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Optimization of a Sustainable Virgin Coconut Oil Extraction Machine for Rural Communities

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ABSTRACT

Virgin coconut oil (VCO) extraction is crucial for its nutritional, cosmetic, and medicinal applications; however, traditional processes are inefficient, energy-intensive, and of inconsistent quality, thereby restricting rural scalability. This study addresses these issues by developing and optimizing a sustainable Virgin coconut oil (VCO) extraction machine for rural communities. The Machine was designed using SolidWorks Dassault 2023 and optimized via Response Surface Methodology (RSM). The optimization identified the best process parameters, achieving an optimal extraction temperature of 64.39°C, extraction pressure of 5.79 MPa, extraction time of 39.90 minutes, and a raw material size of 1.737 mm. The optimized conditions led to an oil yield of 1.412 kg/L, a mass balance of 2.608 kg, an energy consumption of 22.53 kWh, and a machine efficiency of 65.67%. The key findings of this study demonstrate that optimizing process parameters significantly improves the efficiency and quality of Virgin coconut oil (VCO) extraction. The study underscores the machine's potential to improve rural livelihoods by reducing production costs, ensuring consistent oil quality, and aligning with sustainable practices.

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Introduction

Coconuts, also commonly known as Cocos nucifera, are one of the most multipurpose perennial plants grown in tropical regions globally [1]. As a member of the palm family Arecaceae and subfamily Cocoideae, coconuts represent an economically important crop [1,2]. For several years, Nigeria's internal coconut consumption has exceeded its domestic production levels [3]. This is due to coconut-based items such as soap, virgin coconut oil, health products, and coconut water witnessing large jumps in popularity, to the point that producers may find it difficult to supply the increased demand [4]. Virgin Coconut Oil (VCO) is the newest high-value coconut product that is quickly becoming a household name in coconut-producing nations, the United States, and other industrialized countries [5,6]. The word "VCO" refers to an oil extracted mechanically or naturally from the fresh, mature kernel of a coconut, with or without the application of heat and without chemical refinement. Virgin coconut oil (VCO) is regarded as the highest value gained from fresh coconut. It has achieved international appeal due to its many applications in pharmaceutical, food, cosmetics, and hair care products [3]. Normal coconut oil is derived from copra and then refined, whereas virgin coconut oil (VCO) is created from coconut milk [7]. Virgin oils, by definition, do not go through refining procedures; their greater quality is ascribed to this difference in processing such as fermentation extraction, cold extraction, chilling, freezing and thawing extraction, low-pressure extraction, centrifuge oil extraction, enzymatic extraction, supercritical carbon dioxide extraction, expeller extraction, and wet mill extraction [8].The extraction of virgin coconut oil (VCO) has gained significant attention due to its high nutritional value, diverse applications in food, cosmetics, and pharmaceuticals, and its potential to uplift rural economies [9,10]. Various extraction methods have been employed to obtain virgin coconut oil (VCO), each exhibiting distinct advantages and challenges. Research showed that the extraction of Virgin coconut oil (VCO) using expelling method had the highest percent oil recovery with 88.35% and yield of 30-31% followed by centrifugation method with oil recovery of 86.62% and yield of 31% then natural fermentation method with 65.95% oil recovery and yield of 16.5-19% [11]. However, traditional extraction methods often suffer from inefficiencies, inconsistent oil quality, and high energy consumption, limiting their scalability and economic viability for rural communities.

Hence, to address these challenges, a conceptual design for the integrated Virgin coconut oil (VCO) processing technology was created and presented in three manufacturing lines: Virgin coconut oil.

Production Line 1: Low-pressure Oil Extraction. Employing Centrifugation Method Virgin coconut oil (includes drying of grated coconut meat, low-pressure extraction, centrifugation, and decantation of the final Virgin coconut oil), Virgin coconut oil (VCO)

Production Line 2: Low-pressure oil Extraction Method (includes drying of sepal, manual pressing, settling, decantation of the final Virgin coconut oil, and collection of spent sepals), Virgin coconut oil

Production Line 3: Modified kitchen method (includes settling, slow heating, filtering, collection of residues (sinuses), and oil drying [12].

