food processing standards.

Key assumptions made during the design process:

i. The machine was expected to handle a variety of fruit densities, with pineapple at 680 kg/m³, orange at 725 kg/m³, and cashew at 900 kg/m³.

ii. The screw conveyor was designed to generate sufficient shear and compressive forces to effectively crush and squeeze the fruit, extracting the maximum possible amount of juice.

iii. The cylindrical barrel, housing the screw conveyor, was designed with a 2 mm clearance to ensure effective pressing while preventing excessive wear on the machine components.

iv. The electric motor's power output was carefully matched to the required torque and rotational speed for optimal juice extraction.

Construction of Machine Components

The fruit juice extractor was fabricated using standard manufacturing processes such as cutting, welding, and assembly. Key components included:

Hopper

Fabricated from 2 mm thick stainless steel, the hopper was trapezoidal in shape to ensure efficient feeding of fruit into the chopping and extraction chambers.

Chopping Unit

The chopping blades and shaft were constructed from stainless steel rods, with blades welded onto the shaft to slice the fruit as it passed through the hopper.

Screw Conveyor

A stainless-steel shaft with a tapered screw was designed to crush and press the fruit. The screw was housed in a cylindrical barrel fabricated from 4 mm thick stainless steel for durability and hygiene.

Frame

The machine frame was built from 5 mm thick angle iron, providing the necessary strength and stability to support the machine during operation.

Electric Motor

A 1.5 hp single-phase electric motor provided the necessary power to drive the machine, delivering torque to both the chopping and screw conveyor units via a V-belt system.

Design Calculations

To ensure the machine met the desired operational requirements, detailed design calculations were carried out, focusing on key components such as the screw conveyor, hopper, and power requirements. The power required for chopping and squeezing was calculated using standard mechanical engineering formulas, taking into account the forces exerted by the screw conveyor and the motor's rotational speed. The volume of the feed hopper was calculated based on its trapezoidal shape, ensuring it could hold sufficient fruit for continuous operation. The dimensions of the screw conveyor were optimized to provide the necessary shear and compressive forces while minimizing energy consumption.

Power Requirement for the Chopping Unit

The power required to chop the fruit is calculated using the following equation:

$$P_c = F_c \times v \quad (1)$$

Where:
Pc = Power required for chopping (Watts)
Fc = Centrifugal force applied to the fruit (N)
v = Velocity of the rotating shaft (m/s)
The centrifugal force (Fc) is calculated based on the shear force exerted by the blades on the fruit. Assuming the average shear force for an orange is 90 N, and adding a safety margin of 25%, the centrifugal force becomes:
$Fc = 90+(0.25\times90)=112.5N$
Given a shaft speed of 350 rpm and a diameter of 150 mm, the velocity (v) is calculated as:
$v=(\pi\times D\times N)/60 = 2.75m/s$
Thus, the power required for chopping:
$Pc = 112.5\times2.75=0.309kW$

Volume of the Feed Hopper

The feed hopper is trapezoidal in shape, and its volume (V) can be calculated using the following equation:

$$V=21\times(A+B)\times D\times C \quad (2)$$

Where:
A = Upper length of the hopper (250 mm)
B = Lower length of the hopper (150 mm)
D = Height of the hopper (200 mm)
C = Width of the hopper (250 mm)
Substituting the values:
$V=21\times(250+150)\times200\times250=10,000,000\ mm^3=0.01m^3$

Screw Conveyor Design

The screw conveyor is the critical component responsible for pressing and squeezing the fruit. The diameter of the screw shaft (ds) is calculated to withstand the bending and torsional moments using the formula:

$$d_s^3 = \frac{16}{\pi\times\tau} \times \sqrt{((K_b M_b)^2 + (K_t M_t)^2} \quad (3)$$

