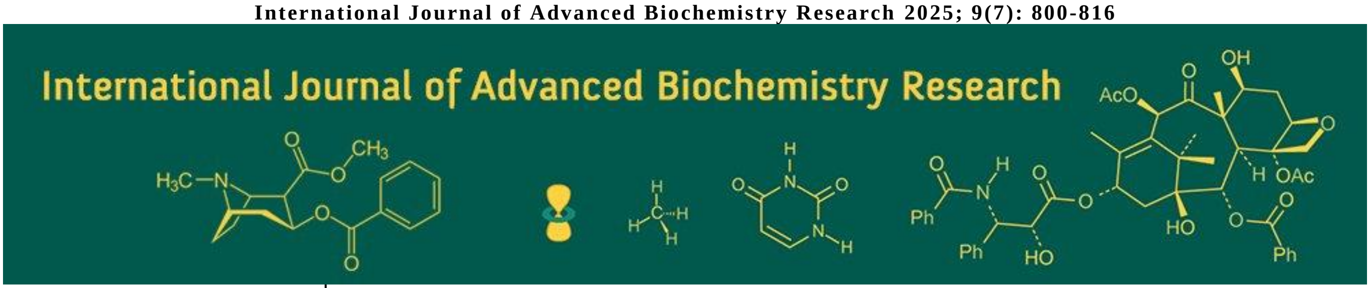

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Innovations in fruit pulping and processing: From traditional methods to smart technologies

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Abstract
The most fundamental by-product of turning fresh fruit into meals is fruit pulp. In addition to being able to be cold-stored for extended periods, fruit pulps have several uses in the production of beverages, desserts, jellies, yogurts, ice cream, and juices. Juices, purees, and other food items with added value rely on pulping fruits. The sector has evolved from manual processes to automated ones, with the goal of improving productivity, quality, and environmental friendliness. Beginning with mechanical and manual processes, this overview traces the development of fruit pulping technology to more recent breakthroughs, including cold pulping, enzyme-assisted extraction, vacuum-based approaches, and ultrasound-assisted systems. An intelligent and efficient pulping process is being achieved via the use of smart technologies such as real-time monitoring, automation, and artificial intelligence. The assessment also delves into sustainability-driven innovations that try to lessen water and energy use, cut down on waste, and makes good use of by-products. This article provides significant insights for academics, equipment developers, and industry stakeholders looking to optimize pulping operations in the ever-changing food processing market. It compares methods based on performance, cost, and appropriateness for different fruits.

Keywords: Fruits, pulp, beyond processing, personalization, local innovative, precision, sustainability, nature

Introduction
Fresh fruit spoilage after harvest is nothing new; in fact, it has long been one of humanity's greatest problems. Severe food security measures are necessary to combat hunger and malnutrition in emerging nations with expanding populations and food shortages. Maximum fruits have a very short shelf life after harvest since they are perishable. Twenty to twenty-five percent of India's produce goes bad before it is used. Pickles, fruit and vegetable beverages, tomato ketchup, fruit jelly, candies, juices, jam, dried and fried fruits, and juices barely account for 1.5% of India's total fruit and vegetable production, even though the country ranks second in the world for this commodity. There are several points of spoiling, and farmers have been losing between 30 and 40 percent of their produce's worth before it reaches the customer. This waste occurs all the way through the supply chain, from harvesting to processing, packing, transportation, distribution, and consumption. A food's shelf life is the amount of time that passes after production or packing when stored according to certain guidelines, during which the product maintains its intended sensory, chemical, physical, and microbiological properties and is safe to eat. Everyone from farmers to dealers to consumers feels the effects of post-harvest loss on their food security, nutrition, and financial stability.

Sustainable food systems are being encouraged. Fruits and vegetables, which are plant-based and good for both humans and the environment, should be more widely produced and eaten as part of these systems. Vital nutrients for optimal bodily functioning and nutraceutical chemicals that, when ingested consistently, contribute to improved health outcomes by preventing the development of chronic lifestyle illnesses are found in fruits and vegetables, making them a vital part of a healthy diet [1]. Consequently, it has been suggested that each person consume 300 to 600 grams of fruits and vegetables every day [2]. In spite of this advice, a staggering 93% of nations in Sub-Saharan Africa still have very low rates of fruit and vegetable intake [3]. According to a study carried out in East Africa, which includes Kenya, the average consumption levels of fruits and vegetables per person range from 4 to 135 grams and 84 to 184 grams, respectively [4]. Considering that Kenya has seen an increase in its fruit and vegetable output, this is perplexing. From 2005 to 2014, for instance, mango output increased by a factor of three, while avocado production increased by a factor of two [5]. Low fruit and vegetable consumption may be attributable, in part, to substantial postharvest losses [6].

Separating the fruit's edible pulp from its inedible peel, seeds, and other by-products is an essential step in the fruit processing industry's fruit pulp extraction process. Many foods and drinks rely on this method for production, including purees, jams, nectars, and juices [7]. Increased output, better yield, and higher quality products are all results of the industry-altering breakthrough in pulp extraction machinery [8]. In order to maximize the use of raw resources, decrease food waste, and fulfill the increasing demand for processed fruit products, fruit pulp extraction is crucial. Modern fruit pulp extraction machines are energy efficient, have a high throughput, and produce very little waste as a result of the growing concern for environmental and economic sustainability [9].

Literature Review

Although fruit juice is now made by processing specifically cultivated species, it was initially made as a by-product of the overproduction of fruits. Tropical fruits in Tanzania are not available all year due to the high postharvest loss rate (40 to 50%) in the horticultural industry [10]. In order to overcome these limits, substituting fruit juice for fresh fruit might be a good option. The natural liquid contained in mature fruits is extracted by mechanically pressing or squeezing out the fruit, without the use of heat or solvent, to produce fruit juice [11]. The second greatest thing to fresh fruit, according to [12], is fruit juice. Fruits like guava, oranges, pineapples, and mangoes are now the most popular in Tanzania when it comes to fruit juice [13]. Keeping fruits fresh for an extended period of time is challenging. This means that ripe fruits may be eaten raw or transformed into juice and other unique goods [14]. Due to metabolic processes that persist long after harvest, most fruits begin to deteriorate practically immediately after harvest, rendering them perishable in their natural condition [15]. Fruits are notoriously difficult to store and maintain due to their perishable nature.

Therefore, processing and preserving fruits is very necessary to provide a consistent supply of fruits at reasonable costs [16]. This is because, with time, the nutritional content and flavor of fruits gradually diminish. Thus, it is necessary to create machinery for efficient fruit juice extraction in order to lessen post-harvest loss, provide year-round access to juice at affordable prices, and extend the product's shelf life. Researchers came up with fruit pulping machines for a variety of fruits; for example, [17] created a machine to process Baobab and Parinari Curatellifolia fruit, while [18] produced a machine to process granadilla fruit utilizing a blade mechanism and gravity separation. The laboratory studies conducted by [19] used a small-scale fruit juice extraction apparatus to measure the juice production of several fruits, including grapes, watermelon, pineapple, and tangerine. This multi-fruit juice extractor was developed, built, and tested by [20] using melon, pineapple, and orange as its test fruits. Shear and compressive squeezing force were the basis for the machine's operation.