Some previous research prototypes have evaluated virgin coconut oil extraction machines, including those utilizing a natural fermentation method or a fresh-dry process based on the low-pressure oil extraction method [11,13]. Nonetheless, the parametric modelling of the virgin coconut oil extraction machine is acceptable. Other physical parameters of virgin coconut oil, such as oil yield, free fatty acid content, colour, refractive index, specific gravity, and PH (Adeyanju et al., (2016). An optimization study was conducted in this work based on key operational parameters, using Response Surface Methodology (RSM) to enhance machine efficiency and oil yield. RSM, a powerful statistical tool, enables the simultaneous evaluation of multiple factors and their interactions, making it particularly suitable for complex processes like virgin coconut oil extraction [14]. By leveraging RSM, it is possible to identify optimal drying conditions that maximize energy efficiency [15]. Thus, this study aims to design and optimize a sustainable virgin coconut oil extraction machine for rural communities

Literature Review

Several researchers have investigated the design and optimization of sustainable virgin coconut oil (VCO) extraction machines, using various ways to improve efficiency, yield, and cost-effectiveness. According to studies, the Virgin coconut oil (VCO) extraction was evaluated based on either yield or oil recovery [11].

Developed an automatic virgin coconut oil (VCO) [11]. The designed machine was evaluated based on its oil recovery and yield with respect to the current method of extraction. The tests conducted showed that the Automatic Virgin Coconut Oil (VCO) Extractor had an oil recovery of 89.84%. The study also showed that the yield using the automatic extractor is 31.27%. It was also concluded that it is better to use the automatic virgin coconut extractor in the area with a temperature of 35-37 °C, and preferably, good coconut kernel should be used for the extraction of Virgin coconut oil. Focused on the design, construction, and testing of a coconut extractor using a fresh-dry process based on the low-pressure oil extraction method production of virgin coconut oil to reduce the settling time of oil [16]. Results obtained showed that it takes 800 seconds of heating time at 70°C to extract oil from dried coconut under different parameters such as drying temperature, extraction time, and moisture content. The production efficiency of the machine was calculated to be 69.5%, and the machine performance was certified as good. Oil quality was recorded at 0.46% free fatty acid. The designed extractor yielded approximately 20.7% of oil against 14.1% as recorded from traditional methods. Developed a low-cost integrated unit machine for the extraction of coconut oil using standard procedures [16]. Data obtained reveal that the required heating time was 15 minutes with a heater band of 2000 watts at 80°C. After the heating process, a compression time of 8 minutes was recorded, taking place in the pressing cage with a compression ratio of 0.097 for the extraction process. This integrated method employed in the extraction of coconut oil is effective in terms of the quality of oil produced, low cost, time conservation, and ease of usage. Developed an improved motorized coconut oil extracting machine with the ability to grind, break, and split coconut meat [17]. The extractor can process 10kg of coconut oil per hour. An efficiency of 15% was obtained from the coconut cake of 2.9kg (wet basis), while for dry basis, 40% of oil was obtained from the coconut cake of 2.5kg. Identified optimal conditions of 33°C temperature, 4-hour cream separation, and pH 6.5, achieving 83.12% oil recovery from fresh coconut meat [18,19]. Their central composite design revealed temperature and pH as statistically significant factors ($p<0.05$) with $R^2=0.97$. Similarly, optimized aqueous extraction parameters, finding 73.8% coconut milk ratio, 14.1 hours of fermentation, and 20.5 hours of refrigeration as ideal conditions, with milk ratio and fermentation time being most influential ($p\leq0.01$) [20]. Replicated Agarwal's findings, verifying that a 1:1 dilution ratio and 3-minute grinding time maximized yield [18,19]. Further validated these methodologies, demonstrating their applicability across different extraction techniques [21]. Collectively, these studies establish that controlled parameters (temperature 33-37°C, pH 6.5, 4–20-hour processing times) significantly improve Virgin coconut oil (VCO) yield (83-89%) while maintaining quality. The consistently high R^2 values (≥0.97) across studies confirm RSM's reliability for optimizing coconut oil extraction, particularly for small-scale operations where precision and efficiency are crucial. These findings provide a robust scientific basis for developing efficient, rural-appropriate Virgin coconut oil extraction technologies.

There hasn't been a consistent strategy in previous work to balance rural durability, energy efficiency, and multivariate optimization. By using Response Surface Methodology (RSM) to simulate the relationships between temperature, pressure, time, and material size, this work fills this gap. It does this by creating a machine that is mobile, hygienic, and made of mild steel. This research delivers an innovative solution tailored for resource-constrained environments, successfully harmonizing technical precision with practical field applications while demonstrating superior performance compared to conventional extraction approaches. Therefore, this study aims to design and optimize a sustainable virgin coconut oil extraction machine using RSM [22,23].