Where:
τ = Allowable shear stress for mild steel (55 MPa)
K_b = Shock and fatigue factor applied to bending (1.5)
K_t = Shock and fatigue factor applied to torsion (1.0)
M_b = Maximum bending moment (0.02 kNm)
Mt = Maximum torsional moment (6.02 kNm)

$$d_s^3 = \frac{16}{3.142\times55\times10^6} \times \sqrt{((1.5\times0.2)^2 + (1.0\times6.02)^2}$$

ds = 16 mm

Power Requirement for Juice Extraction

The power needed to extract juice from the fruit is determined using the following equation:

$$Pe= 4.5\times Qvc\times ls\times p\times g\times f \quad (4)$$

Where:
Pe = Power required for juice extraction (kW)
Qvc = Volumetric capacity of the machine (0.0173 m^3/hr for oranges)
ls = Length of the screw shaft (550 mm)
p = Density of the fruit (725 kg/m^3 for oranges)
g = Acceleration due to gravity (9.81 m/s^2)
f = Machine factor (0.4)
Substituting the values:
$Pe=4.5\times0.0173\times0.55\times725\times9.81\times0.4=0.132\,kW$

Total Power Requirement

The total power required to operate the juice extraction machine is the sum of the power required for chopping and juice extraction, plus the power required to drive the sprockets and shaft:

$$Pt = Pc + Pe+ Ppi + Psi \quad (5)$$

Where:
Ppi = Power for driving the sprockets (0.015 kW)
Psi = Power for driving the shaft (0.016 kW)
Thus:
$Pt = 0.309 + 0.132 + 0.015 + 0.016 = 0.472\,kW$

Motor Power Selection

The power required to drive the system is provided by a 1.5 hp electric motor. The motor's power output is calculated as:

$$Pm=Pt/\eta \quad (6)$$

Where:
Pm = Motor power (kW)
η = Motor efficiency (85%)
Substituting the values:
$Pm = 0.472/0.85 = 0.555\,kW \approx 0.74\,hp$
Thus, a 1.5 hp motor provides more than enough power to drive the juice extraction machine.

Experimental Procedure

After fabrication, the machine was tested to evaluate its performance in extracting juice from pineapples, oranges, and cashews. The machine was operated under controlled conditions, with juice output and extraction efficiency recorded for each fruit type. The results were analyzed to determine the machine's overall effectiveness, energy consumption, and operational stability.

RESULTS AND DISCUSSION

Performance Evaluation of the Juice Extraction Machine

In this section, we present the performance evaluation of the motorized fruit juice extraction machine, focusing on the operational parameters and performance measures. The evaluation is essential to determine the machine's efficiency and effectiveness in extracting juice from fruits such as pineapple, orange, and cashew. The main parameters analyzed include the juice yield, extraction efficiency, and extraction loss across different operational settings. The performance of the machine was tested under various feeding rates and extraction speeds, which were systematically varied during the experiments.

Performance Evaluation Parameters

The performance evaluation of the juice extraction machine was carried out post-fabrication to identify the optimal juice extraction parameters. The evaluation focused on two main categories: operational and performance factors. The operation factors involved adjusting the feeding rate at three distinct levels (F1 = 2.5, F2 = 3.0, and F3 = 3.5 kg/min) and varying the extraction speed across five levels (S1 = 95, S2 = 210, S3 = 320, S4 = 475, and S5 = 635 rpm). In terms of performance parameters, the key metrics analyzed included juice yield (Jy), extraction efficiency (JE), and extraction loss (EL).

Test Procedure

Freshly harvested pineapples, oranges, and cashews were procured from a local market in Auchi, Edo State, Nigeria. The fruits were cleaned, and any damaged pieces were discarded. They were then divided into three sets, each weighing 2.5 kg, 3.0 kg, and 3.5 kg, respectively. The juice extraction machine was powered on, and the pre-weighed fruit samples were fed into the chopping unit via the hopper. The machine's auger system (screw conveyor) crushed, pressed, and squeezed the fruit, separating the juice from the pulp. The mass of the juice extracted and the residual pulp were recorded for each sample. Conducting each test three times for pineapple, orange, and cashew while maintaining standard error handling techniques ensured accuracy and repeatability of the test.

Calculation of Performance Metrics

The machine's performance was evaluated using the following formulas for juice yield (Jy), extraction efficiency (JE), and extraction loss (EL) based on the mass of juice extracted, the residual waste, and the feed sample mass.