Sustainability and Waste Management

Utilizing by-products such as animal feed, biofuel, or natural fertilizers, new machines are designed to reduce waste by processing residual skins, seeds, and fiber. This method generates more income while reducing the negative effects on the environment caused by fruit pulp extraction [21]. Reduce operating expenses and contribute to environmental objectives with machines fitted with innovative water and energy recycling technologies. These advancements are changing the face of fruit pulp extraction for the better, making it more eco-friendly and flexible to meet a wide range of industrial demands. Automation, resource efficiency, and high-quality output are the larger developments in food processing, and they are in line with those. Several methods exist for making fruit pulp extraction machines more efficient, with the main goals being to maximize operating performance, decrease energy usage, minimize waste, and improve output quality [22]. It is possible to greatly improve the pulping process by adjusting the machine's blade configuration. Blades that are sharp, long-lasting, and adaptable for various fruit kinds make it easier to remove the pulp, seeds, and skins. Implementing self-sharpening blades and precise cutting mechanisms decreases wear and maintains constant performance over time [23]. If you want to get the pulp out of the seeds and skins, you need a sieve mechanism. Higher yields and improved pulp quality may be achieved by enhancing the mesh design or material of the sieves, such as by employing sophisticated synthetic materials or fine-mesh stainless steel. Improved throughput and less clogging are the results of a well-designed sieve.

You may greatly decrease the machine's power usage by upgrading to motors and driving systems that are energy efficient. For instance, VFDs provide precise regulation of motor speed, which in turn reduces energy waste under low-load situations by guaranteeing that the machine only uses what is really needed for the work at hand [24]. Thermal recovery systems may be integrated into machines that produce surplus heat while extracting. These systems are designed to reduce the total energy consumption of the facility by capturing waste heat and reusing it for other operations like drying or pasteurization. The throughput may be enhanced by maintaining a constant rate of fruit feeding into the machine. Conveyors or automated feed systems may control the fruit flow to meet the pulping capacity of the machine, eliminating bottlenecks and maintaining a constant output tempo [25]. If you want to maximize productivity, you need to make sure that you can switch between batches or fruit varieties quickly. There is less downtime between operations because of modular machinery that can be easily adjusted or replaced (e.g., blades or sieves). Because fruits differ greatly in size, shape, texture, and fiber structure, it is possible to increase pulp production by adjusting machine parameters such as blade speed, pressure, and sieve size according to the fruit in question. With little or no human intervention, automated equipment with preset parameters may change fruits [26]. Fruit pulp may be more easily extracted by using ultrasound to break down the cell walls. With this method, you can get more pulp out of even the most delicate fruits, like berries, without sacrificing any of the nutrients or quality of the end result [27].

Various types of peeler/pulpers

Cassava peeler

Manual peeling

Manual operation is tedious, time-consuming, and operated by hand to facilitate the removal of the peel from the cassava tuber. The output of the skilled person for manual peeling is about 25 kg/h with a 25-30% loss of weight in the peels (Gumanit and Pugahan, 2015) [28]. Some broken cassava is referred to as mechanical damage and not losses in peeling. The mean peeling efficiency is 75.46%, with a mean flesh loss of 8.801% in 10 kg feed. The capacity of the machine that could peel was about 60 kg/h, where the cassava was loaded every 5 minutes compared to manual peeling for the skilled person of 25 kg/h. The grating and pressing capacity is 21.216 kg/h while the mean grating and pressing efficiency is 83.779%. For the overall machine, the mean duration time from peeling to dewatering per 10 kg batch basis is 22 min 15 sec. The mean recovery for three trials of testing for 10 kg feed is 6.4 kg with fine cassava grates as a final output of the machine. However, the designed machine will not peel all sizes of cassava.

Moreover, the machine is restricted up to medium sizes, specifically 254 mm length of cassava, to facilitate peeling. For further improvement of this research, the researchers recommend that the material used for design must be locally available, particularly on machine elements, for ease and affordability and an avoidance of the delay of fabrication. In the following line of study and further modification of the fabricated machine, a speed regulator can be installed to regulate the motor speed during peeling and improve the chute door mechanism for transferring the peeled cassava. For the grating unit, increase the teethed cylinder diameter to increase the surface area in contact for grating cassava tubers. It is suggested that the pressing unit be openable for easy cleaning. In addition, the rotation of the presser should be lowered to 40-50 rpm to attain better-pressed cassava grates. Further improvement and extensive literature review could still be made to this study to enhance more effective and acceptable performance.

Mechanical Peeling

Gumanit and Pugahan, (2015) [28] created a pressure, grating, and peeling machine for cassava in batches. The uncooked cassava is run through a peeler that has a mesh of holes stitched into its inside edge. Peeling of cassava tubers occurs when the bottom of the circular drum spins in a counter-clockwise direction to the perforated tool. To clean and wash the root pieces and to remove the peel, water is applied.

A cassava peeler that can handle cassavas of varying sizes was created and manufactured by Odigboh (1976) [29]. Two cylinders, one with knives and one with corrugations, make it up. On a parallel frame, they are 20 mm apart. A 1 horsepower electric motor (1425 rpm, single-phase) powers the machine, while a belt that rotates to the right at 200 rpm drives the series of blades. Through gearing with the knife cylinder, the internal cylinder likewise rotates in the same direction at 88 rpm. Large quantities of cassava provide the finest results. While the peeling effectiveness was 75% when used with roots of varying sizes, it reached 95% when used with roots of a specified range of sizes. Peeling a day after harvest does not significantly reduce peeling efficiency. It could handle 185 kg of throughput per hour. An inconvenience is that it is time-consuming to trim the material to a length of around 100 mm. The amount of manual cutting that has to be done once the machine is adjusted for a certain root size is minimal. However, for roots that are 40 mm or smaller, manual pruning is still necessary.

A 65.5% efficient cassava peeler was created and manufactured by Baba Hassan (2012) [30]. After being manually loaded, the linear tubers were transported to the peeling drum by rail. The machine's simplicity, performance, and affordability make it a welcome addition to industries.

Garlic peeler

Rajesh *et al*., (2018) [31] designed and developed a mechanical garlic peeler Garlic peeling is time-consuming, tedious and labor intensive. Traditional methods are used for peeling the garlic for many years. These methods bring forth unhygienic practices, laborious, and cause more damage to garlic segments. The angular and flat iron was used for the main frame and supporting the primary units. A food-grade rubber and mild steel pipe were used in the rubber roller to remove peel from garlic.

Mechanical peeler cum juicer for sweet orange and kinnow: To simplify the process of preparing sweet orange and kinnow juice, a mechanical peeler and juicer was created. The machine's important components include an 80 mm long cutting knife, a 570 mm long rotating shaft with a 25 mm clearance, two fruit holders, and a spur gear assembly. A gear set, motor, and a number of pulleys worked together to make this possible. In order to extract juice from peeled fruits, it was equipped with a feed hopper that had a flat base. A performance study was conducted using the fruit's rotating speed (220, 260, 280, 300, and 360 rpm) as an independent parameter. Determinants of the process were peeling efficiency (%), time (s), percentage of fruit surface area that remained unpeeled (%), and percentage of juice lost (%). Mahawar *et al*. (2020) [32] found that the sweet orange and kinnow fruits performed best when processed at speeds of 260 and 220 rpm, respectively, with respect to peeling efficiency and loss of juice.

Jackfruit peeler cum corer

Expecting the minimum processing time and bulb wastage with higher efficiency by using three sizes of jackfruit, the speed of the corer pulley (110, 130, and 150 rpm) and fruit holder (90, 120, and 150 rpm) was optimized. The peeling operation at optimized speed (90 rpm) showed minimum bulb wastage for small (7.85%), medium (7.24%), and large (6.20%) sized fruits with high peeling efficiency of 85.27, 83.51, and 80.64%, with a trend of increasing operational time of 38.24, 44.58, and 50.34 sec respectively. Similarly, coring operation at optimal speed (130 rpm) showed processing times of 16.98, 22.39, and 24.83 sec and high coring efficiency of 92.85, 90.32, and 82.03%, with bulb wastage of 10.337, 7.81, and 6.09% respectively. The average power consumption of optimal operational speeds for medium-sized jackfruit with load was found as 0.0149 ± 0.0029 kWh/fruit, whereas in without load condition was found to be 0.0104±0.0007 kWh/fruit. The average time for peeling, cutting-coring, and bulb separation in manual and mechanical process was 28.8 min and 13.3 min/fruit respectively. The maximum throughput in manual and mechanical process was 17.36 kg/h and 37.5 kg/h respectively. The cost of the machine was estimated as Rs. 46950/-. The operational cost by manual and mechanical process was Rs. 47.5/h and Rs. 52.97/h respectively. The benefit-cost ratio of the developed machine and manual process was 2.32:1 and 2.66:1 respectively.

