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Research paper

Design, Development, and Efficiency of Modern Fruit Pulp Extraction Machines: A Review

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Abstract

Fruit pulp extraction plays a pivotal role in the global food processing industry, particularly in tropical regions where the mass production and preservation of fruits are essential for economic growth and food security. The design, development, and performance of several fruit pulp extraction machines are examined in this review, which contrasts contemporary automated systems with conventional manual techniques. Significant gain in scalability, efficiency, and hygiene has permitted to shift towards mechanical extraction, which enables the system to cater to the requirement of commercial expectations. The key challenges encountered in the design of machines, such as power constraints, maintenance related issues and the capacity to process a wide variety of fruits, are discussed. Moreover, this study emphasizes the need to choose suitable materials for machine building to guarantee food safety, keep cost-effectiveness, and preserve economy. To overcome current constraints, the food processing machinery must be integrated with automation enabled with energy saving technology. In the fruit processing sector, continuous improvements in fruit pulp extraction techniques are essential to lower post-harvest losses, increasing efficiency and promoting sustainability.

Keywords: *Fruit pulp extraction, pulp extraction machines, fruit processing efficiency, post-harvest loss reduction, mechanized extraction systems, commercial fruit processing*

1. Introduction

Fruit pulp extraction is absolutely crucial to the global food processing industry, especially regarding mass production and commercial purposes. With changing consumer demand for quick and healthy food, demand for processed fruits, such as juice, puree, concentration, and other worth-added products has grown rapidly during recent years. A simple first step towards manufacturing these products is fruit pulp extraction, as it ensures removal of fruit seeds, skin, and other non-eatable portions, leaving only the edible parts of the fruit. Ensuring maximum output, maintaining plant efficiency, and minimizing waste during mass production all depend on efficient fruit pulp extraction operation [1]. Fruit pulp extraction is pivotal to the food manufacturing business if something is to produce a range of products including jams, beverages, sauces, and baby food. Particularly with industrialized and urban centres, global demand for these products requires efficient mass production procedures. Huge quantities of fruits are expected out of large-scale fruit pulp recovery systems, which also keep both integrity, colour, flavour, and nutritional attributes of products intact. Bringing down cost of operation generally and enhancing food manufacturing company profitability relies upon these systems. Gaining consistency in texture and flavor is crucial for commercial purposes to deliver a premium product that meets consumer demands. Automatic pulper, destoner, mechanical separator, and others advanced technologies in pulp recovery machinery have significantly improved dependability and efficiency of these processes. Present procedures do facilitate companies to diversify their product offerings and reach a larger market by producing various kinds of fruits [2].
Perishable fruits thought to be mangoes, pineapples, guavas, papayas, and bananas are most successful at extracting pulp especially under tropical and subtropical conditions. Well known for health benefits, these fruits contain high levels of vitamins, minerals, and antioxidants besides other essential elements. Tropical fruits, however, are sensitive to both conditions of temperature and humidity and to conditions of transport and hence easily spoil, causing huge postharvest loss if not promptly handled. Through converting perishable products into stable forms of produce that can be easily transported and stored, pulp extraction is responsible for maintaining tropical fruits hence preventing post-harvest losses [3]. The process reduces the fruit's risk of rot during distribution and extends its shelf life. As a semi-processed commodity, fruit pulp can be transported to regions where demand for products based on tropical fruits is high but availability of fresh fruits low or further processed to various products. The Food and Agricultural Organization (FAO) puts postharvest loss at an estimate of a major portion of food loss globally, especially in developing countries with limited cold storage facilities. Successful fruit pulp extraction presents a simple and scalable means of fruits processing shortly after harvesting, thus significantly reducing these loss rates. Moreover,

pulp extraction helps producers and farmers to value their goods, therefore promoting economic growth in areas mostly dependent on agriculture [4].

Especially for mass production, one of the main difficulties in fruit pulp extraction is streamlining the process to guarantee optimum yield with minimum loss. Labor-intensive traditional fruit processing techniques such hand peeling and manual extraction can yield less since they cannot completely separate the edible portions from the waste. Furthermore, hand techniques could not be sufficient to meet the demands for consistent quality control and cleanliness, which are vital aspects in the food processing sector. The modern pulp extraction methods have arisen to solve these constraints by integrating automation to the extraction process and enhancing the recovery of useable pulp. Also, employing mechanical, hydraulic, or pneumatic systems, these technologies improve extraction rate and efficiency. Some of the more sophisticated systems have sensors and control systems that track the operation in real-time, therefore ensuring that ideal conditions are kept for every kind of fruit being handled [5].

Moreover, the design of extractive equipment has changed to fit the several physical characteristics of different fruits. For instance, whereas softer fruits like papayas or strawberries demand different extraction methods, fibrous fruits like mangoes and pineapples do. Many contemporary machines are built with interchangeable components that let processors transition between several fruit kinds without sacrificing the quality or yield of the extracted pulp, hence improving efficiency. Apart from machine development, creative pre-processing methods including thermal blanching and enzymatic treatments have been included to boost pulp recovery. Fruit's cell walls can be broken down by enzymes, therefore enabling more effective pulp from seed and fiber separation. Similarly, heat blanching assists in relaxing the skin, so improving the efficiency of the next extraction operation and so lowering the mechanical wear on processing machinery [6].

This review aims to examine the design, development, and efficiency of many mass production fruit pulp extraction systems. It investigates postharvest losses and supports sustainable food processing in line with technical developments meant to increase yield, quality, and operational efficiency.