Juice Yield (J_y)

$$J_y = (100 \times W_{JE}) / (W_{JE} + W_{RW}) \quad (7)$$

Where:
W_{JE} = Weight of juice extracted (kg)
W_{RW} = Residual waste or dry chaff (kg)

Juice Extraction Efficiency (J_E)

$$J_E = (100 \times W_{JE}) / W_{FS} \quad (8)$$

Where:
W_{JE} = Weight of juice extracted (kg)
W_{FS} = Weight of feed sample (kg)

Extraction Loss (E_L)

$$E_L = (100 \times W_{FS} - (W_{JE} + WRW)) / W_{FS} \quad (9)$$

Where:
W_{FS} = Weight of feed sample (kg)

The juice constant (X) for each fruit type (pineapple, orange, and cashew) was also calculated to determine how much juice can be extracted relative to the feed sample weight. The juice constant (X) was calculated as:
$X = (W_{JE} + W_{RC}) / W_{FS}$
Where:
W_{RC} = Juice in the residual chaff (kg)
The juice constants were determined to be:

Table 2: Juice constant for the various fruit types

Fruit Type	Juice Constant (X)
Pineapple	0.75
Orange	0.86
Cashew	0.92

These values were then applied to calculate the juice extraction efficiencies for each fruit type.

Results of the Juice Extraction Process

The performance evaluation yielded the following results for each fruit type under various extraction speeds and feed rates:

Pineapple

Juice yield ranged between 76.28% and 98.07%, with extraction losses recorded at 8.68%.

Orange

Similar results were observed for orange, with juice yield ranging from 70.80% to 98.40%.

Cashew

Cashew extraction efficiency reached as high as 98.20%, with lower juice yield compared to pineapple and orange, indicating the need for optimized settings to handle cashew fruits effectively.

Data Analysis

The following tables summarize the raw data collected during the performance evaluation:

Table 3: Juice Extraction Results for Pineapple

Extraction Speed (rpm)	Feed Sample (kg)	Juice Extracted (kg)	Residual Waste (kg)	Extraction Time (min)
95	2.5	0.32	0.54	3.0
205	3.0	0.54	0.85	2.8
635	3.5	0.46	0.95	1.5

Table 4: Juice Extraction Results for Orange

Extraction Speed (rpm)	Feed Sample (kg)	Juice Extracted (kg)	Residual Waste (kg)	Extraction Time (min)
95	2.2	0.14	0.66	3.3
205	2.4	0.24	0.61	3.0
635	3.0	0.24	0.54	1.5

Table 5: Juice Extraction Results for Cashew

Extraction Speed (rpm)	Feed Sample (kg)	Juice Extracted (kg)	Residual Waste (kg)	Extraction Time (min)
95	2.2	0.04	0.44	2.5
205	2.8	0.26	0.55	2.2
635	3.0	0.35	0.56	1.0

Split-Plot Design Analysis

The performance of the juice extraction machine was analyzed using a split-plot design to evaluate the effects of different operational parameters. This design was chosen to handle the complexity of varying multiple factors, particularly the extraction speed and feed rate, which influence the machine's efficiency. The split-plot design allows for the simultaneous assessment of both "hard-to-change" factors, such as extraction speed, and "easy-to-change" factors, such as feed rate. This approach provides a robust framework for determining how these variables interact to impact juice yield.

Factors Considered in the Split-Plot Design

Two key factors were considered in this experimental design:

Extraction Speed (S), Which Was Set at Five Levels

95 rpm, 205 rpm, 345 rpm, 465 rpm, and 635 rpm.

Feed Rate (F), Which Was Tested at Three Levels

3.0 kg/min, 3.5 kg/min, and 4.0 kg/min.

The extraction speed was treated as the whole plot factor because adjusting the machine's speed requires stopping and reconfiguring the setup, making it a hard-to-change factor. The feed rate, on the other hand, could be adjusted easily and was thus assigned as the subplot factor.

Juice Yield Evaluation

The performance of the machine was measured by evaluating the juice yield across different combinations of extraction speed and feed rate. A total of 45 experimental runs were conducted, with each run replicated three times for pineapple, orange, and cashew. The primary response parameter in this experiment was the juice yield, which was calculated in kilograms for each fruit type.