Litchi Peeler

Le *et al*., (2019) [33] developed a litchi peeler which works based on the principle of shearing and friction. The main components of this device are two rubber covered rollers and a pressing belt. This can reduce the juice and pulp loss, breakage, and flesh damage compared to a peeler using pure friction. The critical peeling force of lychee fruits was recorded as 10.5 N. Both rollers rotate in opposite direction at 159 rpm to separate the peel from the litchi fruits. The pressing belt which is parallel to the rollers provide exerting pressure of 13.5 N on the fruits. The roller diameter, length, and clearance between the rollers can greatly affect the efficiency of the peeler.

Mango Peeler

The peeling of the mango is traditionally done which is timeconsuming. And there is the loss of pulp within the peel and seed. It results in low quality and less efficiency and consumes more time, chances of hand injuries. A peeler machine was designed and developed for mango to make the peeling process easy. This machine consists of the spur gears, frames, sample, blade and screw shafts, and blade (Girma Tura, 2020) [34].

The power is transmitted to the sample shaft through spur gears from the feeding section. Spur gears are having 34 and 86 teethand gear ratio of 2:5.

Onion Peeler

The main components of onion peeling machine are main frame, inlet and outlet openings, peeling drum, collection basin, power transmission system, and water and air supply systems. The machine was evaluated using large, medium and small onion bulb sizes. The evaluation process was conducted under peeling residence times (1, 2, and 3 min), drum rotational speeds (30, 40, and 50 rpm) and batch loads (18, 24, and 30 kg). The peeling efficiency of 74.9, 65.24, 80.08, and 85.45% were obtained at 24 kg batch load (0.36 ton/h.), 2 min peeling residence time, and 40 rpm for small, medium, mixed and large sizes onion bulbs, respectively (El-Ghobashy *et al*., 2012) [35].

The objective of this study is to design and assess an onion peeling and trimming machine suitable for small and mediumscale production units, including restaurants, hotels, and small onion drying facilities. Peeling experiments were conducted on Giza 6 and Beheri onions, with average moisture contents of 79.6% and 81.1% (w.b.), respectively. The fabrication, development, and testing of the onion peeling machine were carried out. Various parameters were considered, including four open flat belt speeds (15, 20, 25, and 30 rpm), onion sizes (small, medium, and large), and two popular onion cultivars: Giza 6 (white) and Beheri (red). Results indicated that the peeling efficiency, peeling capacity, and total cost were higher for Giza 6 onions compared to Beheri onions when using the peeling machine. For Giza 6 onions, the highest peeling capacity of 140.61 kg/h was achieved at an open flat belt speed of 30 rpm with large-sized onions.

The key findings can be summarized as follows

1. Peeling efficiency, peeling capacity, and total cost were higher for Giza 6 onions compared to Beheri onions when using the peeling machine.
2. To achieve optimal peeling and trimming quality, lower costs, and power requirements for Beheri and Giza 6 onions, the recommended speed is 15 rpm with mediumsized onions.
3. Sizes smaller than medium onions are more suitable for home use, pickling, etc., due to lower cost feasibility.
4. For enhanced economic viability, onion grading and sorting equipment should be implemented prior to the peeling machine.
5. Further experimentation is recommended to reduce machine size and incorporate electronic control units for improved peeling quality, keeping up with advancements in agricultural processing machines (Ghanem, 2020) [36].

Vegetable peeling and cutting machine

The vegetable peeling process is time-consuming and becomes inefficient during weekly breakdown maintenance. It is vital for both food processing industry and domestic point of view. The main component of machine are drum, abrasive peeling section, and cutting section. The design of the machine is based on the idea of combining all the processes in one, which helps to reduce the manpower and satisfies the needs of industries and households. The machine is simple to operate, safe, and easy to repair. The technology is affordable and less expensive when compared to existing peeling machines. It has a low operating cost.

Pneumatic Pineapple peeler

Harvested pineapple may go to waste before they are consumed due to a lack of appropriate technology and infrastructure. A pneumatic pineapple peeler was developed for slicing the pineapple to create a cylindrical pulp. It has a cylindrical blade used to strip the pineapple flesh. It can remove the leaves, core of the pineapple and peel the outer surface. In 7 hours, roughly 2100 pineapples could be peeled (Madhankumar *et al*., 2021) [37].

Power-operated plantain peeler

Plantains are usually processed into chips, and the peel is used to prepare pickles. The nendran type plantain is preferred chiefly for making chips. The commercial chip manufacturing process involves peeling, slicing to small wafers, frying, and packaging. At present, the peeling of plantain is done by traditional methods using stainless steel knives. This conventional method poses a danger to the operator's finger by inflicting injury, less capacity, time-consuming, and laborintensive. So, a power-operated plantain peeler was fabricated. The plantains with a moisture content of 80 ± 2% was used. The peel and pulp were weighed to determine the pulp-to-peel ratio. This peeler consists of feeding unit, peeling unit, pushing unit, collection unit, power transmission assembly, frame assembly. The feeding unit consists of 4 cylindrical guides of different diameters placed 90º apart and fixed to a flat plate of 266.7×266.7 mm. Four MS hollow cylinders with diameters of 44, 47, 47, and 55 mm, a height of 200 mm, and a thickness of 2 mm were used to fabricate a cylindrical guide. The peeling unit separates the peel from the pulp. Four high carbon steel blades of width 25 mm are bent to form circular type openings of diameters 25, 32.5, 32.5and 40 mm for respective cylindrical guides through which plantain passes. Pushing rod consists of a piston rod, screw shaft, and pulley. The lowering and lifting of the piston are achieved by a screw shaft mechanism. Screw shaft with outer square threads meshed with cast-iron pulley with inner threads. It converts the rotary motion of the pulley into the linear motion of the screw shaft. A 1.0 hp single phase reversible electric motor of 1425 rpm was fitted as the power source. The speed of the plantain peeler was optimized using a gearbox. The speed reduction gear was connected with the motor to reduce the motor speed in the ratio of 5:1 rpm. The belt and pulley were used to transmit power from one shaft to another. 5 V-grooved pulleys (3 pulleys of 150 mm diameter, 200 mm, and 50 mm) made up of cast iron were used for power transmission. The outlet chute was made of SS sheet with a 45º inclination towards the horizontal to facilitate easy discharge. A collecting tray of 270 x 270 x 50 mm was made from an SS sheet of 1 mm.

The average peel thickness of plantain was measured as 2.36 mm. The pulp-to-peel ratio of the nendran variety varies between 1.75 and 1.77, with an average value of 1.76. The maximum and minimum diameters with peel were 40.3and 23.29 mm, respectively. The corresponding values for without peel were 33.55 and 24.67 mm, respectively. The maximum load required to cut a cross-sectional slice of peel and pulp was 47 N and 27 N, respectively. The machine's overall capacity for the 42 mm diameter feeding cylinder varied from 5.98 to 7.15 kg/h with an average value of 6.62 kg/h. Similarly, the machine's overall capacity for 47mm and 54mm diameter feeding cylinders varied from 12.44 to 14.09 kg/h and 15.07 to 17.45, respectively. The average overall capacities for 42 mm, 47 mm, and 54 mm diameter feeding cylinders were estimated to be 6.62, 13.23, and 16.81 kg/h, respectively. A maximum capacity of 16.81 kg/h was obtained using a 54 mm diameter feeding cylinder and a minimum capacity of 6.62 kg/h for a 42 mm diameter feeding cylinder. It is understood that the machine's capacity increases with the diameter of the feeding cylinder. Maximum capacity was obtained using a 54 mm diameter cylindrical guide, and the minimum for 42 mm. This is because the weight of the plantain increases with size, and the time taken for peeling operation was constant for all sizes of plantain. The peeling efficiency of 96.65% using a 42 mm diameter feeding cylinder was observed.