2. Traditional vs. modern fruit pulp extraction techniques

Improving the efficiency and scalability of fruit processing sectors depends on the evolution of fruit pulp extraction methods. Although conventional hand techniques have been in use for millennia, modern mechanical systems intended for mass production, improved hygiene, and greater efficiency are progressively substituting themselves for them. Focusing on their benefits, drawbacks, and industry changes, this part investigates both conventional and contemporary approaches.

2.1 Traditional manual extraction methods

The traditional manual fruit pulp extraction methods, like hand squeezing, pressing, and using rudimentary devices like wooden or metal sieves, have found their inherent application in domestic and small-scale businesses. Moreover, these techniques have been the primary means of separating pulp from seeds and skins in regions with an abundance of tropical fruits, such as mangoes, papayas & oranges. Though, several studies show the shortcomings of manual techniques, especially with regard to time and yield. Manual extraction techniques usually produce lower pulp yields due to inadequate separation, with a considerable proportion of pulp remaining attached to the skin or seeds, as Eyeowa, et al. [7], have observed, particularly with juicy fruits like watermelon, orange and pineapple, this inefficacy results in a pulp extraction rate as low as 71.3%, 65.8% and 63.8% respectively. Figures 1 and 2 demonstrate conventional techniques of juice/pulp extraction.

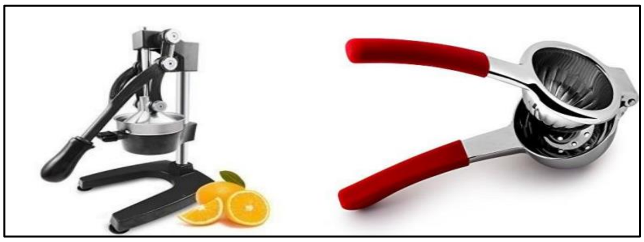

Fig. 1: Image of lever action hand juicer and hand squeeze Juicer [8]

Fig. 2: Image of Hand –held citrus juicer; [b] Component parts of dome [9]

Moreover, Wang et al. [10] underlined how labour-intensive manual extraction is and how limited its feasibility is for scale manufacturing. Low throughput of these conventional approaches shows in large-scale operations to be ineffective and expensive. Another important issue connected to hand extraction techniques is hygiene. Direct human interaction with fruit during extraction runs the danger of contaminating it. Concerning microbial contamination and food safety, Akhtar et al. [11] noted that conventional methods sometimes fall short of the strict hygienic criteria needed in contemporary food processing. Furthermore, the absence of standardizing hand extraction adds to the unpredictability in product quality, which is unwelcome in business environments where consistency is very important.

2.2 Modern mechanical extraction methods

The advent of mechanical fruit pulp extraction techniques marks a remarkable shift in the fruit processing industry, highlighting many of the inadequacies associated in traditional manual methods. The modern mechanical fruit pulp extraction includes various devices, such as screw (auger) conveyor, pulp masticators and centrifugal extractors, which are designed to enhance pulp yield, ensure hygiene and increase processing capacity. The ability to achieve higher extraction efficiency is one of the primary advantages of mechanical extraction system. Wu, et al. [12] reported that, with the use of mechanical extractors, higher pulp yield & lower pulping time is realised, which is significant improvement over traditional methods. Commonly used for citrus fruits, centrifugal systems efficiently separate pulp from seeds and peels using fast rotations, therefore improving productivity and lowering waste. As Muhammad, et al. [13] highlighted the customize solar operated pulping machines for pineapple and other fibrous fruits maximize pulp extraction by means of blades and sieves. Apart from efficiency, contemporary mechanical systems provide better hygienic standards. Turatti et al. [14], claim that many of these devices are built of food-grade stainless steel and intended to minimize direct human contact with the fruit, therefore lowering the danger of infection. Enclosed systems and automated cleaning capabilities improve hygiene even more, therefore guaranteeing that the finished pulp product satisfies food safety criteria worldwide. In large-scale operations where the volume of products being handled increases contamination hazards, this is especially crucial. Ideal for commercial application, mechanical extraction techniques are also quite scalable and flexible. Fantoni et al. [15] showed that mechanical systems may be tuned to fit a wide spectrum of fruit kinds and processing quantities, therefore enabling constant operation in industrial environments. This scalability guarantees effective processing of big amounts of pulp, therefore satisfying the rising demand for fruit-based goods on worldwide markets. Furthermore, mechanical systems greatly minimize running expenses by reducing the need of manual labor. Math et al. [16], claimed that the labor expenses in facilities running on mechanical system are lowered, hence improving the cost-effectiveness of these technologies in high- volume manufacturing settings.

A major progress in fruit pulp extraction is the change from conventional hand extraction techniques to contemporary mechanical technologies. Although conventional methods might still be useful in small-scale or household environments, their shortcomings especially with relation to efficiency, hygiene, and scalability make them inappropriate for commercial use. By contrast, mechanical extraction techniques provide greater sanitation, higher pulp yields, and the mass production scalability required. The dependence on current mechanical extraction techniques is probably going to rise as the fruit processing sector expands, which will inspire more innovations aiming at improving efficiency and quality in fruit pulp extraction.

3. Design and Mechanisms of Fruit Pulp Extraction Machines

Improving the efficiency and scalability of fruit pulp extraction for industrial usage depends much on the design and mechanics of fruit pulp extraction machines. These machines have been designed to manage a range of fruits with technical developments, so enhancing extraction efficiency, reducing pulp loss, and preserving product quality by means of their adaptation. Based on published studies, this part investigates the operational concepts and mechanisms of several fruit pulp extraction machines with an eye on design, efficiency, and commercial-scale fruit processing applicability.

