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DESIGN AND COMPARATIVE ANALYSIS OF BEATER KNIFE MECHANISM FOR MANGO PULP EXTRACTION

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ABSTRACT

The purpose of this research work was to design, fabricate and evaluate an enhanced fruit pulp extraction unit to convert the available fruit into pulp to increase profitability and to limit post-harvest losses. This study introduced a newly developed mechanism with beater-type blades having serrated knives. As compared to the existing screw-type pulpers this newly developed pulping machine is quite lightweight, cheap, easy to fabricate, requires low maintenance, and has a low running cost. The major factors that were considered while planning included cost-effectiveness, manufacturing ease, high efficiency and user-friendly operation. The machine works by applying shearing and centrifugal forces on the fed fruits through an innovatively designed set of blades. The data like mass of fruits and residual waste, extracted juice volume and time taken for juice extraction were collected and used to calculate the key performance indicators (KPIs) which included juice yield, extraction efficiency and extraction loss of the unit. The mango types like Sindhri, Chaunsa and Langra were used and maximum average juice yield and extraction efficiency were obtained for Chaunsa variety at 600 rpm with 700-micron diameter sieve mesh size and 25 mm beater and sieve mesh clearance. The beater-type and screw-type pulpers have juice yield percentages of 63.40% & 34.56%, extraction efficiencies of 56.70% & 54.15%, power consumption of 1HP & 2.5HP and manufacturing costs of USD1275 & USD2000 respectively. The processing capacity of this pulp processing unit is 60-70kg/h.

Keywords: beater shaft, centrifugal squeezing, extraction chamber, pulp extraction, performance indicators, post-harvest losses, sieve mesh cylinder.