A comparison of manual and mechanical peeling was conducted. It is observed that skilled labor can peel approximately 25 kg of plantain in one hour, whereas the power-operated plantain peeler could peel 105 kg in one hour. The peeling capacity of the developed machine is found to be four times more effective than manual peeling.

Lye Peeling Machine for Small Capacity of Potato

This machine was tested using potato and it sprays pressurized water on the potato soaked in hot NaOH solution. Water pressure from the nozzle is controlled by using potentiometer's pulse width modulation (PWM) method. NaOH treatment concentrations were 9%, 11%, and 13%. The treatments are carried out using three duty cycle values with the analog input setting value on the microcontroller. It resulted in three variations of water pressure i.e., 60% (4.2038 Pa), 80% (5.6051 Pa), and 100% (7,0065 Pa) respectively for low, medium, and high levels. The percentage of perfectly peeled skin close to 100% was obtained at 11% NaOH with a duty cycle value of 60% and 80%; and 13% NaOH with a duty cycle value of 80%. The smallest weight loss calculation is 14.96% at 9% NaOH duty cycle 100%, and the highest percentage of weight loss is 35.89% at 13% NaOH 80% duty cycle (Sandra *et al*., 2021) [38].

Grating and peeling apparatus for fruits and vegetables

Grating holds great significance, particularly for salad preparation and decorative purposes. For effective execution of the decorative process, it is crucial to have a suitable grater. However, manual peeling by hand can be laborious and time-consuming, necessitating multiple workers and resulting in higher operational costs. To address this, a machine was innovatively developed to combine both grating and peeling functions into a single device. This newly invented machine is specifically designed for domestic use and boasts a portable nature. It incorporates essential components such as a clamping mechanism, grater, peeling blade, movable arm, and a pair of end-cutting blades. Through rigorous testing, the prototype successfully automated the grating and peeling process. Additionally, manual peeling was performed on selected fruits and vegetables to compare the effectiveness. The results demonstrated that the prototype significantly reduced peeling time by 94% compared to manual peeling (Siti *et al*., 2010) [39].

Jackfruit peeler cum cutter machine

The machine exhibits remarkable capabilities in effectively washing, peeling, and cutting tender jackfruit. It offers versatility by accommodating tender jackfruits of all sizes, boasting an impressive throughput capacity of 25 kg/h. To ensure food safety, all components that come into contact with the food are made of stainless steel, specifically grade 304. The machine's performance was optimized by adjusting parameters such as the rotating speed of the jackfruit, forward speed of the peeling arm, and rotating speed of the cutter, resulting in maximum efficiency and minimal loss during the processing of tender jackfruits.

With a return on investment value of 209.61%, the machine proves to be financially advantageous. Moreover, the investment's pay-back period is exceptionally low, estimated at just 34 working days. These factors make the fabricated machine a highly favorable option, offering lower operating costs, a low breakeven point, and a high return on investment. Additionally, it significantly reduces the costs associated with minimal processing and packaging of tender jackfruit slices (Rana, S. S., 2019) [40].

Latest peeling methods for tough-skinned fruit and vegetables: Automated or semi-automated techniques are employed for peeling tough-skinned fruits and vegetables like jackfruit, pineapple, wood apple, melon, and pumpkin. However, both methods suffer from significant peeling losses. To address this issue, this research has introduced four novel mechanical peeling methods that leverage the specific mechanical properties of such fruits and vegetables. A groundbreaking approach involves the utilization of an abrasive-cutter brush as the optimal peeling method for tough-skinned produce. This innovative device employs abrasive and cutting forces simultaneously to efficiently remove the peel (Emadi B, 2005) [41]. Notably, the developed method offers consistent peeling efficiency in both concave and convex areas and boasts high productivity. Moreover, it prioritizes ecofriendliness by minimizing water consumption and reducing peeling waste.

Orange juice extractor

Manual extraction

One portable manually operated household orange juice extractor was developed. The diameter and height was 160 mm and 350 mm, respectively. It was designed on the basis of beating and chopping, often by macerating. It is mainly consists of a goblet and a manually operated mechanical unit. The mechanical unit consists of a pair of two bearings, bevel gears, and two shafts. The bevel gear casing is constructed by a 2 mm thick mild steel sheet. Similarly, the goblet is formed using a 1 mm thick mild steel sheet. Small sharpened blades are fixed in the impeller shaft. A dynamic seal is put between the bearings, shaft, and goblet to prevent leakage. The goblet and gear casing are connected using an Oldham coupling designed for misalignment. The machine capacity is about 180-220 oranges/h (Aye and Ashwe, 2012) [43].

Mechanical extraction

The design and construction of an orange juice extractor were undertaken to extract pure orange Juice, free of squashed seeds and peels. It has a cutting chamber, which is made up of a rotary shaft, an inclined tray, and knives attached at both ends. The squeezing section comprises the rammer, a crankshaft, and a sieve. The shaft diameter, torque, and power transmitted as 12 mm, 14252 N mm, and 1.5 kW, respectively. The pulley has a linear speed of 10.74 m/s, and the cross-sectional area of the squeezing chamber (flat plate) is 12,000 mm2 with a force of 5.32 N on the plate due to pressure from the orange. The net force acting on the plate is 3059 N. The machine's capacity and efficiency were 5.73 kg/h and 76.04%, respectively. More juice can be extracted using this machine than by a turning screw (Maduako, 2015) [43]. The device has a rotary handle through which power is introduced into the system, a spur gear train mounted on a base, a power screw, and a cutting blade that performed the peeling function. The fabricated device has a peeling efficiency of 97%, generated 2.6% over peeled and damaged oranges, and has a peeling capacity of about 140 oranges/hr compared to hand peeling that can produce 32 oranges/h. (Ademoh and Akaba, 2015) [44].

Kendu Pulper

Hmar *et al*., (2018) [45] devised a kendu pulper that involves manual feeding of ripe and matured kendu fruits into the hopper. An optimized amount of water is added to aid smooth flow. The water quantity is fine-tuned through trial and error to ensure optimal flow with minimal water usage. The feeding of fruits and removal of by-products (seeds and peel) occur simultaneously. The feed rollers effectively break the tough outer covering of the kendu fruit and extract the pulp along with partially separated seeds. Subsequently, the primary shaft, equipped with brushes, presses the ruptured fruit against a perforated screen cylinder, extracting the pulp while leaving behind the broken outer covering and seeds.

The pulper has a throughput of 50 kg/h. The overall extraction efficiency of the pulper is 78.36% at an optimized speed of 260 rpm and a feed rate of 2.5 kg/min (Hmar *et al*., 2018) [45].

Mango Pulper

The mango pulper was created to assist rural farmers in reducing fruit deterioration. The mainframe, hopper, teflon-mounted brushes, shaft, extraction chamber, motor, perforated sieve, fruit residue, and bearings make up its stainless steel (SS-304) construction. Feed rates of 2.0, 2.5, and 3.0 kg/min and extraction speeds of 500, 900, and 1400 rpm were all used to test the machine. Also performed was the physicochemical evaluation of the pulp that was removed. The most impressive figures were an extraction efficiency of 96.03%, a maximum pulp output of 77.03%, and a maximum extraction loss of 9.3%. According to Akram *et al*. (2021) [46], the equipment that extracted mango pulp was simple to use and didn't cost a fortune.