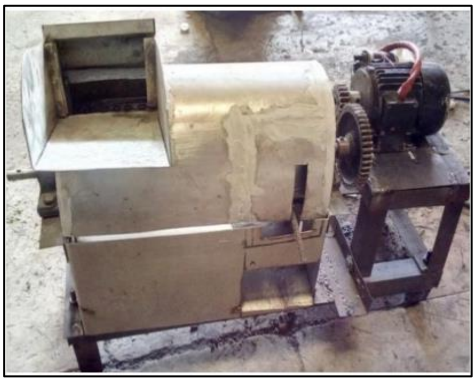

Fig. 1: Potato peeling machine [17]

3.1 Principles of Operation

Core operational ideas guiding the design of fruit pulp extraction machines help to effectively separate pulp from seeds, peels, and other unwanted elements. Among the most often occurring ideas are screw conveyance, compression, tapping forces, and centrifugal force. Based on their physical characteristics such as hardness, size, pulp content - each principle fits particular kinds of fruits.

3.1.1 Screw conveyor mechanism

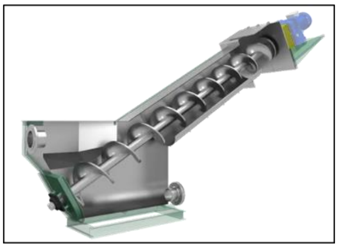

Fig. 2: Screw Conveyor Mechanism in pulp extraction machine [18]

Fruit pulp extraction machines make great use of screw conveyors because they effectively crush and transfer fruit materials, therefore separating pulp from seeds and skins. As the fruit passes through the machine, the screw mechanism continuously pressures to progressively break down the fruit and squeeze out the pulp. For their capacity to manage fibrous fruit textures, mango pulp extraction machines for example frequently make use of this mechanism. Figure 4 displays the screw conveyor mechanism found in a pulp extraction machine.

3.1.2 Compression and tapping force

Particularly in fruits with tougher skins or seeds, some machines extract pulp by using compression coupled with tapping or percussion forces. Machines intended for fruits like pomegranates apply this idea; the tapping force helps release the pulp while compression separates it from the seeds. This technique offers a regulated strategy for pulp extraction that lowers seed breakage, which is essential for preserving the quality of some fruit products.

Fig. 3: Centrifugal systems [18]

3.1.3 Centrifugal force

Centrifugal systems harness rotational motion power to quickly spin juice out of seeds and skins. The process is effective with fruits containing a high juice content and soft pulp, such as citrus fruits and berries. With use of a shearing action created by centrifuge motion, pulp is separated and waste solids are pushed out, thus ensuring maximum efficiency of extraction with minimal loss of pulp. Figure 5 sets out centrifugal mechanism used by a pulp extracting machine.

3.2 Types of Mechanisms

3.2.1 Screw conveyor-based systems

Large-scale pulp extraction, especially for fibrous and big fruits like mangoes and papayas, often uses screw conveyor-based devices. With pressure to break down the fruit material and separate the pulp from seeds and skins, the rotational action of the screw drives the fruit material forward. Screw- Mechanically driven machines are well-known for their effectiveness in handling dense fruits, generating a high pulp production with minimum human involvement. These systems are preferred for their capacity to manage fruits with high pulp content and enable constant processing, which is vital for mass production.

3.2.2 Brush and sieve mechanisms

To scrape and filter pulp from seeds and skins, the brush and sieve system uses spinning or stationary brushes along with sieve. In pomegranate and mango pulp extractors, this approach is commonly utilized since mild action is needed to effectively remove the pulp without injuring the seeds. The brushes guarantee a smooth texture in the obtained pulp by helping to split the fruit open and push the pulp through the sieves. The sieve is essential in eliminating unwanted elements like broken seeds or skin, so improving the quality of the pulp.

3.2.3 Centrifugal systems

For fruits heavy in juice or pulp, such as tomatoes and citrus fruits, centrifugal systems are quite efficient. With minimum effort, the fast-spinning motion generates centrifugal forces separating pulp from seeds and skins. For fruits that must be handled fast and in great quantities, this approach is very helpful. Designed to effectively handle soft fruits, centrifugal extractors have low pulp loss and great throughput over mechanical pressing methods. Many times, these machines have variable speed controls that let operators adjust the operation depending on the kind of fruit they are extracting.

3.3 Evaluation of Machine Designs

Operating concepts and procedures involved in various machine designs influence efficiency, capacity, and pulp loss within those systems. For fruits with high pulp contents and fibrous textures, screw conveyor type machines yield high throughput with minimal waste. But due to wear upon the screw mechanism, especially with large quantities of fruit, they can require more frequent maintenance. While gentle and successful for maintaining seed integrity, brush and sieving systems may be slower and less successful for processing larger fruits or those with heavy skins. On specialty fruits, for example, pomegranates, where retaining seed shape is important, they are quite fitting, nonetheless. In contrast, centrifugation methods yield fast and efficient pulp removal, particularly with soft and juicy fruits, but potentially result in a inferior quality of pulp due to shearing forces that have potential to introduce air into the pulp, thus potentially affecting texture. These methods aren't ideal for all types of fruits, but are quite well adapted for large operations where speed is needed.