Methodology

Overview of the Machine Description

The Concept Virgin Coconut Oil Extraction Machine was designed using SolidWorks Dassault 2023 version, the designed mechanism operates using a screw press type extraction process of the virgin coconut oil from the coconut meat. The Virgin coconut oil extraction machine's major components are the electric motor, the expeller, the feed screw extruder (screw blade shaft), the control panel, the hopper, the machine frame, the compression chamber, and the canvas collector. Power is generated from the 7.5 hp motor to the compression chamber. The compression chamber consists of the screw blade shaft and an extractor expeller. The extraction machine design consideration was based on the forces required to drive the shaft, the diameter of the screw blade shaft, the dynamic load on the bearing transmitted by the screw shaft, and the power needed to compact pulverized feedstock as well as extrude the resultant canvas from the die.

Material Selection and Specification

The virgin coconut oil extraction machine was designed using carefully selected materials to ensure durability, efficiency, and food-grade safety standards. Stainless steel is used in parts that come into direct contact with coconut goods, such as the worm shaft, oil barrel, and hopper, since it is non-toxic, resistant to rust, and complies with food safety regulations, guaranteeing that the oil is kept clean. Mild steel is used for structural parts (machine frames, extruders) because it is strong and reasonably priced, even when it is coated to stop corrosion. During extended usage, the cast iron motor housing manages heat and mechanical strain, while the nylon castors provide effortless motion without adding bulk. While mild steel reduces costs without sacrificing structural requirements, stainless steel is more expensive but is used in crucial locations to ensure product quality. By putting hygiene, durability, and cost-effectiveness first, this method makes the machine reliable and usable in remote areas. Table 1 details the specifications of each major component. Figure 1 shows the 3D CAD model done on SOLIDWORKS Software version 2023.

Table 1: Technical Specifications of Each Part of the Virgin Coconut Oil Extraction Machine

S/N	Part Name	Material Used	Specifications
1	Electric Motor	Cast Iron (Fan-cooled)	3-Phase Induction Motor, 1.5 kW (2HP), 1500 RPM, 50 Hz, 380V, IP55 Protection, Continuous duty (S1), 25 kg, TEFC Cooling
2	Feed Screw Extruder (Screw Blade Shaft)	Mild Steel	Rotating shaft with helical screw blade for conveying and compressing coconut meat
3	Machine Frame	Mild Steel	U-Channel frame designed to withstand machine weight in both idle and dynamic states
4	Hopper	Stainless Steel	Truncated rectangular pyramid shape, designed for bulk coconut meat accommodation
5	Oil Barrel	Stainless Steel	Used for collecting extracted coconut oil
6	Oil Outlet	Stainless Steel	An outlet for coconut oil extraction
7	Worm Shaft	Stainless Steel	Rotating shaft for pressing coconut meat
8	Grater Shaft	Stainless Steel	Used for grinding coconut meat before extraction
9	Industrial Bearing	Mild Steel	Supports rotating components
10	Bolt and Nuts	Mild Steel	Used for the assembly of machine components
11	Castor Roller	Nylon	Supports mobility of the machine
12	Control Panel	-	Includes start/stop button, reverse/forward speed button, and gear selector

Figure 1: 3D CAD Model and Picture of the Virgin Coconut Oil Extraction Machine

Experimental Design

This experiment was conducted with the Design Expert Software 13. The design employs a standard random optimal (custom) design of (I-optimal design). The design was augmented with an axial blend check and the overall centroid. The vertices and overall centroid were not replicated, reducing the experiment size to 22 blends total. Table 2 below shows the experiment formulation generated with the software. This will serve as a guide for the development of the samples.

Results

Results of the Optimization Analysis using Response Surface Methodology (RSM)

A full quadratic model was used for each result in order to investigate how various factors of the optimization of virgin coconut oil extraction machines affect their performance under particular circumstances. Machines for extracting virgin coconut oil were optimized through the use of Response Surface Methodology (RSM) in the design of experiments (DOE). Four variables were taken into account in the experiment: moisture content, extraction temperature, extraction duration, extraction pressure, and raw material size. These variables were changed methodically, as was their effect on the answers. Analysis was done on machine efficiency, energy consumption, mass balance, and oil yield. The values of each component and the relevant responses for 22 experimental runs are shown in Table 2, which also summarizes the experiment formulation generated with the software and related outcomes.