Table 6: Juice Yield in kg for Pineapple, Orange, and Cashew at Various Extraction Speeds and Feed Rates

Fruit Type	Extraction Speed (rpm)	Feed Rate (kg/min)	Juice Yield (kg)
Pineapple	95	3.0	1.72
Pineapple	205	3.5	2.28
Orange	345	4.0	2.68
Orange	635	3.5	1.72
Cashew	95	4.0	3.13
Cashew	465	3.5	2.14

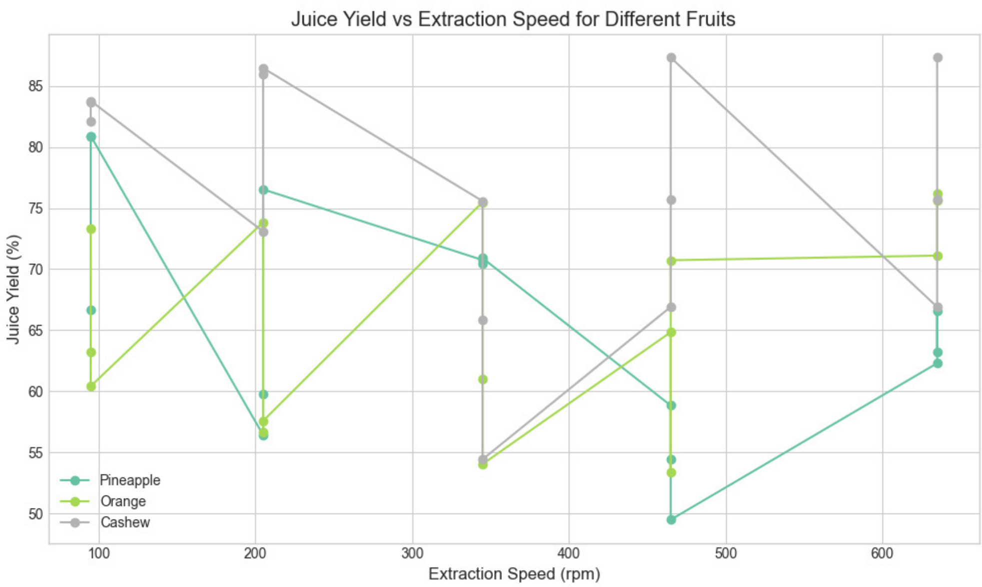

Figure 2: Juice yield vs extraction speed for the fruits

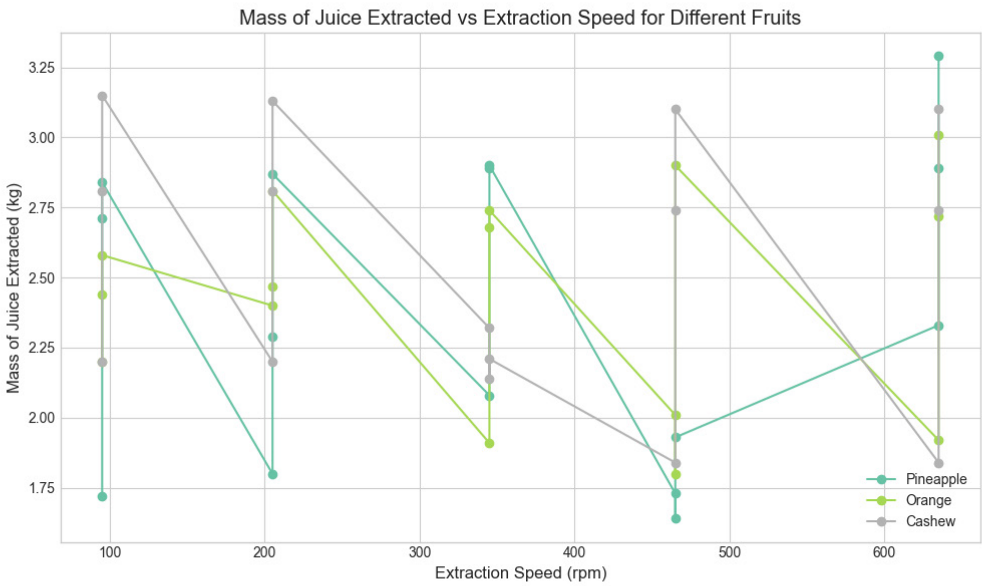

Figure 3: Mass of juice extracted versus extraction speed for the fruits

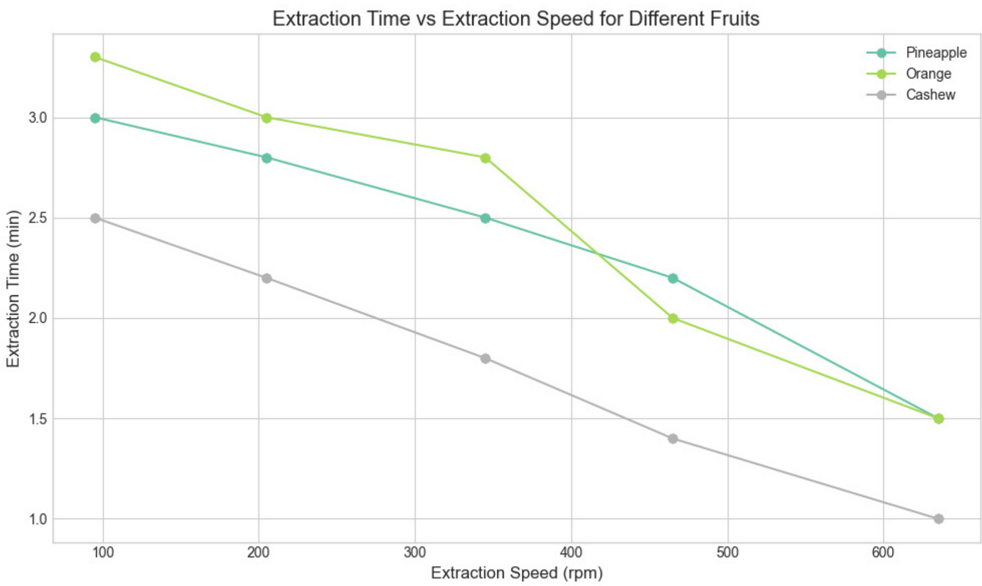

Figure 4: Extraction time versus extraction speed for the fruits

The results showed significant variations in juice yield depending on both the extraction speed and feed rate. Pineapple yielded the most juice at moderate extraction speeds, while cashew extraction was most efficient at higher speeds. The split-plot analysis confirmed that juice yield improved when feed rates were optimized for each fruit type.

Analysis of Variance (ANOVA) for Split-Plot Design

The results of the ANOVA revealed that both extraction speed and feed rate had significant effects on juice yield. The extraction speed demonstrated a statistically significant effect, with an F-value of 4.32 (p-value = 0.0148). Feed rate also showed strong significance, with an F-value of 45.04 (p-value = 0.0018), indicating that higher feed rates could enhance throughput but might slightly reduce extraction efficiency due to shorter processing time.

The interaction effect between extraction speed and feed rate, however, was not statistically significant, with

Table 7: ANOVA Results for Extraction Speed and Feed Rate

Source	Sum of Squares	df	Mean Square	F-Value	p-Value