4. Performance and Efficiency of Fruit Pulp Extraction Machines

Fruit pulp extracting machine's commercial viability relies heavily on how well and effectively they perform. Assessing their overall performance relies heavily on various factors such as efficiency of extraction, capacity, yield as pulp, and power consumption. Findings of recent research into these measures of efficiency, prototype operation, and performance-affecting factors, such as feed rate, retention time and fruit variety are presented in this section.

4.1 Efficiency Metrics

Fruit pulp extracting machine's performance to extract fruit pulp is at times determined based on the efficiency of fruit pulp being separated from fruit bulk. Efficiency is influenced by operating conditions, fruit characteristics, and machine design for both [19]. For soft & less fibrous fruits such as Kendu, a brush type pulping system provides higher efficiency of 78.36%. Particularly those designed for citrus fruits, centrifugal systems have provided efficiency of 91.13% [20]. These systems suit soft fruits with high water content as they offer efficient separation without appreciable pulp loss.

Typically quoted as kg/h, fruit pulp extracting machinery capacities range significantly by machinery type and design. Depending on machine size & type of auger, screw-driven systems have been found to deliver 5.10-15.80 kg/h pulp [21]. Conversely, especially in citrus and tomato extraction, centrifugal machines, meant for faster and more continuous operation, have shown processing capacity of up to 38.89 kg/h [22]. But feed rate and retention time affect capacity; so, greater feed rates can lower general extraction efficiency by means of partial fruit breakdown [23].

Another important statistic is pulp yield, which shows the proportion of removed pulp to starting fruit mass. Depending on machine design and operating conditions, studies on beater-type & screw-type pulpers on mango observed the pulp yield 63.40% & 34.56% [24]. Due to the reduced mechanical resistance during the extraction process, pulp yields for centrifugal systems can reach an average value of as high as 70.35% [25]. Although they work well for some fruits, such as watermelon, beater blade and sieve systems usually produce high yields of 78.11% because of complete separation of pulp from seeds [26].

4.2 Factors Affecting Efficiency

Both extraction efficiency and processing capacity directly depend on the feed rate, that is the pace at which fruit enters the machine. Too high feed rates could overwhelm the machine and cause incomplete extraction and lower efficiency. Different machine type and fruit properties affect optimal feed rates; screw-based systems gain from slower feed rates that enable complete mechanical breakdown of fibrous components [27]. For high-throughput operations, centrifugal machines, which can handle larger feed rates without sacrificing efficiency are therefore perfect [28].

Extraction results also depend on retention time, that is the period of time fruit stays inside the machine. Particularly in screw conveyor systems, which use mechanical pressure to remove pulp [29], longer retention durations can increase extraction efficiency and yield. For industrial-scale uses, however, higher retention duration may slow down the general processing capacity, so a compromise between efficiency and throughput is necessary.

Machine performance is strongly influenced by the physical characteristics of the fruit under processing, including water content, fiber content, and seed-to-pulp ratio. Using screw conveyor-based systems gives fibrous fruits like pineapple the required mechanical force to break down difficult fruit material [30]. On the other hand, soft and juicy fruits such as tomatoes and citrus are more efficiently handled with centrifugal systems, which divide pulp from juice with minimum pulp loss [31].

4.3 Prototype Testing

With an eye on optimizing their design for both small-scale and large-scale commercial uses, many studies have concentrated on testing prototype fruit pulp extraction machines.

With pulp outputs of 73.60% and extraction efficiency of 92.08%, prototype machines for apple, employing screw press mechanism had shown encouraging results [32]. These systems are appropriate for commercial uses since they also process vast amounts of fruit with minimum human involvement. But given wear on the screw components, especially when processing fibrous fruits, regular maintenance is needed [33]. In prototype testing, centrifugal extractors, especially ones meant for soft fruits like citrus and tomatoes, have shown great extraction efficiency and output along with far faster processing times than screw conveyor systems [34]. These systems are favored for mass production, although concerns about energy consumption and machine complexity remain [35].

With pulp yield of 28.20%, prototypes using hydraulic pressing mechanisms for pomegranate pulp extraction have proven less efficient than pneumatic pressing mechanisms resulted in high pulp yield of 33.30% [36]. Because of their reduced throughput and yield, these machines are less appropriate for large-scale processing even if they are efficient in preserving seed integrity and generating high-quality pulp. However, they are perfect on applications where product quality and seed preservation take front stage [37]. An analysis of the developed fruit pulp extraction machine with existing systems reported in the literature is presented in Table 1.

Table 1: An Analysis of Fruit Pulp Extraction Machines

Machine Type	Fruit Processed	Pulp Yield (%)	Extraction efficiency (%)	Extraction Loss (%)	Remarks	Ref
Rotating adjustable blades & sieve system	Mango	63.44	56.70	10.44	Comparable pulp yield but lower extraction efficiency	[38]
Hydraulic basket press system	Apple	61.9	-	-	Lower yield as compared to screw press system	[39]
Screw-press system	Apple	71.60	-	-	Higher yield for hard apple	[39]
Digester Screw-press system	Palm	-	89.10	-	Higher efficiency and higher throughput capacity	[40]
Twin-screw extruder	Pear Carot	84 37	- -	- -	High yield, low wastage Comparative Lower yield	[41]
Pneumatic-assisted extraction	Pomegranate	33.50	-	-	Lower yield but good quality pulp	[42]
Rotary drum system	Mangosteen	-	68.54	-	High yield, effective for soft & small fruits	[43]

5. Materials and Construction

Dependent upon considerations of performance, longevity, and food-safe standards compliance, components used to make fruit pulp extracting machines have a large role to play. Commercial usage and mass production rest upon equipment's ability to withstand operational stresses and uphold sanitary conditions. With a focus upon material selection, price, and scalability concerns, this section reviews the most common components employed in constructing pulp extracting machines.