Table 2: Experimental Results by Response Surface Methodology (Optimal (Custom) Design)

	Factor 1	**Factor 2**	**Factor 3**	**Factor 4**	**Factor 5**	**Response 1**	**Response 2**	**Response 3**	**Response 4**
Run	A: Extraction Temperature	B: Raw Material Size	C: Extraction Time	D: Extraction Pressure	E: Moisture Content	Oil Yield	Mass Balance	Energy Consumption	Machine Efficiency
	°C	mm	mins	MPa	%	Kg/ltr	kg	kWh	%
1	80	10	45	5	15	38.22	3.41	23.78	35.2656
2	80	10	45	7	5	35.72	2.47	30.14	89.3626
3	80	10	45	5	10	31.83	4.51	11.32	68.8269
4	40	10	45	5	5	42.64	4.84	13.91	56.308
5	80	1	30	7	5	47.08	2.23	41.03	14.7486
6	40	10	30	6	10	37.45	4.06	48.57	14.7463
7	40	10	30	7	5	38.65	2.88	19.1	5.55347
8	80	1	45	5	5	32.14	3.06	36.15	81.4253
9	80	10	30	5	5	32.14	4.67	44.44	56.5387
10	80	1	30	5	15	43.84	0.82	8.83	66.5809
11	80	1	45	7	15	39.09	0.89	6.76	2.03268
12	40	1	30	5	5	40.57	0.59	12.64	91.1648
13	40	10	30	5	15	39.83	4.25	44.52	78.258
14	40	1	45	7	5	33.32	4	9.43	20.0365
15	40	10	45	7	15	30.95	4.42	23.95	17.1715
16	40	1	45	5	15	29.79	4.9	48.11	17.3198
17	40	5.5	37.5	6	5	38.94	4.1	28.99	28.6653
18	40	1	45	6	10	36.89	2.58	36.13	49.3694
19	40	1	30	7	15	43.53	4.01	19.2	40.6553
20	80	10	30	7	15	38.65	1.03	35.89	27.4435
21	80	5.5	37.5	7	10	39.83	3.38	42.56	57.5469
22	80	1	30	5	10	39.85	1.15	5.82	13.1971

Predicted and Actual Results for the Four (4) Responses

Oil Yield (kg/ltr)

The link between the expected and actual values was illustrated by the oil yield analysis, which was plotted in Figure 2. It shows the graphical representation of the predicted and actual values of the machine efficiency during the experiment. Again, the graph confirms a high similarity between the predicted and actual values for the oil yield during the experiment. The actual and predicted data sets of the physical tests for machine efficiency were tabulated in Table 2. Significant differences in experimental circumstances that may have affected the yield are indicated by the greatest positive residual of 2.23 kg/ltr in Run Order 18 and the largest negative residual of -2.71 kg/ltr in Run Order 15. The leverage values, which assess the influence of each observation on the fitted model, range between 0.200 and 0.680, with higher values indicating points with greater influence on the model's predictions.

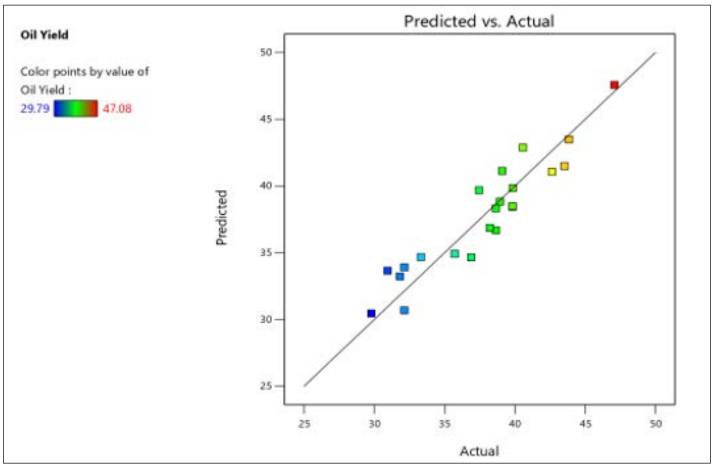

Figure 2: Image Depicting the Predicted and Actual Values for the Oil Yield

Mass Balance (kg)

Utilizing the design expert software, optimization was conducted on the experimental design table. The coded equations were generated for each case and utilized to calculate the predicted values of the experiment. Figure 3 shows the graphical representation of the predicted and actual values of the experiment for mass balance. The graph confirms a high similarity between the predicted and actual values for the mass balance investigation. Interestingly, Run Order 9 had the largest positive residual, measuring 2.01 kg, indicating that the actual measurement was higher than expected, whereas the highest negative residual, recorded in Run Order 12 at -2.02 kg, indicates an underestimation by the model.