Extraction Speed	1.403502	4	0.3509	4.32	0.0148
Feed Rate	4.093631	2	2.0468	45.04	0.0018
Interaction (S x F)	0.683524	8	0.0854	1.05	0.4410

an F-value of 1.05 and a p-value of 0.441. This suggests that the individual effects of extraction speed and feed rate are more critical to optimizing juice yield than their combined interaction.

Model Validation and Residual Analysis

To ensure the accuracy of the split-plot model, residual analysis was performed. The normal probability plot of the residuals (Figure 5) confirms the formation of a normal distribution, with no significant outliers detected and the overall symmetry of the distribution. This indicates that the model fits the data well and that the assumptions underlying the ANOVA are valid. In Figure 6, the externally studentized residual confirms high consistency in the overall data, showing that the model has a high viability. Additionally, plots of residuals versus predicted values Figure 7, shows no discernible patterns, indicating that the data's variance was stable. Table 8 details the ANOVA model validation chart using the values for the first 10 runs.

Table 8: ANOVA model validation table

Run	Actual	Predicted	Residual	Leverage	Standard Error	Externally Studentized Residual	P Value
1	2.58	2.5	0.08	0.1000	0.0857	0.9832	0.3543
2	2.2	2.3	-0.1	0.1741	0.0821	-1.3392	0.2173
3	2.44	2.4	0.04	0.1194	0.0848	0.5024	0.6289
4	2.4	2.45	-0.05	0.1053	0.0855	-0.6181	0.5536
5	2.47	2.6	-0.13	0.1159	0.0850	-1.6263	0.1425
6	2.81	2.75	0.06	0.2058	0.0805	0.8356	0.4410
7	1.91	1.95	-0.04	0.6430	0.0540	-1.2392	0.2503
8	2.78	2.7	0.08	0.1670	0.0825	1.0622	0.3191
9	2.68	2.6	0.08	0.1159	0.0850	1.0008	0.3462
10	2.9	2.8	0.10	0.2534	0.0781	1.4814	0.1767