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INTRODUCTION

Fruit production in Pakistan was about 6,567,286 tonnes in the year 2016. In Pakistan, 30% production of fruits and vegetables gets wasted as per the assessment of the Department of Agriculture & Agribusiness Management because of the absence of processing facilities. (Ministries of Industries and Production, Small and Medium Enterprises Development Authority, Lahore, Pakistan, unpublished data). The fruit processing business has a lot of potential for growth in Pakistan. Pakistani mango is a worldwide attraction among fruits because of its taste, aroma, enriched minerals and supplements. Nonetheless, the mango is a short-lived item, thus its usability time-span is quite less. This results in high losses to processors, fruits merchants and farmers. So, it becomes a necessity to convert it into pulp form so that it can be preserved and stored easily for consumption all along the year. As the beverages industry have an ample demand for fruit pulp; so, in this emerging global fruit juice market, mango pulp can get its vital share as a crude food source (Trends and challenges 2017, Food and Agriculture Organization of the United Nations, Rome, Italy, unpublished data). Michael *et al*. designed, constructed and evaluated the performance of a manually-operated and simple juice-extracting machine for different fruits in terms of extraction capacity, extraction efficiency, juice yield and extraction loss. (Odewole, Falua *et al*. 2018) Gbasouzor and Okonkwo worked on the designing and fabrication of a fruit juice extractor. (Ikechukwu and Okonkwo 2014) The machine was structured to slice and extract juice from vegetables and fruits like orange, mango, pineapple, grape, apples, tomato, passion fruit and aloe vera. Olowaseun *et al.* designed and fabricated a motorized juice extractor and calculated its performance evaluation with pineapple, orange and golden melon fruits. (OO Martins and OH Adeyemi 2018) Hopper, extracting chamber, slicing chamber, frame and 2 hp motor were the main components of the machine. Oguntuyi (Oguntuyi 2013) designed and developed a manual multipurpose fruit juice extractor and performed its performance evaluation. Adebayo *et al.* designed, fabricated a prototype motorized juice extractor and evaluated its performance. (Adebayo, Unigbe *et al*. 2014) The prototype machine was assessed for two operating factors i.e., feed rate and extraction speed. Dikson (Dikson 2015) designed a system in which the operating principle was to convey the fruits by auger screw against a stationary sieve, due to frictional and shear forces the fruit pulp was separated from the seed (peeling principle). Suleiman *et al.* fabricated the machine which consisted of frame, hopper, pulley, auger shaft, cylinder, juice inlet for pulping. (Suleiman, Bello *et al.*) The machine was run at a predetermined speed of 1400 rpm using 3 mm, 5 mm and 7 mm cone clearance. Caixia (Caixia WO 8 March 2012) developed a machine that comprises a body, a fruit juice cup, a top cover and a push rod, wherein the machine body was arranged on a pedestal; a power unit was arranged inside the machine body. Wen (Wen. C.L. 2013) fostered a crushing kind of juice extractor that incorporated upper and lower pounding rings for giving both granulating and moving impacts during a cycle of extricating juice. Joao (Joao R. A. 2015) and Shrader developed an extractor that included first and second cups being relatively moveable for compressing a fruit in between them during extraction. Tsung (Tsung. C.C. 2016) developed a juice extricating gadget that contained a collection assembly, metal body and a pump. The collection assembly incorporated a cavity, an open section having a pouring opening, an assortment fragment having a directing opening. William and Shen (William. A.B. and Z. Shen. 2016) developed a juice extractor that had a fruit receiving cavity, having a centre axis with first and second cavity portions movable along the centre axis. The first and second cavity portions are sufficiently spaced away from each other to allow the fruit to be inserted therein and then the cavity portions were brought towards each other to compress the fruit. Dale (Dale. W.E. 2017) manufactured a squeezing machine and strategies for squeezing juice from staple fruits, the machine incorporated epitomes having a removable squeezing chamber and at least one channel which might be amassed and stacked with a macerated food item to frame flimsy layers isolated by a squeezing plate. Kim *et al*. developed a juice extracting machine in which a rotary brush was installed. (Kim. and Y. K. Gimhae. 2017) The rotary brush continuously brushes the outer surface of the strainer to remove the residue from the net holes of the strainer and to allow highly viscous juices to easily flow down through the strainer. Yan (Yan. K. W. 2015) developed a multi-purpose juicer, that consisted of a frame, a base assembly and a drive chamber. Rivera and Adrian (Rivera and A. Whittier 2017) developed a juicer; constructed using a base containing a motor, apparatus and shaft which ascends as a unit lifting and turning the squeezing cone. Olaniyan *et al.* designed and fabricated an abrasion-macerating device (AMD) that was used for mango pulp extraction at a small scale. (Olaniyan 2014) The design considerations taken into account were quality and cost of construction, low cost of extraction, high juice yield; high extraction efficiency and juice quality and an extraction chamber which can lodge different quantities of mango fruit as required. Sonar *et al*. planned and fabricated a mango pulp extractor with a bush-type mechanism that was run by an electric motor. (Sonar, Chindhe *et al.* 2018)

The literature review revealed that no comprehensive study has been done so far to gauge pulp extraction efficiency by using a mechanism with serrated knives in the beater blades. Therefore, an initiative was taken to design, fabricate and test this new mechanism to produce mango pulp. Previously only screw-type mechanisms were used to squeeze pulp from the fruits. These mechanisms are quite heftier with high manufacturing costs. This study introduced a newly developed mechanism with beater-type blades having serrated knives. As compared to the existing screw-type pulpers this newly developed pulping machine is quite lightweight, cheap, easy to fabricate, requires low maintenance, and has a low running cost.

MATERIALS AND METHODS

Design of Beater Knife Mechanism

The machine comprised of a food-grade stainless-steel frame, tapered blender shaft with sharp edges having teeth, assortment, pulp extraction and perforated chambers, set of pulleys and an electric motor. Mechanical design of the mango pulp processing unit was a complex and iterative process. Firstly, the nature of the design was addressed in general and then the design calculations were carried out for all mechanical components. The factors such as consistent economics, user safety, compliance with codes and standards, and considerations for product liability were prioritized over the development process of the machine. Typically, strength and stress define the survival probability of a mechanical component. (Khurmi R S and Gupta J K 1979, 511-514) As the machine operation always imparts dynamic loading, so fatigue failure theories were kept in mind during the design. The concepts of initial design considerations stated above were applied to design the mechanical components of the pulp extraction unit to the analysis, selection and design of the shaft, beater-blades, fasteners, sieve mesh cylinder, rolling contact bearings, weldments, frame, pulleys and belt. Auto CAD and Solid Works software tools were used for modelling and fatigue analysis.