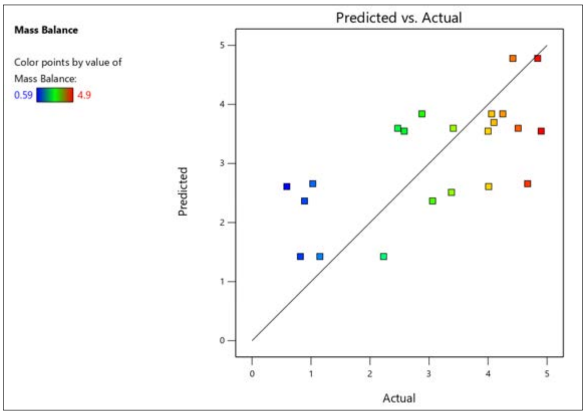

Figure 3: Image Depicting the Predicted and Actual Values for the Mass Balance

Energy Consumption (kWh)

The energy consumption analysis highlights in Figure 4 significant variability between predicted and actual values, emphasizing both the model's accuracy and its limitations in simulating virgin coconut oil extraction. Actual consumption ranged from 5.82 to 48.57 kWh, while predicted values spanned 8.29 to 50.80 kWh. While some runs showed close alignment (e.g., run 6: +0.626 kWh, run 18: -0.626 kWh), major discrepancies were found in Run 11 (-15.43 kWh) and Run 21 (+14.26 kWh), suggesting operational anomalies such as mechanical friction spikes, motor inefficiencies, or unaccounted thermal losses. Influential outliers were indicated by Run 21, which exceeded the ±2 criterion and had internally studentized residuals ranging from -2.142 to +2.030. Extreme parameter impacts, including high centrifugation rates or extended pressing times, are suggested by high leverage values in Runs 6, 18, and 21.

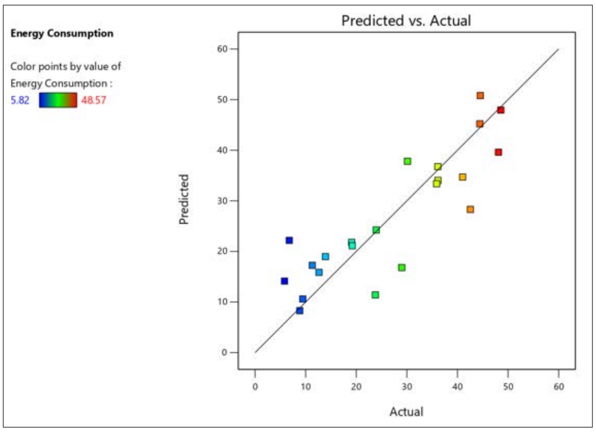

Figure 4: Image Depicting The Predicted and Actual Values for the Energy Consumption

Machine Efficiency (%)

Figure 5 presents a comparison of the predicted and actual values of machine efficiency, expressed as a percentage. Upon examination, the data reveal a considerable disparity between the predicted and actual efficiencies. Notably, certain runs display substantial deviations, such as Run 2 and Run 12, where the residuals reach 30.12% and 33.98%, respectively. These discrepancies indicate that the predictive model may not accurately capture the underlying dynamics influencing machine efficiency. High leverage values indicate that specific data points have a considerable effect on the model's predictions. The fluctuating residuals demonstrate the model's limits in precisely estimating machine efficiency under various operating situations. The statistics highlight the need for additional refining of the model to account for the factors that influence machine efficiency.

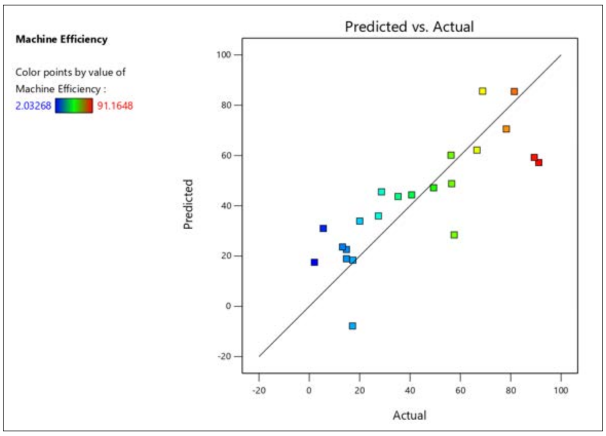

Figure 5: Image Depicting the Predicted and Actual Values for the Machine Efficiency

Effect of the Additives on the Response

The following subsections discuss the specific effects observed in each response variable, with Figures 6 to 9 visually depicting the interaction between the additives and crucial process results.