5.1 Material Selection

The performance, durability, and compliance with food safety criteria of fruit pulp extraction machines depend much on the materials used in their construction. Large-scale manufacturing and commercial use depend on the machines being able to bear operating strains while also preserving hygienic conditions [44], [45]. Emphasizing material selection, pricing, and scalability issues, this part investigates the common components utilized in the design of pulp extraction machines. [46], [47].

Furthermore, some machine uses a food-grade plastics, particularly in non-critical parts like seals and hoppers. Also, Food-grade polymers such as polyethylene and polypropylene are often employed in parts that do not directly interact with the fruit pulp but are exposed to external conditions. These materials are preferred as they offer lightweight and cost-effective solution without compromising safety or functionality [48]. However, plastic components are less durable than stainless steel and are prone to wear, particularly in high-speed or high-torque sections of the machine, such as screws or rotating blades [49].

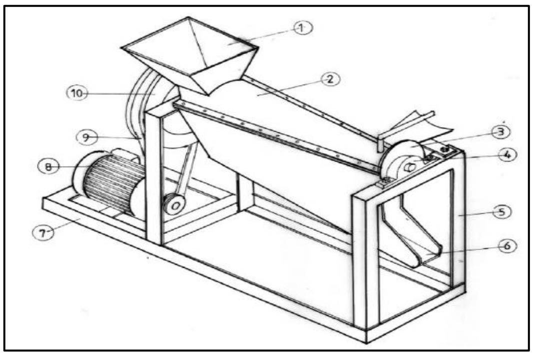

Fig. 4: Isometric view of orange pulp extractor: 1 Hopper; 2 Extraction Chamber; 3 Dic plate; 4 Bearing; 5 Main frame; 6 Juice collector; 7 Motor stand; 8 Electric motor; 9 Transmission belt; 10 Pulley [50]

In certain applications, other metals like aluminium are used in components that require lower weight and cost without sacrificing mechanical strength. Aluminium offers a cost-effective alternative for small-scale machines but is not as durable or hygienic as stainless steel, especially when exposed to acidic fruits over prolonged periods [51]. Studies comparing the use of stainless steel and aluminium found that while aluminium reduced initial manufacturing costs, the long-term durability and performance of stainless steel outweighed the initial savings [52].

Coatings and surface treatments are also integral to the construction of pulp extraction machines. To enhance a machine’s resistance to wear and tear by reducing friction, food-safe coatings, such as Teflon or ceramic coatings, are applied over moving parts [53]. These coatings not only contribute to the wear and tear resistance but also facilitate ease of cleaning, thereby promoting hygiene standards in food processing.

5.2 Cost and Scalability

Materials, machine size, and intended use all affect the cost and scalability of pulp extraction equipment. Cost is a major deterrent to using stainless steel machinery for small-scale, handcrafted manufacturers. Although they are less expensive, machines built of food-grade plastics or aluminium have limited lifetime and efficiency [54]. Low-cost solutions, while functional, may not satisfy industrial standards for hygiene or lifespan in areas where initial capital expenditure is limited.

Although their initial cost is more, stainless steel equipment are commonly chosen in large-scale, commercial uses because of their durability, simplicity of maintenance, and conformity with worldwide food safety rules [55]. Patel et al. [56] conducted research showing that although stainless-steel machines cost is more than their counterparts, they had a longer operating lifetime and fewer maintenance downtime. In large production settings, where the size of activities necessitates efficiency and minimal interruptions, these elements help to reduce general costs.

Another important factor is scalability, especially in areas where small-scale producers or farmers demand reasonably priced, quick fixes. Key machine components can be replaced or enhanced depending on scale in modular designs, therefore enabling scale-based replacements or improvements. While industrial versions of the same machines are built with more strong materials to manage greater throughput [57], [58], screw-based pulp extraction systems can be adjusted for small-scale operations using less expensive materials. With studies showing that modular designs improve accessibility without sacrificing general machine performance [59], this adaptability lets manufacturers serve both small-scale and industrial users.

Material choice and cost also heavily rely on the availability of machine parts in many areas. To keep manufacturing costs low, local producers in underdeveloped nations, where access to specialized materials and parts may be restricted, often give cost-effective, locally sourced materials, including aluminium or lower-grade stainless-steel top priority [59]. These concessions, however, can limit the commercial viability of the machines by resulting in lower machine efficiency and later increased maintenance expenses [60].

5.3 Performance vs. Cost Trade-offs

The compromise is made between the cost of materials and the performance of the machine. Stainless-steel, comparatively more expensive, provides greater resistance to corrosion, wear, and contamination, ensuring compliance with stringent food safety standards [61]. Whereas, the machines constructed with food-grade plastics or aluminium, even though less expensive, but require more frequent maintenance and replacement of parts, which can disrupt the production activities in high-demand environments [62].

The overall cost-effectiveness of a machine depends on its intended use. The machines with less expensive materials might be sufficient for small-scale operations, where the extraction volume is relatively low. However, for industrial-scale production, the longevity and efficiency of stainless steel-based machines justify the higher initial investment. Research by Patel et al. [56] shows that for large-scale commercial applications, stainless steel machines provide a return on investment through reduced downtime and lower maintenance costs over the machine's operational life. Table 2 summarizes the work that has been carried out on pulp extraction machine along with the important parameters.