Design of Blades and Beater Shaft

The blender shaft is a treated steel hollow shaft of circular cross-section with 30 mm distance across. The two closures of the shaft are press-fitted in the metal bearings to help take the load and secure the shaft inside the chamber that would build up stress on the mango which in result extracts the pulp. Maximum stress developed during the process of compression is determined by using the condition and formulae mentioned in Shigley's Mechanical Engineering Design. (Nisbeth J K and Budynas R G 2011, 890) Orthographic projections of rotary beater with knives and fruit pulp processing unit are shown in Figure1 and Figure-2.

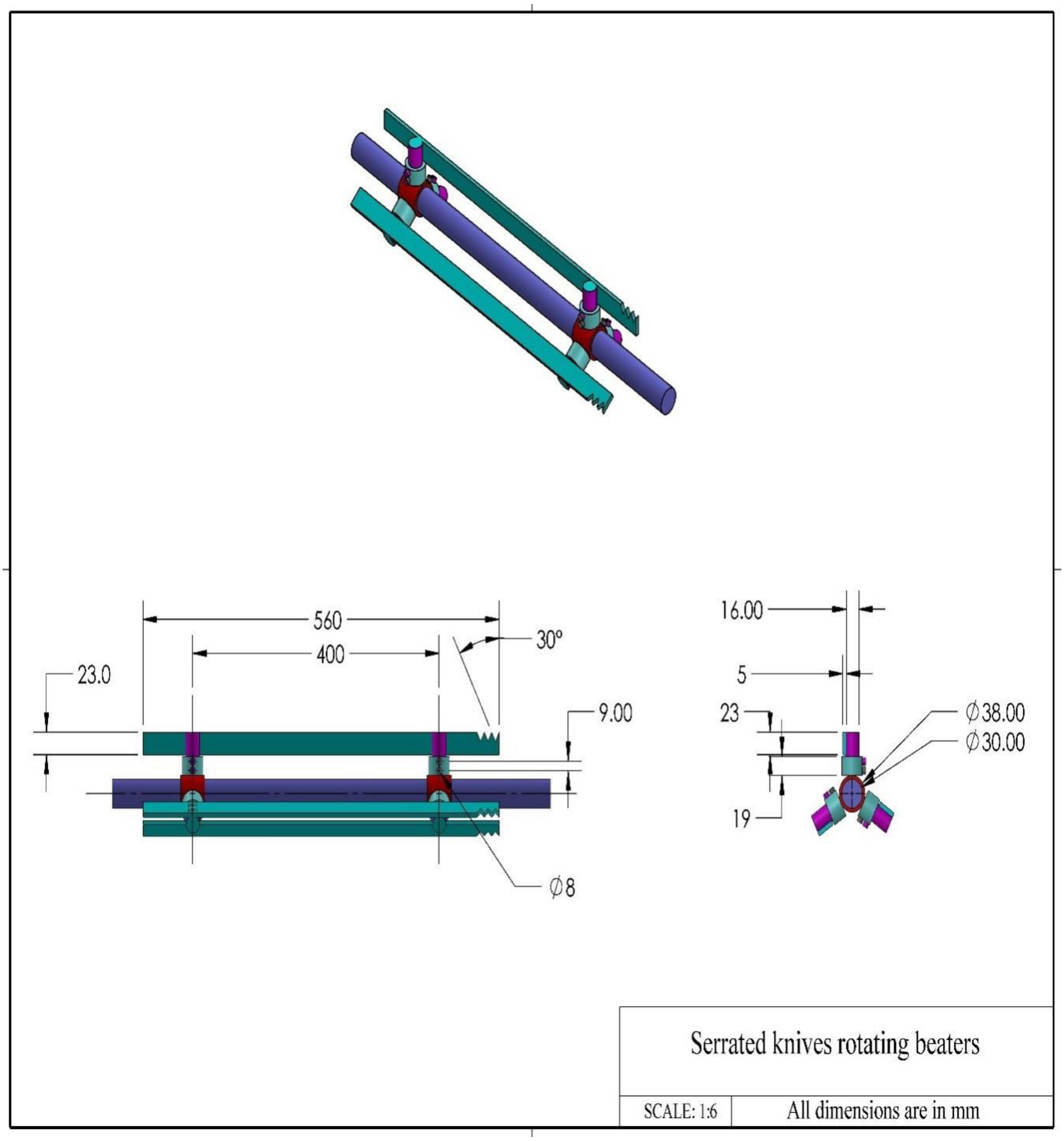

Figure-1. Orthographic projection of beater blades with knives (mm).