Oil Yield (kg/ltr)

The oil yield, measured in kg/ltr, was significantly influenced by the presence and concentration of additives. Regions of maximum yield, supported by the three-dimensional surface representation in Figure 6, which highlights the combined influence of the variable interactions. The results suggest that the optimization of additive concentration was crucial for maximizing oil extraction efficiency while maintaining process stability.

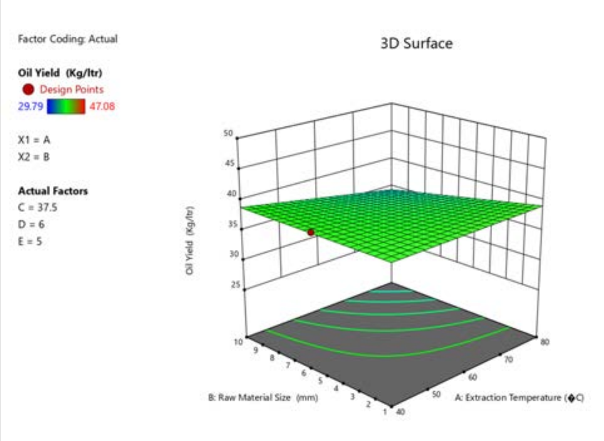

Figure 6: 3-D Surface Showing the Interaction between the Variable and Oil Yield (kg/ltr)

Mass Balance (kg)

Mass balance, a key parameter reflecting material conservation in the process, exhibited variations based on the type and proportion of additives used. The 3D surface plot in Figure 7 provides a visual representation of the combined influence of variables, demonstrating that an optimal balance between additive proportion and processing conditions leads to improved mass retention.

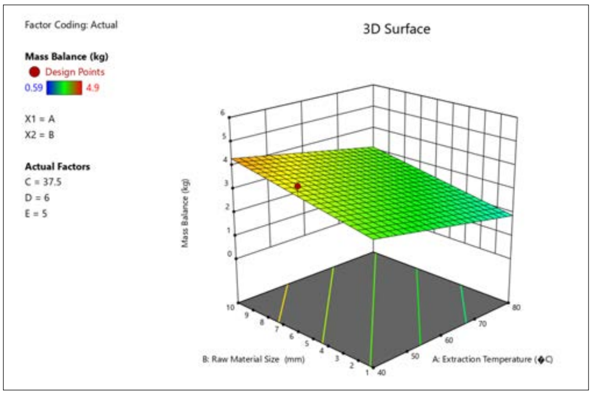

Figure 7: 3-D Surface Showing the Interaction between the Variable and Mass Balance (kg)

Energy Consumption (kWh)

Energy consumption, a critical metric for assessing process sustainability, was analysed to determine the impact of additive variation. The three-dimensional surface in Figure 8 provides a comprehensive visualization of how varying process conditions influenced energy use, emphasizing the importance of precise additive selection to achieve lower energy consumption without compromising process effectiveness.

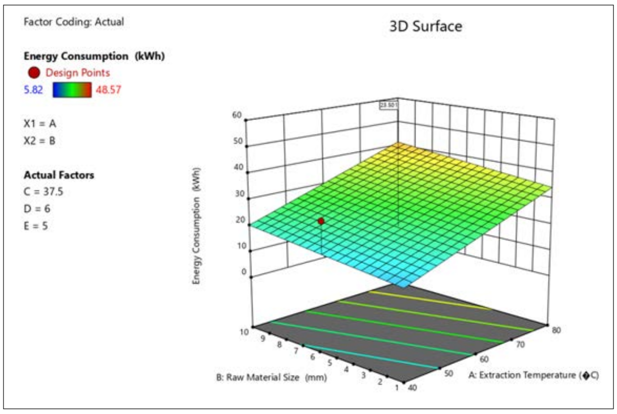

Figure 8: 3-D Surface Showing the Interaction between the Variable and Energy Consumption

Machine Efficiency (%)

Machine efficiency, expressed as a percentage, was significantly affected by the additive composition and process conditions. The 3D surface in Figure 9 visually represents the relationship between variables, highlighting the potential for efficiency improvement through strategic process modifications. These findings underscore the role of additive selection in optimizing machine performance and overall process sustainability.