Table 2: Summary of Research on Fruit Pulp Extraction Machines

Machine Type	Extraction Mechanism	Fruit Type	Efficiency	Challenges	Outcomes	Ref
Screw Conveyor-Based Machine	Screw conveyor crushing and pressing	Apple	90% pulp extraction	High initial cost, difficult to process fibrous fruits	Suitable for small-scale operations, high juice quality, slow process	[63]
Brush and Sieve Mechanism	Rotating brush with sieve separation	Watermelon	90.14% extraction efficiency	Sieve clogging, regular maintenance	Effective for seed-pulp separation, moderate maintenance required	[64]
Centrifugal Extraction Machine	Centrifugal force with shear mechanism	Citrus,	84.54% extraction efficiency	High power consumption, machine wear over time	High efficiency, ideal for mass production, but energy-intensive	[22]
Blade and Sieve - Based Machine	Chopping and compression	Pineapple, Orrange	88% yield	Fast operation, least manual intervention	High yield, low waste, high juice quality, fast process	[65]
Rotary ball gear-Type Pulp Extractor	Dual-Ball crushing and shearing	Citrus	60-70% extraction rate	Difficult to maintain uniform pressure, risk of fruit damage	Good for pulpy fruits, easy to operate but lower efficiency for fibrous fruits	[66]
Hydraulic Press-Based Machine	Hydraulic compression and separation	Apple	61.90% extraction efficiency	High energy consumption	High throughput, ideal for continuous operation, needs careful loading	[39]
Auger-screw Based Pulp Extractor	Auger screw for pulp and juice separation	Orange, Pineapple	79.30% extraction efficiency	High energy consumption, costly parts	High efficiency, suitable for tropical fruits, energy-intensive	[67]
Pneumatic Pulp Extraction Machine	Compressed air for pulp separation	Pomegranate	33.30% yield	Requires stable power source, inconsistent output	Gentle on delicate fruits, low yield compared to mechanical methods	[36]
Belt-Driven Pulp Extractor	Belt conveyor with mechanical pressing	Mango	200kg/hr Pulp yield	Space-consuming, requires frequent belt adjustments	High output, minimal fruit damage, but maintenance-intensive	[68]
Rotatory Drill based Pulp Extractor	Rotating drill for shearing pulp	Watermelon, pineapple	97% extraction efficiency	High mechanical wear, frequent drill replacement	Suitable for soft fruits, consistent extraction but requires maintenance	[69]
Motorized Grinder Pulp Extractor	High-speed rotating blade grinder	Apple	60-70% extraction rate	High heat generation, risk of fruit oxidation	Good for hard fruits, fast processing, but heat can affect juice quality	[63]
Multi-Functional Extractor	Combination of screw press and sieves	Mixed fruit types	70-90% extraction rate	Complex maintenance, higher initial investment	Adaptable to multiple fruits, efficient but costly maintenance	[65]
Masticating Juicer Machine	Low-speed Masticating juicing	Tomato	80% yield	Energy-intensive, low output	High efficiency, suitable for household application	[70]
Rotating knife and screw-type Machine	Combination of Cutting and squeezing	Pineapple	76.73% yield	frequent knife replacement, low output	Suitable for small-scale use, cost-effective	[71]
Auger-Screw and Brush type Pulp Extractor	Squeezing and pulp separation	Mango	96.03% extraction efficiency	Frequent drum clogging, maintenance required	Effective for cottage industry, gentle extraction, but prone to clogging	[72]
Twin Screw-type Press Machine	Screw compression and separation	Apple	61.90-71.60% yield	Complex design, difficult to clean	Suitable for small-scale operations, high efficiency for hard apples	[39]
Spiral Pulp Extractor	Spiral auger with seed separation	Apple, Orange	83% extraction rate	Risk of seed crushing, power consumption	High throughput, minimal seed contamination, power-intensive	[73]

6. Applications and Impact on the Fruit Processing Industry

Especially as they offer efficient and scalable methods of processing, fruit pulp extract machines are crucial to fruit process industries. The machines are contributing to commercialization of fruit products since demand for fruits as juice, purée, or concentration increases. Commercial application of fruit pulp extract machines across different environments is considered herein alongside impact on reducing post-harvest loss and future trends that may enhance efficiency and incorporation into modern food process systems.

6.1 Commercial Use

From juice stores to hotels to small-scale fruit processing companies, fruit pulp extraction equipment finds extensive uses in many different commercial sectors. These devices are utilized at juice stores in urban and semi-urban areas to on-demand prepare tropical fruits including mangoes, pomegranates, and citrus fruits. Small-scale enterprises find their appealing solution in their rather low cost and compact design. Small-scale juice manufacturers reportedly use mechanical pulp extractors to satisfy daily consumer needs, according to a study by Olaniyan et al. [74] which also reported lower labor costs and improved operational efficiency over hand techniques. Particularly at hotels and resorts, fruit pulp extraction equipment helps the hospitality industry to quickly prepare fresh drinks and fruit-based sweets. Studies show that by reducing direct touch between the fruit and workers, mechanical solutions not only increase food cleanliness but also speed and consistency of fruit pulp extraction [75]. In food service environments, this then promotes improved quality control and client satisfaction [25].

Especially for regions with good tropical fruit harvests, small fruit processing firms depend heavily on pulp extract machinery for creating products, which range from jams and sauce to frozen pulp. Mahendran et al. [76], argue that these machines have empowered small firms to expand production without comprising product quality or investing heavily in capital. Use of mechanical pulp extraction across different industries has proven to reduce lead times and increase yields, thus enhancing profitability and allowing for easier fulfilment of market demands.