The optimum operating speed of the electric motor for pulp extraction was 900 rpm for mango fruits, while the optimum mango feed rate was 2.5 kg/min, but it can also operate at 3.0 kg/min.

Manually Operated Cashew Juice Extractor

A manually operated cashew juice extractor working on the screw press principle was designed, fabricated, and tested.

Apple crushing was by pressing a wooden piston against a steel-reinforced end plate. Juice output was 1.02 liters/h, and the average juice extraction efficiency was 85.38% (Ogunsina and Lucas, 2009) [47].

Motorized Fruit Juice Extractor

Fruits and vegetables are vital elements in human food, but they are highly perishable. On that account, a significant quantity of this worthy produce gets wasted due to improper post-harvest management. Virtually entire fruits and vegetables exhibit short harvesting intervals of roughly 1-2 months. Over this short period, fruits and vegetables are available in ample quantity. There is a need for an effective means to conserve this fruit ingredient for the long term; hence, conserving these fruits in the form of juice is the best way to preserve fruit nutrients. The juice extraction commences with a tiresome manually squeezing method to motorized juice extraction machines worldwide. Various manually and motor-operated machinery is available in the market. The traditional method of hand squeezing is modest and proficient, but it requires more time. Manually functioned machines are cheaper but show limited output, while the motorized extractors are fully automated but may require high power consumption. Manually and motor-powered juice extractors reviewed in this work shall support the developers in designing cost-efficient and affordable machinery that gratifies the demand of juice processors. Several juice extractors accompanied by their corresponding functioning and performance were discussed in this work to promote more refined and superior juice extraction in the future (Patil *et al*., 2021) [48].

Juice extraction is productive or fruitful means of nutrient sustentation. Numerous juice extractors have lasted long, yet certain constraints were linked with this previously practiced extractor. Hence, to improve their performance intends to write reviews. An abundant quantity of fruits is available during the peak harvesting season. Still, much fruit production gets wasted during this period, necessities to be preserved for the period when there is no fruit production which requires a superior mechanical device to extract the juice from fruits. Various manually and power-operated extractors were developed earlier. Several machines were extravagant, high power, and lengthy processing time-consuming in addition to extraction loss, lower efficiency and sedimentation were the common problems with extractors. Hence, there is a significant requirement to advance this prevailing machinery by emphasizing high extract yield, ease in operation and maintenance, hygiene, and affordability to farmers and fruit juice processors.

Limitations/Disadvantages of Manual Fruit Pulping
Manual fruit pulping, while simple and low-cost, has significant drawbacks that limit its efficiency and applicability, especially in modern commercial settings. Below are the key limitations

Labor-Intensive and Time-Consuming
- Manual pulping requires extensive human effort for tasks like peeling, deseeding, and mashing, making it slow and impractical for large-scale production.
- Example: Pulping a batch of mangoes by hand can take hours compared to minutes with automated pulpers.

Inconsistent Quality
- The quality of pulp varies due to differences in worker skill, technique, or fatigue, leading to non-uniform texture, flavor, or color.
- Inconsistent pulp can affect downstream processing, such as juice or jam production.

Low Yield and High Product Loss
- Manual methods often fail to extract all pulp, leaving significant amounts attached to skins or seeds.
- Example: Manual mango pulping may result in 10-20% lower yield compared to enzymatic or mechanical methods.

High Risk of Contamination
- Handling fruits by hand increases the risk of microbial contamination from improper hygiene or unclean tools.
- Lack of controlled environments can introduce dirt, insects, or pathogens, compromising food safety.

Limited Scalability
- Manual pulping is suited for small-scale or household use but cannot meet the demands of commercial production or export markets.
- Scaling up requires more workers, which increases costs and coordination challenges.

Physical Strain and Ergonomic Issues
- Repetitive tasks like squeezing or mashing can cause physical strain or injuries to workers, reducing productivity over time.
- This also raises ethical concerns about worker welfare in labor-intensive settings.

Poor Preservation and Short Shelf Life
- Manual processes lack integration with modern preservation techniques (e.g., aseptic packaging or high-pressure processing), leading to rapid spoilage without immediate consumption or basic preservation (e.g., boiling).
- Pulp is prone to oxidation, nutrient loss, or flavor degradation during manual handling.

Inefficient Waste Management
- Manual methods generate significant waste (e.g., peels, seeds) that is often discarded without valorization.
- Unlike modern systems, there’s no mechanism to extract by-products like pectin or oils, reducing overall value.

Lack of Traceability: Manual processes typically lack documentation of fruit origin, handling, or quality control, making it difficult to meet regulatory or consumer demands for traceability.

Unsuitability for Diverse Fruits: Some fruits (e.g., berries or fibrous fruits like pineapples) are challenging to pulp manually due to their structure, leading to inefficiencies or poor-quality output.

Quality and Nutritional Considerations in Fruit Pulping and Processing: Quality and nutritional considerations are critical in fruit pulping and processing, as they directly impact the sensory attributes (taste, texture, color, aroma), nutritional value, and marketability of the final product. Both traditional manual methods and modern technologies influence these factors differently. Below is a detailed exploration of quality and nutritional considerations, with a focus on how processing methods affect them.

1. Quality Considerations
Quality in fruit pulp encompasses sensory attributes, consistency, safety, and shelf stability. Key factors include:

a. Sensory Attributes
Taste and Flavor
- **Manual Pulping:** Prolonged exposure to air during manual processing can lead to oxidation, altering flavor profiles (e.g., loss of fresh fruit taste in mango pulp). Inconsistent handling may also introduce off-flavors from contamination.
- **Modern Methods:** Controlled processing (e.g., aseptic systems) preserves volatile flavor compounds. For instance, high-pressure processing (HPP) retains the fresh taste of citrus pulp better than heat-based methods.

Texture and Consistency
- **Manual Pulping:** Uneven mashing or sieving results in inconsistent texture, with lumps or fibrous residues. This is common in manually processed guava or pineapple pulp.
- **Modern Methods:** Refiners and homogenizers ensure smooth, uniform texture. Twin-stage pulpers remove fibrous material, producing consistent pulp for applications like smoothies or baby food.

Color
- **Manual Pulping:** Enzymatic browning due to prolonged air exposure darkens pulp (e.g., banana or

apple pulp turns brown). Lack of immediate preservation exacerbates discoloration.

- **Modern Methods:** Technologies like vacuum pulping or blanching before processing minimize browning. Additives like ascorbic acid or inert gas flushing (e.g., nitrogen) maintain vibrant colors.

b. Consistency and Standardization

- **Manual Pulping:** Variability in worker techniques leads to non-standardized pulp, affecting downstream applications (e.g., inconsistent viscosity in juice production).
- **Modern Methods:** Automated systems with sensors (e.g., IoT-enabled pH or viscosity monitors) ensure consistent pulp characteristics. AI-driven quality control optimizes parameters for specific fruit varieties.

c. Food Safety

- **Manual Pulping:** High risk of microbial contamination from unhygienic handling, tools, or environments. For example, improper washing of mangoes can introduce E. coli or Salmonella.
- **Modern Methods:** Aseptic processing, HPP, and UV sterilization eliminate pathogens. Real-time microbial monitoring ensures compliance with food safety standards (e.g., FDA, EU regulations).

d. Shelf Stability

- **Manual Pulping**: Without advanced preservation, manually processed pulp spoils quickly (within hours to days) due to microbial growth and oxidation.
- **Modern Methods**: Aseptic packaging extends shelf life up to 12 months without refrigeration. Freeze-drying or vacuum concentration preserves quality for long-term storage.

e. Appearance and Market Appeal

- **Manual Pulping:** Irregular appearance (e.g., uneven color or texture) reduces consumer appeal, especially for commercial products.
- **Modern Methods:** Technologies like enzymatic clarification or microfiltration produce visually appealing, clear pulps. Packaging innovations (e.g., transparent pouches) enhance marketability.