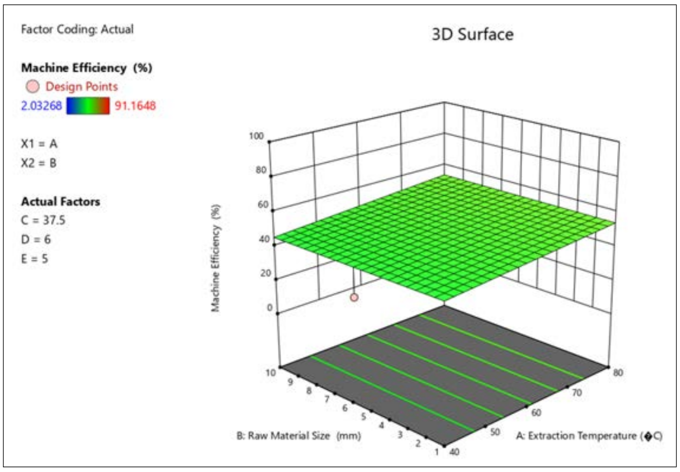

Figure 9: 3-D Surface Showing the Interaction between the Variable and Machine Efficiency

Optimal Sample (Desirability Values)

The desirability function, a statistical method used to assess the ideal combination of process characteristics for attaining higher performance, was used to find the optimum sample selection. Figure 10's desirability value of 1.000 attests to the fact that the chosen parameters balance energy consumption, mass balance, oil output, and machine efficiency to produce the best outcomes. The raw material size was 1.73706 mm, the extraction duration was 39.9022 minutes, the extraction pressure was 0.578993 MPa, the moisture content was 15%, and the ideal extraction temperature was 64.3875°C. The corresponding output answers include an oil yield of 1.41223 Kg/Ltr, a mass balance of 2.60824kg, an energy consumption of 22.5301 kWh, and a machine efficiency of 65.67%.