6.2 Post-Harvest Loss Reduction

Their ability to reduce post-harvest loss is one of the most critical consequences of mechanical fruit pulp extraction. With poor storage methods and the perishable nature of fruits, post-harvest loss, particularly in tropical and subtropical regions, is a matter of major concern. By converting freshly picked fruits to more stable states, like pulp or puree, which can be stored for an extended period, the mechanical fruit pulp extraction offers a viable solution. By allowing fruit to be handled shortly after being picked, and not relying upon time-consuming manual methods, Elik et al. [77], ascertained that implementing mechanical extracting machines significantly reduces post-harvest loss. The machines ensure fruits which could otherwise be lost are efficiently dealt with, hence ensuring that they are used for food production and not discarded. Where agricultural production is not only a principal economic driver, this process not only increases revenue for fruit growers but improves food security as well [78]. Experiments with pulp extractors employed in rural and semi-rural areas have found large reductions in wastage of mangoes, guavas, and tomatoes, which are most susceptible to spoilage after harvest [79]. For an Indian mango-producing region, for instance, Patel et al. [80] found reductions in postharvest loss as high as 30%. Mechanized pulp extracting methods were responsible for this. These devices are rather important in increasing the shelf life of fruits by changing them into more easily storable forms in areas where cold storage facilities are few. Quick and effective processing of big volumes of fruit also enables growers to pick more fruit at ideal maturity without worrying about rotting, therefore enhancing the general quality and nutritional content of the processed goods [81].

6.3 Future Trends

Future developments in fruit pulp extraction machines are probably shaped by advancements in automation, machine learning, and smart technology as the fruit processing sector keeps changing. Food processing has already been transformed by automation; completely automated pulp extraction machines able to handle vast production lines without major human involvement [82]. Automation lowers labor costs and guarantees constant product quality, hence boosting manufacturing capability.

Integration of data analytics and machine learning is supposed to improve pulp extraction machine efficiency even more. Through data analysis including fruit kind, size, and ripeness, machines may optimum operating parameters including feed rate and pressure, so optimizing yield and minimizing waste. Studies on the application of artificial intelligence (AI) in pulp extraction have shown that efficiency can be greatly enhanced and operational mistakes much lowered [83]. Better general system dependability and less downtime result from AI-based systems monitoring machine performance in real-time, predicting maintenance needs, and adjusting settings for best extraction [84]. The creation of environmentally friendly equipment that uses less energy and produces less waste is yet another developing tendency. Ukoba et al. [85] claim that design of energy-efficient devices using renewable energy sources, such solar power, especially in areas where electricity access is erratic, is attracting increasing attention. This not only lessens the environmental effects of fruit handling but also increases the accessibility of these machines to rural small-scale farmers. In-line with this, progress in the area of material science, might inspire the creation of more reasonably priced and robust machinery, particularly for small scale operations. Researchers are investigating the use of recyclable and bio-based materials for machine building, thereby lowering the environmental impact of these machines as well as manufacturing costs. The continuous advancement in this area would ascertain the pulp extraction machine's effectiveness and durability while making them more reasonably priced for small manufacturers.

7. Challenges and Recommendations

Especially for regions including tropical and subtropical regions with abundant fruit yield, fruit pulp extracting machines have become unavoidable for food processing industries. Though, their importance is increasing, several issues hindered their common acceptance and proper functioning, particularly for underdeveloped countries. These issues impact the overall efficiency of these machines and pulp quality through different technical and operational issues as well as infrastructure limitations. The common challenges during design and operation of fruit pulp extracting machines are explained in this section along with proposals for future studies and development.

7.1 Challenges

Availability of a stable supply of power is one of the principal hindrances to implementing fruit pulp extracting machinery in rural regions. Most small fruit farmers, particularly rural farmers, lack full access to power or experience power shortages. In rural regions, the performance and effectiveness of pulp extracting machinery may be significantly impacted, leading to inefficient operation. Additionally, as is evident with the case of mango and guava processing units based in rural India, machinery requiring high inputs of power are not sustainable in regions with scarce power resources. Adoption of these technologies remains significantly constrained by dependency upon either fuel-operating equipment or electric supply. We have an additional, critical problem with machine maintenance, specifically for small players in the fruit-processing industry who do not necessarily have technical expertise to perform regular maintenance and repairs. Continuous exposure to acidic fruit juice, pulp, and seeds leads to heavy wear and tear of machinery involved in fruit pulp removal that corrodes machine parts and leads to mechanical failure. Inadequate periodic maintenance of simple components like blades, sieves, and motors lead to frequent machinery malfunction and increased production downtime. Unavailability of skilled personnel or spare parts, especially in under-developed regions, aggravate the problem. Sustainable operation rests with machines being long-lasting and trustworthy. Fruit properties range greatly and need for diverse approaches of extraction. Particularly when switching from soft fruits like mangoes to harder ones like pomegranates or citrus fruits with seeds, machines made for one type of fruit may not operate successfully for another. Designing universal machines able to process several kinds of fruits with consistent efficiency is challenging given the great variance in fruit size, seed structure, and juice content. Particularly hard-seeded fruits provide mechanical difficulties that call for the creation of specific components and mechanisms including varying sieve diameters and pressure settings [86]. This limits the versatility of current fruit pulp extraction machines. Fruit pulp extraction raises serious hygienic issues since, particularly in large-scale processing facilities, incorrect handling and equipment sanitation can cause contamination. To guarantee that the pulp stays un contaminated during extraction, machines must be built with food-safe materials & surfaces in contact with food must be coated with Antimicrobial Edible Coatings [87], [88]. Small-scale processors, especially in areas with little government control, could lack the means to guarantee frequent cleaning and sanitation of their machines, therefore compromising food safety regulations. Another difficulty is metal component corrosion brought on by fruit acidity; so, corrosion-resistant and food-safe materials are needed. [89]. Moreover, corrosion of metal components due to fruit acidity poses an additional challenge, requiring the use of corrosion-resistant materials that are also food-safe.