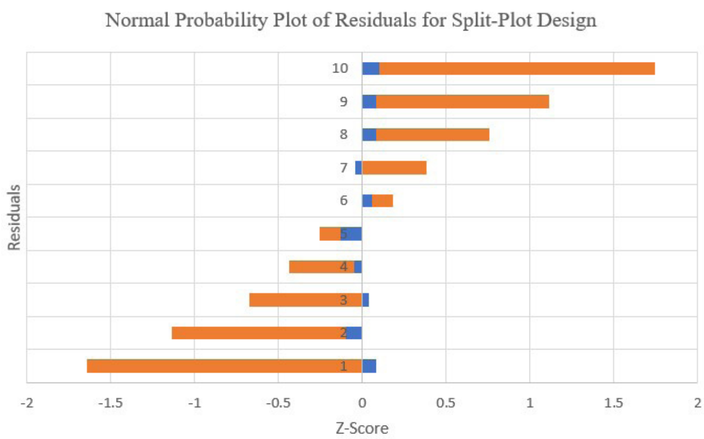

Figure 5: Normal Probability Plot of Residuals; a Split-Plot Design

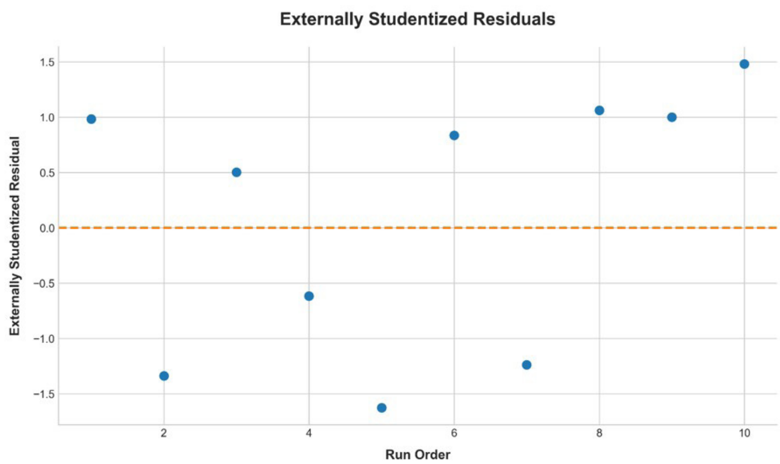

Figure 6: Plot of Externally studentized residuals

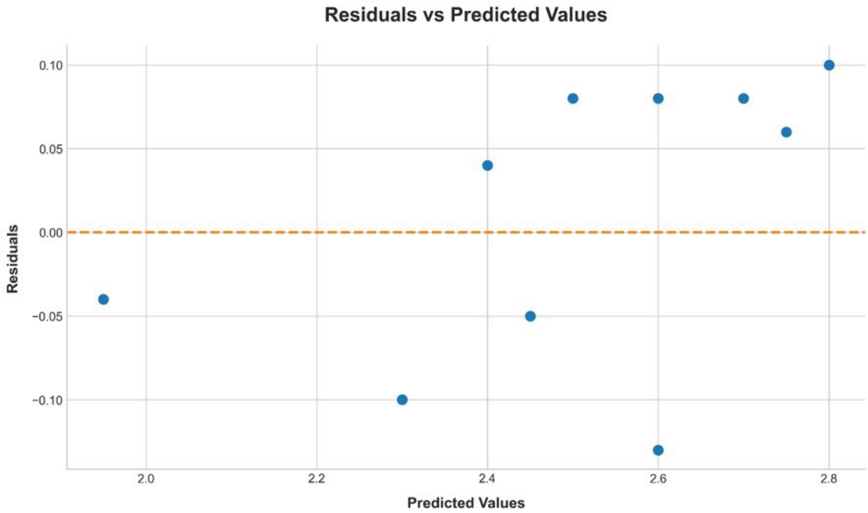

Figure 7: Plot of Residuals versus predicted values

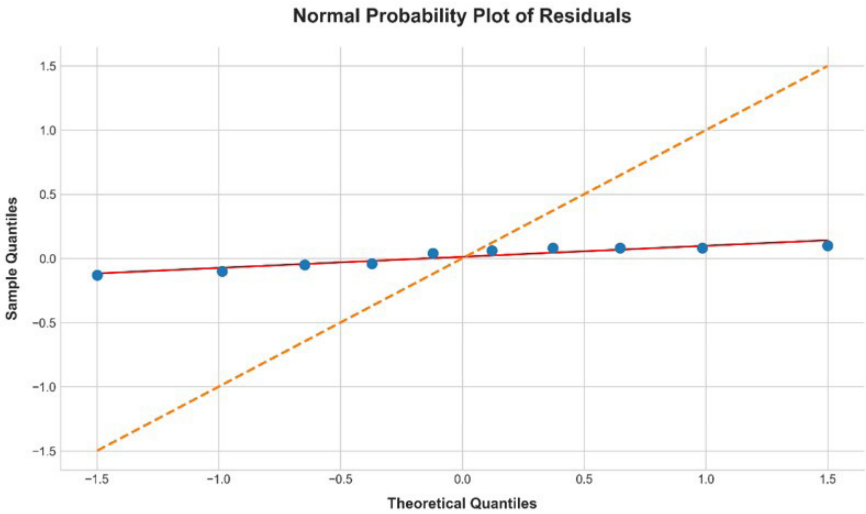

Figure 8: Normal probability plot residuals using theoretical and sample quantiles

Discussion of Results

The computer output for the split-plot experimental design, analyzed using the Design-Expert software, revealed from the ANOVA analysis (Table 3) that both extraction speed and feed rate significantly affected the amount of juice extracted. The p-value for extraction speed was 0.0148, and for feed rate, it was 0.0018, indicating that both factors had a statistically significant impact on juice yield at a 95% confidence level. Additionally, the ANOVA analysis (Table 7) demonstrated that the interaction effect between extraction speed and feed rate did not significantly affect juice yield, with a p-value of 0.441. This suggests that while each factor individually plays an important role in the machine's performance, their interaction does not provide any additional influence on the juice extraction process. Model adequacy was verified through residual analysis. The normal probability plot (Figure 5) showed that the error distribution was normal, as the plot presented a straight line, confirming the model's adequacy. Similarly, the externally studentized residuals (Figure 6) did not reveal any outliers. The absence of outliers in this analysis is crucial as outliers can distort the ANOVA results, typically arising from errors in data entry, coding, or experimental miscalculations. The plot of residuals versus predicted values (Figure 7) showed no apparent pattern, meaning there was no need for a variance-stabilizing transformation. Based on this graphical analysis, it can be concluded that the split-plot design and the ANOVA results are valid, as the model assumptions were met without issue. Furthermore, the ANOVA for the nested experimental design (Table 7) revealed that extraction speed