2. Nutritional Considerations

The nutritional value of fruit pulp (vitamins, minerals, antioxidants, fiber) is influenced by processing methods, which can either preserve or degrade key nutrients.

a. Vitamin Retention

Vitamin C (Ascorbic Acid)

- **Manual Pulping:** Prolonged exposure to air and heat (e.g., during boiling for preservation) degrades vitamin C. For example, manually processed orange pulp may lose 20-50% of vitamin C.
- **Modern Methods:** HPP and cold pulping minimize vitamin C loss, retaining up to 90% in citrus pulps. Aseptic processing avoids heat-related degradation.

Other Vitamins

- **Manual Pulping:** B-vitamins and fat-soluble vitamins (e.g., vitamin A in mangoes) are susceptible to oxidation or leaching during manual washing or boiling.
- **Modern Methods:** Controlled processing (e.g., low-temperature vacuum concentration) preserves B-vitamins and carotenoids. Enzymatic treatments maintain nutrient bioavailability.

b. Antioxidant Content

- **Manual Pulping:** Phenolic compounds and flavonoids (e.g., in berries) degrade due to oxidation or improper handling, reducing antioxidant capacity.
- **Modern Methods:** Technologies like HPP or pulsed electric fields (PEF) preserve antioxidants by avoiding heat and minimizing oxygen exposure. For instance, HPP-treated blueberry pulp retains 95% of anthocyanins compared to 60% in heat-processed pulp.

c. Fiber Content

- **Manual Pulping:** Inefficient separation of pulp from skins or seeds may reduce dietary fiber content, as some fiber remains in waste.
- **Modern Methods:** Advanced pulpers and enzymatic treatments maximize fiber extraction. For example, twin-stage pulpers recover more fiber from guava or passion fruit pulp.

d. Mineral Retention

- **Manual Pulping:** Minerals like potassium or magnesium are relatively stable but can leach into water during excessive washing or boiling.
- **Modern Methods:** Minimal water use and closed-loop systems (e.g., in aseptic processing) prevent mineral loss. For example, potassium retention in banana pulp is higher in modern systems.

e. Sugar and Caloric Content

- **Manual Pulping:** Natural sugars are generally preserved, but prolonged processing or improper storage can lead to fermentation, altering sugar profiles.
- **Modern Methods:** Controlled processing maintains natural sugar levels. Technologies like membrane filtration can concentrate sugars without adding preservatives, ideal for low-calorie products.

3. Impact of Processing Methods on Quality and Nutrition

The choice of pulping and processing method significantly affects quality and nutritional outcomes. Below is a comparative summary

Aspect	Manual Pulping	Modern Methods
Flavor Preservation	Poor; oxidation alters taste	Excellent; HPP and aseptic systems retain flavor
Texture Consistency	Inconsistent; lumpy or fibrous	Uniform; refiners ensure smooth texture
Color Stability	Poor; browning common	High; blanching and additives prevent browning
Microbial Safety	High contamination risk	Low; sterilization ensures safety
Vitamin C Retention	Low (20-50% loss)	High (up to 90% retention with HPP)
Antioxidant Retention	Moderate to low; oxidation degrades compounds	High; non-thermal methods preserve antioxidants
Fiber Yield	Low; fiber lost in waste	High; advanced pulpers maximize fiber recovery
Shelf Life	Short (hours to days)	Long (up to 12 months with aseptic packaging)

4. Strategies to Optimize Quality and Nutrition
To address quality and nutritional challenges, the following strategies are employed

Pre-Processing Treatments
- Blanching or steam treatment inactivates enzymes (e.g., polyphenol oxidase) that cause browning and nutrient loss.
- Enzymatic treatments (e.g., pectinases) enhance pulp yield and nutrient extraction without compromising quality.

Non-Thermal Processing
HPP, PEF, and UV-C treatments preserve nutrients and sensory attributes by avoiding heat. For example, HPP-treated mango pulp retains 85% of vitamin C compared to 50% in heat-pasteurized pulp.

Smart Technologies
- IoT sensors monitor pH, temperature, and oxygen levels to optimize processing conditions, minimizing nutrient degradation.
- AI-driven quality control adjusts parameters to maintain consistent sensory and nutritional profiles.

Packaging Innovations
- Aseptic packaging and oxygen-barrier materials (e.g., Tetra Pak) prevent oxidation and microbial growth, preserving quality and nutrients.
- Modified atmosphere packaging (MAP) with nitrogen flushing extends shelf life without chemical preservatives.

By-Product Utilization
Extracting nutrients from waste (e.g., antioxidants from grape skins) enhances overall nutritional value and supports sustainability.

5. Consumer and Regulatory Perspectives
- **Consumer Expectations:** Modern consumers demand high-quality pulp with natural flavor, vibrant color, and high nutritional value. Transparent labeling (e.g., “non-thermal processed” or “rich in vitamin C”) boosts trust.
- **Regulatory Standards:** Agencies like the FDA and EFSA enforce strict guidelines on microbial safety, nutrient claims, and labeling. Modern methods ensure compliance, while manual processes often struggle to meet these standards.
- **Certifications:** Organic, non-GMO, or clean-label certifications require minimal processing and natural preservation, favoring technologies like HPP over chemical additives.

Value-Added Products and By-Products in Fruit Pulping and Processing
Fruit pulping and processing generate not only primary products like pulp but also opportunities to create value-added products and utilize by-products, enhancing economic viability and sustainability. By transforming waste and secondary outputs into marketable or functional items, the industry maximizes resource use, reduces environmental impact, and opens new revenue streams. Below is a detailed exploration of value-added products and by-products, highlighting their applications, processing methods, and significance.

1. Value-Added Products from Fruit Pulp
Value-added products are derived directly from fruit pulp or processed further to create high-demand items with enhanced market value. These products leverage the sensory and nutritional qualities of pulp for diverse applications.

a. Types of Value-Added Products

Fruit Juices and Nectars
- **Description:** Pulp is diluted, filtered, or blended with water, sugar, or additives to produce ready-to-drink juices or nectars.
- **Examples:** Mango nectar, orange juice, guava juice.
- **Processing:** Clarification (enzymatic or membrane filtration), pasteurization, or aseptic packaging to ensure shelf stability.
- **Market Appeal:** High consumer demand due to convenience and nutritional benefits (e.g., vitamin C in citrus juices).

Fruit Purees and Concentrates
- **Description:** Pulp is homogenized or concentrated (via vacuum evaporation) for use in food manufacturing.
- **Examples:** Banana puree for baby food, apple puree for bakery fillings, mango concentrate for beverages.
- **Processing:** High-pressure processing (HPP) or freeze-drying preserves flavor and nutrients. Concentration reduces water content for cost-effective transport.
- **Applications:** Used in smoothies, yogurts, ice creams, and sauces.

Jams, Jellies, and Preserves
- **Description:** Pulp is cooked with sugar and pectin to create spreadable products.
- **Examples:** Strawberry jam, pineapple preserve, mixed fruit jelly.
- **Processing:** Boiling, gelling, and aseptic packaging. Natural pectin from fruit peels can replace commercial pectin.
- **Market Appeal:** Popular for breakfast spreads and bakery applications, with demand for low-sugar or organic variants.

Fruit-Based Snacks and Confectionery:
- **Description:** Pulp is dried, molded, or mixed with binders to create snacks or sweets.
- **Examples:** Fruit leather (e.g., mango or apricot roll-ups), fruit gummies, dried fruit bars.
- **Processing:** Dehydration, extrusion, or freeze-drying to retain flavor and nutrients.
- **Market Appeal:** Appeals to health-conscious consumers seeking natural, portable snacks.