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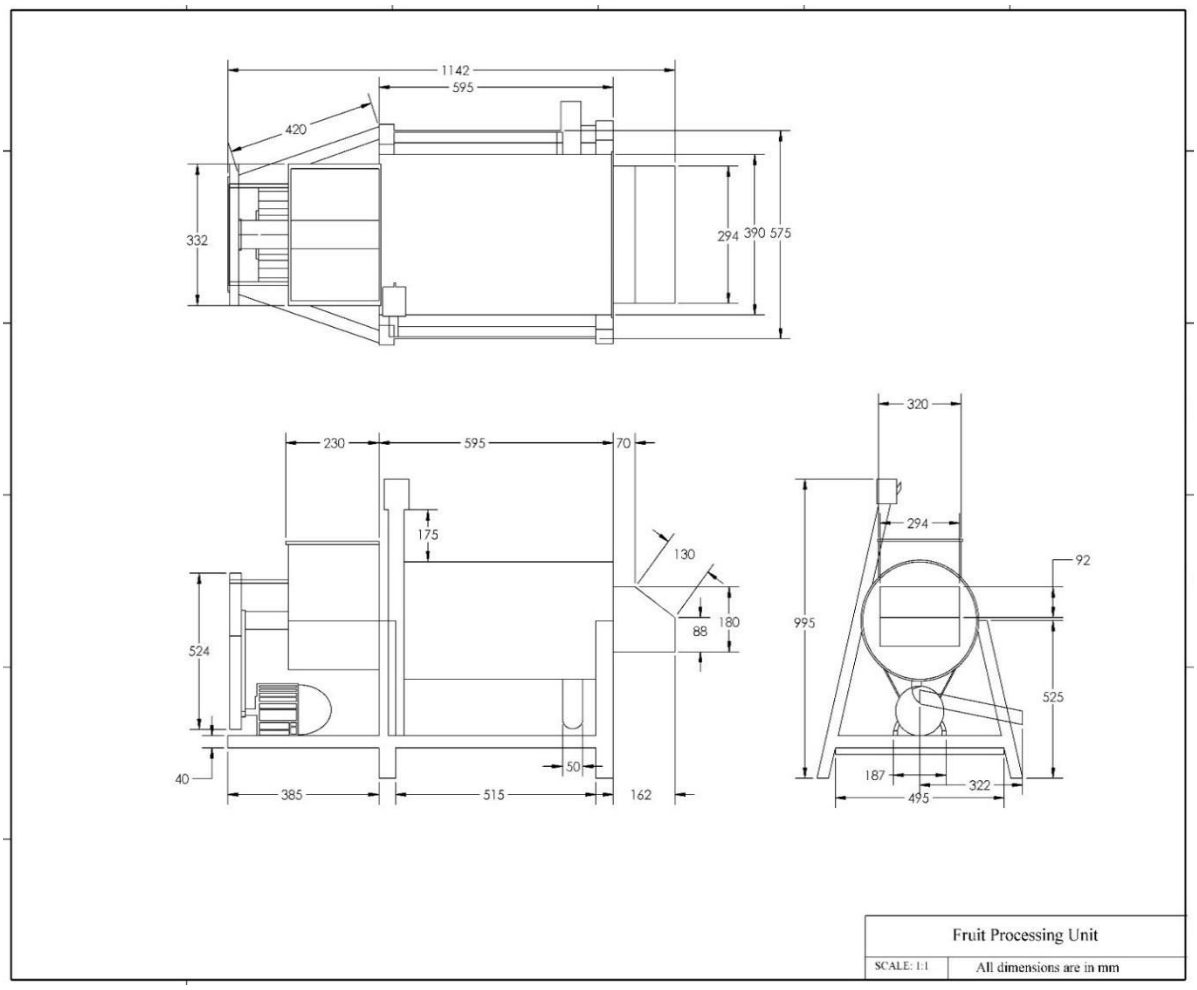

Figure-2. Orthographic projection of extraction chamber (mm).