was the major source of variability in machine efficiency, with a significant p-value of 0.0080. However, as shown in Figure 2 to 4 the different fruit types did not significantly affect extraction efficiency. Diagnostic checks were performed using additional plots to confirm the validity of the model. The normal probability plot (Figure 8) again confirmed that residuals were normally distributed, with no indication of outliers.

CONCLUSION

The fruit juice extraction machine was designed and fabricated to meet the juice extraction needs of small- to medium-scale enterprises. The machine's compact design, powered by a 1.5 hp electric motor, makes it suitable for both rural and urban areas. The machine was built at an affordable cost using locally sourced materials, ensuring ease of production, repair, and maintenance. Performance evaluations, using pineapple, orange, and cashew fruits, demonstrated that extraction speed and feed rate significantly influenced juice yield and efficiency. The split-plot design analysis revealed that extraction speed (with $p = 0.0148$) and feed rate ($p = 0.0018$) had a strong impact on the amount of juice extracted. Notably, the Nested experimental design showed that extraction speed was the most critical factor affecting extraction efficiency, with a p-value of 0.0080. While the type of fruit had minimal impact, the study highlighted the importance of controlling speed to optimize performance. The results also confirmed that there was no significant interaction between feed rate and extraction speed. Based on the results, it is recommended that future research focus on improving the screw conveyor design within the extraction chamber to further enhance juice yield and recovery efficiency. Additionally, further empirical modeling should be carried out to optimize the machine's operational parameters for various fruit types. This project has made a significant contribution by providing an affordable, locally produced alternative to expensive imported juice extraction equipment, supporting agricultural development and sustainability in Nigeria.

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