Dairy and Dessert Products
- **Description:** Pulp is incorporated into dairy or dessert formulations.
- **Examples:** Mango yogurt, passion fruit ice cream, fruit-flavored custards.
- **Processing:** Blending with dairy bases, followed by pasteurization or HPP for safety.

- **Market Appeal:** Combines fruit nutrition with creamy textures, popular in premium markets.

Functional Foods and Beverages

- **Description:** Pulp is fortified with vitamins, minerals, or probiotics to create health-focused products.
- **Examples:** Antioxidant-rich berry smoothies, fiber-enriched guava drinks.
- **Processing:** Fortification, microencapsulation for nutrient stability, and aseptic packaging.
- **Market Appeal:** Growing demand for functional foods addressing specific health needs (e.g., gut health, immunity).

Alcoholic and Fermented Beverages

- **Description:** Pulp is fermented to produce alcoholic or probiotic drinks.
- **Examples:** Pineapple wine, mango cider, kombucha with fruit pulp.
- **Processing:** Controlled fermentation with yeast or starter cultures, followed by filtration and bottling.
- **Market Appeal:** Appeals to niche markets for artisanal or health-focused beverages.

b. Benefits of Value-Added Products

- **Increased Revenue:** Higher profit margins compared to raw pulp (e.g., mango puree sells at 2-3 times the price of raw pulp).
- **Market Diversification:** Targets varied consumer segments (e.g., baby food, snacks, beverages).
- **Extended Shelf Life:** Processing (e.g., aseptic packaging) allows year-round availability, reducing seasonality constraints.
- **Brand Differentiation:** Unique formulations (e.g., organic or low-sugar jams) enhance competitiveness.

2. By-Products from Fruit Pulping and Processing

By-products are the secondary outputs of pulping, such as peels, seeds, pomace, and wastewater, which are traditionally discarded but can be transformed into valuable resources. Modern processing emphasizes valorization to convert these into usable products.

a. Types of By-Products and Their Applications

Peels

- **Source:** Outer skins of fruits like citrus, mango, or pineapple.

Applications

- **Pectin Extraction:** Citrus and apple peels are rich in pectin, used as a gelling agent in jams, jellies, and pharmaceuticals. Example: Orange peel yields 20-30% pectin by weight.
- **Dietary Fiber:** Dried and ground peels (e.g., mango or banana) are added to functional foods for fiber enrichment.
- **Bioactive Compounds:** Peels contain antioxidants (e.g., flavonoids in citrus peels) for nutraceuticals or cosmetics.
- **Animal Feed:** Treated peels are used as low-cost feed for livestock.

Processing: Extraction (solvent or enzymatic), drying, or pulverization.

Seeds and Kernels

Source: Pits or seeds from fruits like mango, apricot, or avocado.

Applications

- **Edible Oils:** Seeds from mango, grape, or passion fruit yield oils for cooking, cosmetics, or pharmaceuticals. Example: Mango kernel oil is rich in oleic acid.
- **Flour and Protein:** Ground seeds (e.g., jackfruit seeds) are used in baking or as protein supplements.
- **Bioactive Compounds:** Seeds contain antioxidants or antimicrobial agents for health supplements.
- **Biofuel:** Oil-rich seeds (e.g., avocado pits) can be processed into biodiesel.
- **Processing:** Cold-pressing, solvent extraction, or roasting.

Pomace

Source: Residual pulp, skin, and fiber after juice or pulp extraction (e.g., apple pomace, grape pomace).

Applications

- **Food Ingredients:** Pomace is dried and ground into fiber-rich flour for bakery products or snacks.
- **Fermentation:** Grape pomace is used for vinegar, spirits (e.g., grappa), or bioethanol production.
- **Animal Feed:** Nutrient-rich pomace is processed into feed pellets.
- **Compost and Fertilizers:** Decomposed pomace enriches soil as organic fertilizer.
- **Processing:** Drying, fermentation, or enzymatic treatment.

Wastewater and Liquors

- **Source:** Water used in washing or processing fruits, containing sugars, acids, or nutrients.

Applications

- **Biogas Production:** Anaerobic digestion of sugary wastewater generates methane for energy.
- **Nutrient Recovery:** Filtration recovers organic compounds for use in fermentation or fertilizers.
- **Water Recycling:** Advanced filtration systems purify wastewater for reuse in processing.
- **Processing:** Membrane filtration, anaerobic digestion, or reverse osmosis.

Other By-Products

- **Essential Oils:** Citrus peels or pineapple residues yield oils for perfumes, food flavoring, or aromatherapy.
- **Enzymes:** Fruit residues (e.g., papaya skins) are sources of enzymes like papain for food or industrial use.
- **Biochar:** Carbonized fruit waste (e.g., coconut shells) is used as a soil enhancer or water purifier.

b. Processing Technologies for By-Product Valorization

- **Enzymatic Extraction:** Enzymes (e.g., cellulases, pectinases) break down cell walls to extract pectin, oils, or antioxidants from peels and pomace.

- **Supercritical CO2 Extraction:** Used for high-value compounds like essential oils or antioxidants, preserving quality without chemical solvents.
- **Drying and Dehydration:** Solar, freeze, or spray drying preserves by-products for long-term storage (e.g., dried citrus peel for pectin production).
- **Fermentation:** Microbial processes convert pomace or wastewater into biofuels, vinegar, or probiotics.
- **Nanotechnology:** Nano-encapsulation stabilizes bioactive compounds from by-products for use in nutraceuticals or cosmetics.

3. Economic and Environmental Significance
a. Economic Benefits
- **Additional Revenue Streams:** By-products like pectin or seed oils command high market prices. For example, citrus pectin is valued at $1,000-$2,000 per ton.
- **Cost Reduction:** Utilizing waste reduces disposal costs and provides low-cost inputs (e.g., pomace for animal feed).
- **Market Expansion:** By-products target diverse industries, including food, cosmetics, pharmaceuticals, and energy.
- **Rural Development:** Small-scale processors in developing regions can monetize by-products, boosting local economies.