Static and Dynamic Analysis of Beater Blades

SolidWorks was used to make the CAD model of the beater blade. Static and dynamic analysis was carried out to identify properties of materials, mesh and contact information, loads and fixtures, resultant forces and to study the effects on the beater blade while the cutting, beating and squeezing operations were performed. The results were quite satisfying as the shear strength of stainless steel is 81 GPa and the shear strength for mango is 10 GPa. As there is a noticeable difference between shear strengths values of mango and stainless steel so it was very easy for a stainless steel beater blade to cut, shear and squeeze mango by beating it against the stationary perforated drum to get the pulp out of it without getting damaged. The yield strength and maximum deformation of the blade are shown in Figure-3 and Figure-4 respectively.

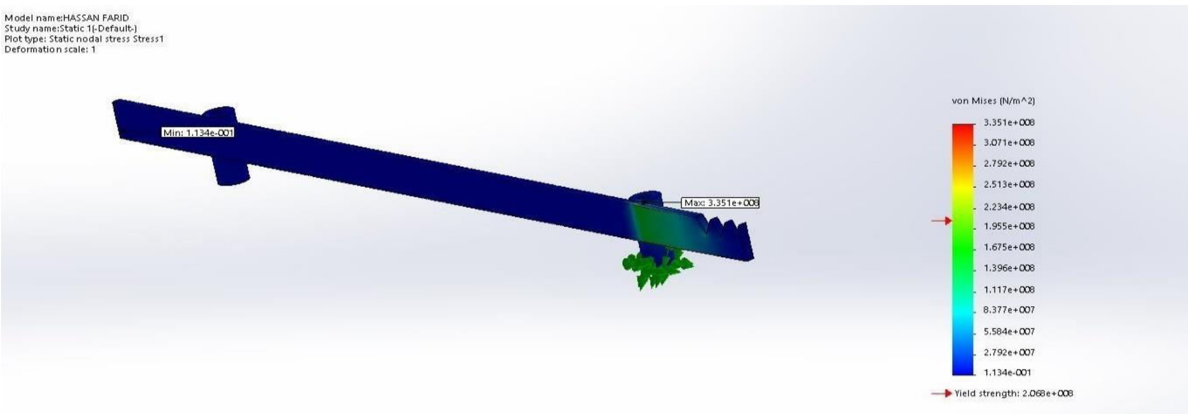

Figure-3. Yield strength of beater blade.

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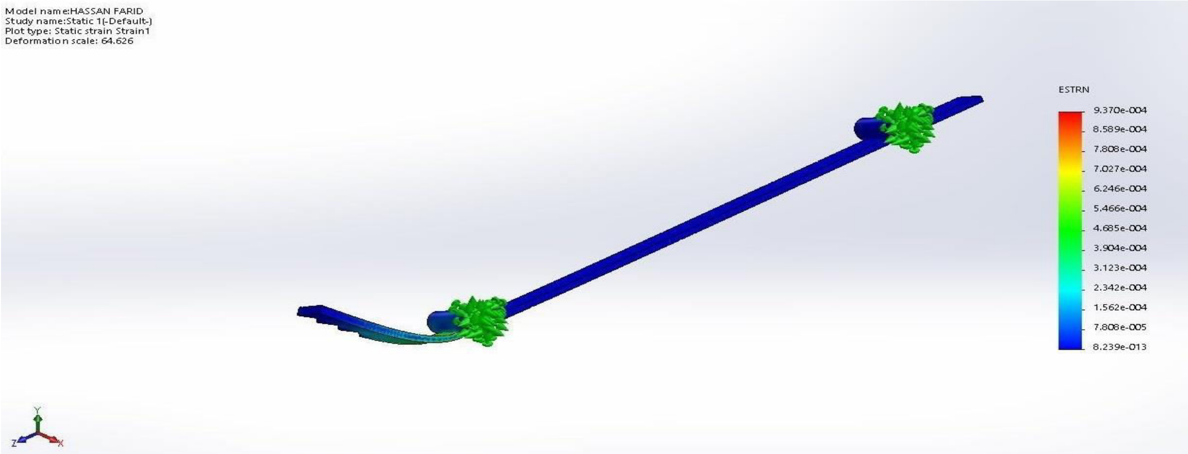

Figure-4. Maximum deformation of beater blade.