7.2 Recommendations

Future studies should be mostly focused on raising the general effectiveness of fruit pulp extraction systems. This covers maximizing pulp yield by optimizing the mechanical architecture to lower friction and energy consumption. Researchers propose the creation of solar or hybrid systems of renewable energy sources, which might greatly lower the energy consumption in places with erratic electricity [90]. These machines could be driven by Effective in small-scale operations, especially in areas with great solar potential [91], solar-powered extraction devices have been demonstrated. Additional research could concentrate on creating low-energy, high-efficiency devices fit for a variety of geographic locations.

Future research should give the development of multi-functional machines capable of processing many sorts of fruits with minimal adjustments top-priority given the variety in fruit kinds and their related processing needs. Greater flexibility and efficiency would come from machines that, for instance, could automatically adjust their pressure settings, sieve sizes, or blade designs depending on the sort of fruit being handled [14]. Furthermore, improving machine utility in various processing contexts are modular designs allowing CPUs to quickly transition between various fruit types without depending on significant reconfiguration or replacement parts [92].

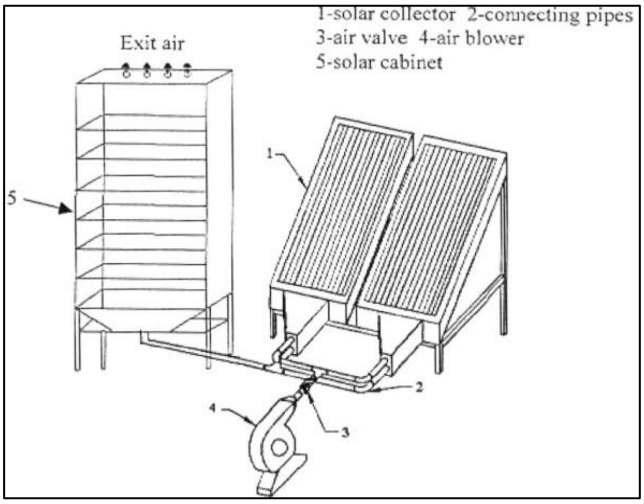

Fig. 5: Illustrate the solar drying [93]

Using smart technologies like IoT (Internet of Things) systems and sensors can help to greatly increase equipment lifetime and maintenance capacity. By means of real-time monitoring of machine components like motors, blades, and sieves, wear and tear can be significant data source for predictive maintenance and danger of sudden breakdowns is lowered [94]. Combining predictive maintenance systems with automated diagnostics could let workers know when a machine component is almost failing, therefore enabling quick repairs and reducing downtime. Small-scale processors who might lack the technical knowledge for routine equipment maintenance might find these technologies very helpful [95].

Future studies should concentrate on creating fruit pulp extraction devices with built-in hygienic and sanitation aspects. Food safety in both small- and large-scale processing environments could be improved by machines with self-cleaning systems or materials that stop bacterial accumulation [96]. Maintaining hygienic standards depends on the use of food-safe, corrosion-resistant materials including stainless steel. Furthermore lowering the risk of contamination are automation methods tracking machine component cleanliness and running frequent self-sanitizing cycles [97]. In areas lacking access to sanitation facilities and clean water, these developments would be very beneficial.

Particularly in underdeveloped areas, researchers must concentrate on developing reasonably priced, scalable systems that can be customized to meet various processing requirements if we hope fruit pulp extraction machines to be widely adopted. Small-scale processors can run on limited money, thus the high cost of modern extraction equipment can be a major obstacle to entrance [98]. Small and medium businesses (SMEs) would find a reasonably priced solution in modular, scalable designs that could be developed over time as the company expands [99]. Expanding the use of these technologies also depends critically on lowering the cost of components and materials without sacrificing food safety or durability.

8. Conclusion

Review of current literature on fruit pulp extraction machines emphasizes the important part, as these technologies perform in the fruit processing sector, particularly in relation to tropical and subtropical fruit production. From hand extraction techniques to advanced mechanical systems, pulp extraction technologies have evolved to greatly increase scalability, efficiency, and hygienic quality. Still, various difficulties exist, especially in underdeveloped areas where fruit diversity, machine maintenance, and power restrictions affect the design and running of extraction equipment. Important conclusions from the literature highlighted the need of using food-safe materials like stainless-steel to prevent foodstuff from contamination and guarantee hygiene. Also, the necessity of integrating machines with energy-efficient technologies to make them fit for areas with erratic power sources, and the benefits of modular and multifarious designs able to manage variety of fruit types. The use of automation, smart technologies and renewable energy systems, particularly in small and medium scale businesses, has significant promise to solve many of these problems accompanied with current machines. Future research must keep an eye on enhancing extraction efficiency and pulp yield, reducing energy consumption and applying advance technologies like machine learning to optimize processes and corresponding parameters. The fruit processing sector might increase the production and significantly lower the post-harvest losses, by addressing these challenges. Furthermore, by adopting emerging technology, fruit processing industry may contribute to support food security and economic growth, especially in regions where agriculture is a significant economic driver.

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