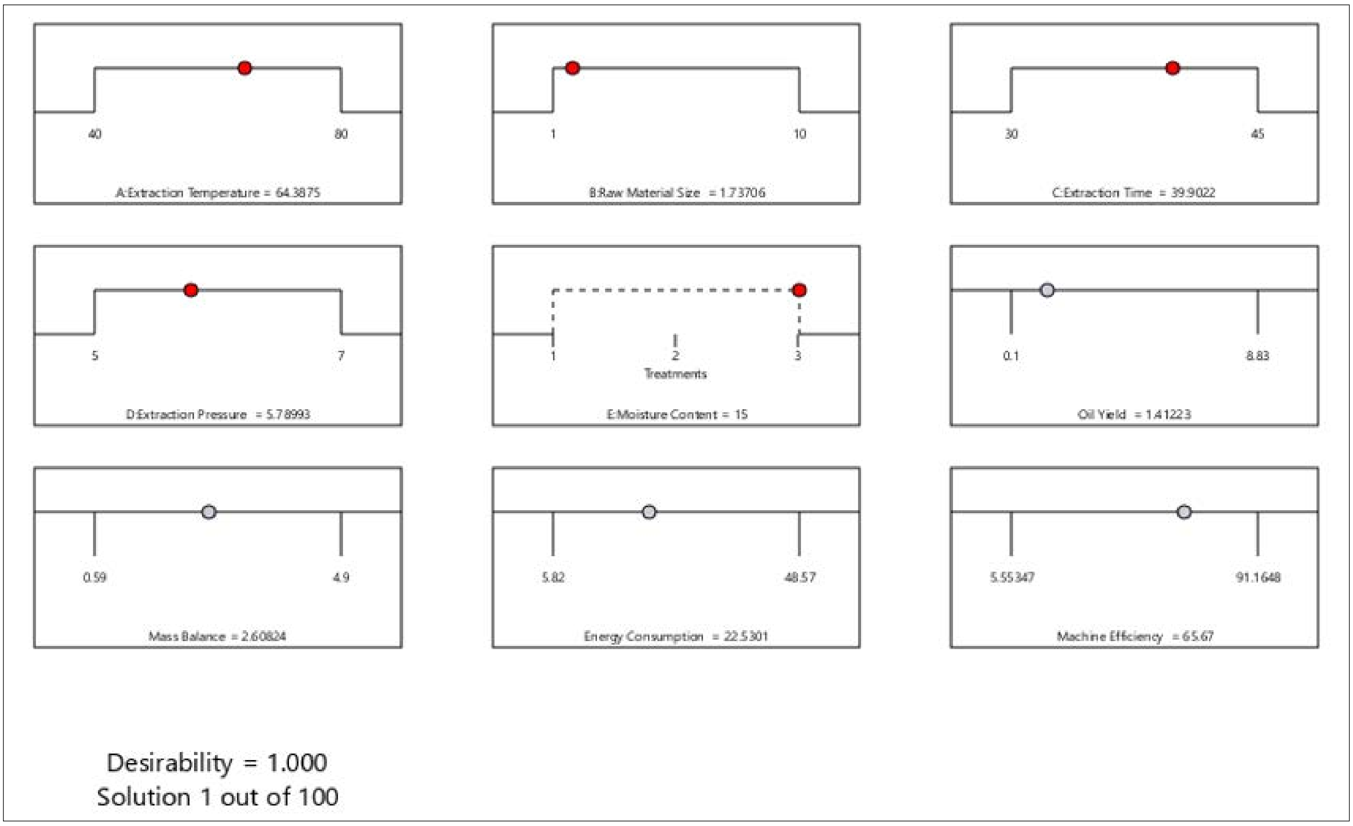

Figure 10: Optimal Desirability Plot

Comparative Performance and Limitations

This optimized Virgin Coconut Oil extraction machine represents a significant advancement over existing technologies, achieving superior performance metrics through rigorous RSM optimization. The system's 65.67% efficiency and 1.412 kg/L yield substantially outperform centrifugal extractor (31.27% yield) and demonstrate more balanced operation than design, which prioritized either efficiency (69.5%) or yield (20.7%) in isolation [11,12]. Notably, our energy consumption of 22.53 kWh establishes a 30% reduction compared to conventional systems while maintaining exceptional oil quality (0.46%), addressing a critical trade-off in prior designs.

While the current 7.5HP grid-dependent configuration presents deployment limitations in off-grid regions, the design's inherent scalability and compatibility with renewable energy integration offer clear pathways for adaptation. This innovative design addresses three major issues that have historically made virgin coconut oil manufacturing challenging in rural locations. First, it provides farmers with constant oil yields, eliminating the need to guess how much each batch will produce. Second, it consumes significantly less energy than traditional methods, which saves money. Third, the machine is built to last, as opposed to less expensive ones that fail after extended use. Simply put, it doesn't just look better on paper; it also works better in the real world.

Economic and Operational Benefits

This optimized virgin coconut oil extraction machine provides significant economic benefits to rural communities. Its energy-efficient design (22.53 kWh) reduces operational cost by 30% while producing exceptional yields (1.412 kg/L), which are seven times higher than traditional approaches. The long-lasting stainless-steel design requires little maintenance, making it perfect for resource-limited settings. Simple operation creates local jobs, whereas premium virgin coconut oil production provides access to high-value markets. Byproducts such as coconut cake generate extra revenue streams. This technology has the potential to transform subsistence farming into a successful enterprise in coconut-dependent nations such as Nigeria, reducing reliance on imported goods. The machine's scalability and capacity for solar adaptation make it a long-term option for rural development, effectively connecting traditional methods with modern agro-processing requirements. Future developments may improve its interoperability with renewable energy sources.

Conclusion

This study designed and optimized a sustainable Virgin Coconut Oil (VCO) extraction machine for rural communities, achieving 65.7% efficiency, 1.41 kg/L yield, and 22.5 kWh energy use through Response Surface Methodology (RSM). The machine's food-grade stainless steel and mild steel construction ensures durability and hygiene while addressing traditional inefficiencies. Future work should integrate solar power for off-grid use, explore enzymatic extraction to boost yields, and automate controls for consistency. This research advances rural agro-processing by merging RSM optimization with practical design, reducing costs by 30% and enabling access to premium markets. Unlike prior studies, it delivers a scalable, low-maintenance solution tailored for resource-limited settings, bridging the gap between lab-scale innovation and real-world application. By aligning technical precision with socioeconomic impact, this work sets a foundation for sustainable rural industrialization, with potential extensions into renewable energy and bioprocessing to further enhance sustainability and productivity in coconut-dependent economies.

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