Design of the Machine Components with Specifications

Table-1 enlists the specifications of all the machine components used to build pulp extraction unit.

Table-1. Specifications of all the machine components.

S. No.	Designed Components	Specifications
1	Working capacity of the extractor machine	25 kg of pulp h^{-1}
2	Power of electric motor	0.75 kW (1 HP)
3	Motor speed	1450 rpm
4	Variable speeds of shaft	600 rpm and 300 rpm
5	Density of stainless steel, grade 304	8000 kg/m^3
6	Density of mango	1002 kg/m^3
7	Selected length of beater shaft	1000 mm
8	Mass of stainless-steel shaft, grade 304	5.07 Kg
9	Selected dimensions of beater blades	560 mm x 23 mm x 5 mm
10	Selected hopper capacity	10 mangoes
11	Mass of beater shaft pulley	2 kg
12	Efficiency of electric motor, NEMA	85%
13	Stress concentration factor	K_t= 1.5
14	Permissible shear stress of stainless steel	81 GPa
15	Friction coefficient between pulley and belt, μ	0.52
16	Shear stress for mango	10 GPa
17	Selected diameter of the motor pulley	53 mm
18	Selected diameter of beater shaft pulley	253 mm

Methodology

The beater shaft has a diameter of 30 mm and is made up of solid stainless steel. For crushing and beating purposes, three stainless steel blades make an angle of 120 degree to each other when they are attached to the main shaft aligned with the help of ball bearings at both ends. The blades of the shaft are shown in Figure-5 and the fabricated machine is shown in Figure-6.

Figure-5. Shaft and beater blades mechanism of fruit pulp processing unit.

Figure-6. Fabricated stainless steel fruit pulp processing unit.

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RESULTS AND DISCUSSIONS

Testing

The machine's performance was evaluated by feeding a calculated mass of 5 kg of every mango variety for example Sindhri, Chaunsa and Langra into the perforated chamber, the fruits were squashed constantly by the compressive force; extracting the pulp out of the mangoes through a fixed punctured strainer. The results of the twenty-four experiments using combinations of different varieties, sieve mesh cylinder, clearance level and beater speeds are shown in Table-2. The cost and benefit analysis of the machine developed in this study is presented in Table-3.

Table-2. Performance of beater knife mechanism w.r.t different variables.

Sr. No.	Factors Combination Code	Variety (V)	Speed (B) (rpm)	Sieve Mesh Size (S) (µm)	Clearance (C) (mm)	Juice Yield (%)	Extraction Efficiency (%)	Extraction Loss (%)
1	V1B2S1C1	Sindhri	600	400	25	62.10	59.36	10.44
2	V1B2S1C2	Sindhri	600	400	35	53.90	45.78	15.08
3	V1B2S2C2	Sindhri	600	700	35	59.30	53.20	10.30
4	V1B2S2C1	Sindhri	600	700	25	63.40	56.70	10.44
5	V1B1S1C1	Sindhri	300	400	25	58.70	44.50	24.22
6	V1B1S2C2	Sindhri	300	700	35	59.90	42.30	29.40
7	V1B1S1C2	Sindhri	300	400	35	53.60	37.40	30.30
8	V1B1S2C1	Sindhri	300	700	25	58.30	40.60	30.40
9	V2B2S1C1	Chaunsa	600	400	25	62.00	58.80	5.40
10	V2B2S1C2	Chaunsa	600	400	35	57.60	45.10	16.48
11	V2B2S2C1	Chaunsa	600	700	25	60.60	52.50	13.34
12	V2B2S2C2	Chaunsa	600	700	35	62.10	55.90	10.00
13	V2B1S1C1	Chaunsa	300	400	25	58.80	51.580	18.40
14	V2B1S2C2	Chaunsa	300	700	35	57.30	48.80	23.10
15	V2B1S1C2	Chaunsa	300	400	35	55.00	39.00	24.66
16	V2B1S2C1	Chaunsa	300	700	25	59.30	46.50	23.20
17	V3B2S1C1	Langra	600	400	25	59.30	51.00	14.00
18	V3B2S1C2	Langra	600	400	35	43.40	38.30	11.80
19	V3B2S2C1	Langra	600	700	25	60.40	52.00	14.00
20	V3B2S2C2	Langra	600	700	35	51.30	43.80	14.76
21	V3B1S1C1	Langra	300	400	25	58.60	47.40	19.20
22	V3B1S2C2	Langra	300	700	35	45.60	36.60	19.80
23	V3B1S1C2	Langra	300	400	35	36.70	31.10	15.00
24	V3B1S2C1	Langra	300	700	25	58.20	47.70	21.40

Table-3. Cost (PKR) analysis of fruit pulp processing unit.

Fixed Economic Cost		
1	Fabrication cost (Material and Labor) of fruit pulp extraction unit	Rs.2,25,000
2	Rate of depreciation (5% of machine cost per year)	Rs.11,250
3	Total depreciation as per life span of the machine (10 years)	Rs.1,12,250
4	Salvage value of machine after 10 years	Rs.1,12,250
Variable Economic Cost		
5	Electricity cost for 10 h/day equals to 7.5 kWh consumed @ Rs.18/kWh	Rs.135
6	Cost of fresh mangoes (400 kg/day) @ RS 75/kg	Rs.30,000
7	Repair and maintenance cost (5% of machine cost)	Rs.12,500
8	One worker @ 1000/head for 10 hours/day	Rs.1000/day
Machine Availability and Production		
9	Machine working period	90 days
10	Pulp recovery rate 58%/kg for 400 kg/day	232 kg
Economic Return		
11	Sale of mango residues/waste 160 kg @ Rs.5/kg (40% of 400 kg)	Rs.800/day
12	Sale of 40 wooden crates @ Rs 30/crate	Rs.1200/day
13	Sale of 1 kg mango pulp @ Rs 170/kg	Rs.39,440/day

$$\text{Profit per day} = \text{Economic Returns} - \text{Operational Costs} = \text{Rs. } 10{,}027$$

Comparison of Existing Screw-Type Mechanism with Newly Developed Beater-Type with Incorporated Teeth Mechanism

After studying the parameters and performance of the mango pulping machines developed by Kim (Kim. and Y. K. Gimhae. 2017), Olaniyan (Olaniyan 2014) and Sonar (Sonar, Chindhe *et al.* 2018); especially the screw-type mechanism developed by Adesoji. A comparison is made between the two mechanisms and shown in Table-4.

Table-4. Comparison of existing screw-type mechanism developed by Adesoji with newly developed beater-type mechanism with incorporated teeth mechanism.

Description	Screw-Type	Beater-Type	Remarks
Juice Yield, (%)	34.56	63.40	High yielding of indigenous varieties
Extraction Efficiency, (%)	54.15	56.70	The aggregate of all varieties including low yielding variety
Extraction Loss, (%)	10.15	10.44	The aggregate of all varieties including low yielding variety
Power Consumption (HP)	2.5	1	60% less power consumption
Variable Speed Option	No	Yes	Provision of VFD (Variable Frequency Drive) to make it useful for multi-fruit pulping
Variable Clearance Option	No	Yes	Provision of height adjusters of beater blades to make it useful for multi-fruit pulping
Fruit Capacity of Beating Chamber	Less	More	The lesser volume of the beating mechanism
Ease of Manufacturing	No	Yes	Straight stainless-steel bars with no contours
Maintenance	Difficult and costly	Easy and cheap	Each bar can be replaced or repaired independently
Cost (PK RS.)	3,50,000.	2,25,000.	Cost saving, 35.70%

CONCLUSIONS

The pulp extraction unit fabricated in this study has a 25% high juice yield. It will consume half of the power as compared to screw type with provisions of variable speed and variable clearance to accommodate different sizes of fruits. It is easy to manufacture, easy to maintain and the manufacturing cost is RS 2,25,000 lesser than a screw type machine. It is portable. It will help the rural communities to reduce the post-harvest losses and value addition of their product and will also aid the small and medium scale mango fruit pulp producers.

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