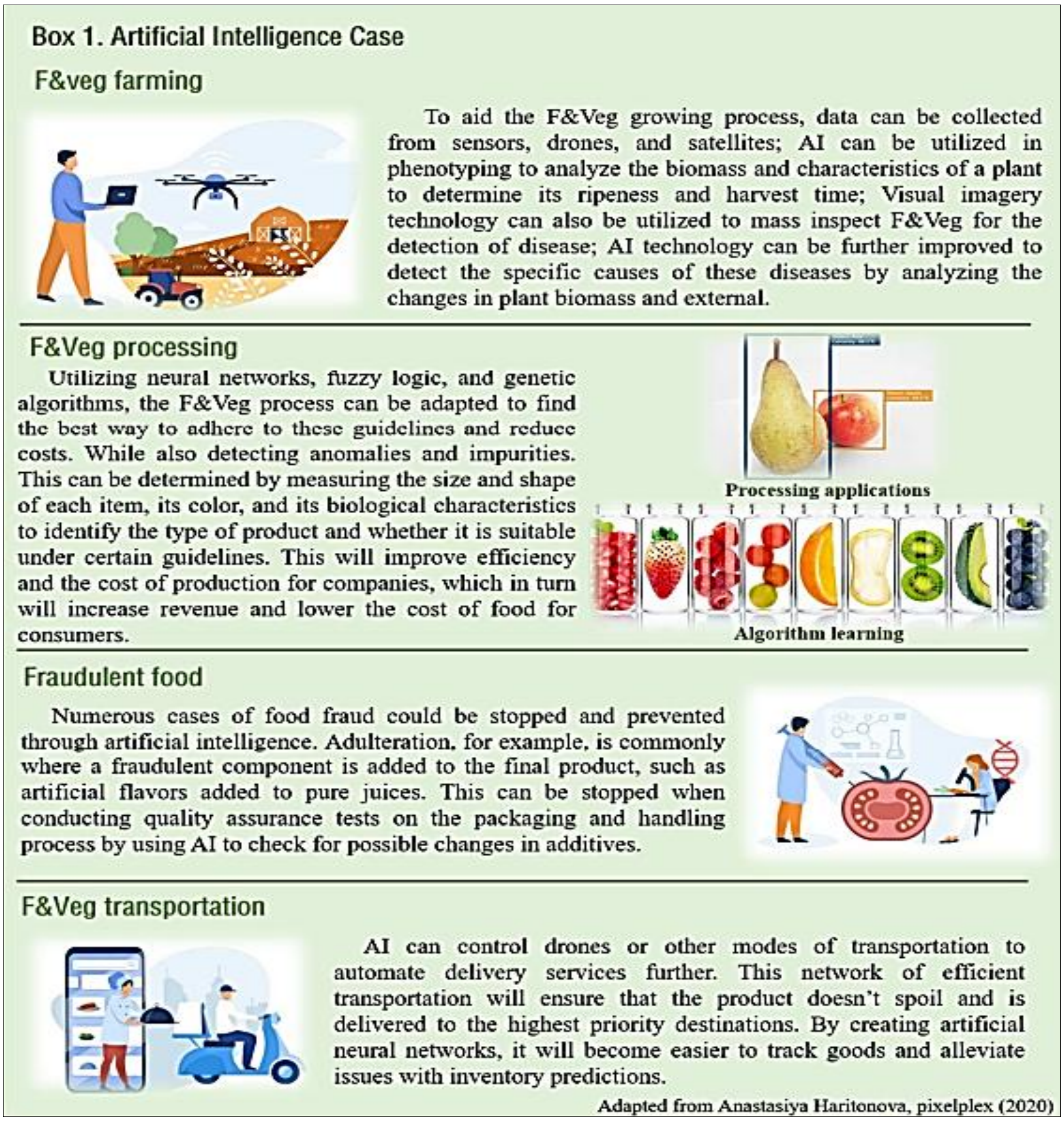
b. Environmental Benefits
- **Waste Reduction:** Valorization minimizes landfill waste, addressing the 30-50% of fruit processing waste typically discarded.
- **Sustainability:** Recycling water and converting waste into biogas or fertilizers supports circular economy models.
- **Lower Carbon Footprint:** Energy-efficient processes (e.g., solar drying) and biofuel production reduce reliance on fossil fuels.
- **Soil Health:** Organic fertilizers and biochar from fruit waste enhance soil fertility, reducing chemical fertilizer use.

4. Case Studies and Industry Examples
- **Citrus Industry (Global):** Orange peel is processed into pectin (used by companies like Cargill) and essential oils for food and cosmetics. Pomace is converted into animal feed or bioethanol.
- **Mango Processing (India):** Mango kernel oil is extracted for cosmetics, while peels are used for pectin or biogas production, reducing waste in India’s $1 billion mango pulp industry.
- **Winery By-Products (Europe):** Grape pomace from juice or wine production is transformed into grappa, vinegar, or antioxidant-rich nutraceuticals.
- **Small-Scale Innovation (Africa):** Solar-dried banana peels are ground into fiber-rich flour for local bakeries, supporting rural processors.

Human-Machine Collaboration
The integration of human intelligence, or human-machine cooperation, maybe the next big thing in smart F&Veg processing and production facilities, even if automation, robotics, and AI technologies are already essential components [49]. Another way to put it is that it's a step up from Industry 4.0, which relied on cutting-edge tech focused on production, to Industry 5.0, which linked the whole value chain to the manufacturing process. Washing, sorting, peeling, coring, and pressing are just a few of the numerous boring and repetitive jobs involved in making F&Veg. As a result, collaborative robots would be crucial, helping with tasks like material and equipment transportation and cleaning, as well as collaborating with people to optimize goods and design as required. At the same time, the collaborative robots handle fresh fruit and vegetables in a totally sanitary setting, which gets rid of any possibility of infection. Because the cleaning procedure generates moisture, the robot's design must accommodate for this potential source of contamination. While maintaining decision-making authority, participants would work with the robots to program algorithms that mimic human perception, comprehension, and inclination; when the going gets tough, as when you have a lot of plants of varying heights and sizes to select or harvest, this comes in handy. Crucially, technology does not replace humans as the primary actors; rather, robots play an increasingly vital role in manufacturing and processing. The cognitive and analytical abilities of workers will harmonize flawlessly with the rapidity and accuracy of automated machinery. For instance, automated collaborative systems handle mundane but necessary tasks like quality screening and data entry, freeing up employees to focus on higher-level quality and production workflow improvement, make decisions in real time, and supervise these processes.

Applications of Artificial Intelligence Thermal Imaging in Post-Harvest Fruit Quality Assessment
Thermal imaging is a painless way to examine all the different areas of a sample's temperature distribution. Agricultural and food products have traditionally been monitored using thermocouples, thermometers, thermistors, and resistance temperature sensors; however, thermal imaging provides the clear benefit of simultaneously and in real-time monitoring of immense regions. This capacity allows for the identification of minute variations in temperature, which might be signs of impending physiological changes or quality faults. In comparison to more traditional approaches, thermal imaging also offers fast data capture, which drastically cuts processing time.

Bruise detection
Bruising is a common kind of surface damage that crops may experience, especially during transit and handling after harvest. It shows up as temperature differences between bruised and non-bruised food. By making use of the fact that injured and healthy tissues have differing thermal characteristics, thermal imaging has become a potentially useful method for identifying bruising. Apples, blueberries, guavas, pears, jujubes, and strawberries are just a few of the fruits that have been the subject of thermal imaging-based bruise detection investigations. A proliferation of non-invasive and non-destructive methods for assessing fruit quality has been seen in the field of precision agriculture. One promising new approach is thermal imaging, a powerful tool for recording changes in temperature. When compared to more conventional visual examination techniques, pulsed-phase thermal imaging has been shown to be more accurate in detecting apple bruises [50].



More specifically, thermal imaging has allowed for accurate bruise characterization by measuring bruise depths [51]. Blueberry bruise detection is another area where thermal imaging has shown its flexibility. Researchers attained an astounding 88% accuracy rate in identifying blueberry bruising by using a mixture of multivariate algorithm feature sets [52]. More recent research has investigated the feasibility of using thermal imaging to assess guava bruises, specifically looking at how temperature changes affect the detectability of bruises [53]. Another example of how this technology might be used for various kinds of fruit is a thermal imaging system that was specifically created to identify and classify bruises on pears [40]. Researchers have suggested a new method that combines convolutional neural networks (CNNs) with thermal imaging to identify bruises in jujube fruits [54]. The potential of deep learning to improve the accuracy of bruise identification was shown by the good results produced by this hybrid system. Another example of how versatile CNNs based on thermal imaging can be is their effective application to strawberry bruise recognition [55]. The results of these experiments show that thermal imaging may be used to accurately and non-destructively identify food product defects, which can improve quality control and reduce food waste.

Maturity identification

As a non-destructive and effective way to identify the ripening stage of different produce, thermal imaging has become an invaluable tool for fruit maturity evaluation. The method is based on the idea that different fruits have different physiological and biological characteristics, which cause them to produce infrared radiation of varying intensities. The surface temperature of ripe fruits rises because their metabolic activity increases. By recording this temperature change, thermal imaging provides a solid measure of the development stage. As a non-destructive way to evaluate citrus ripeness, thermal imaging has been well-used by researchers to spot immature green citrus fruits [56]. To further improve the efficiency and speed of maturity evaluation in this crucial crop, a prototype thermal detector has been created to measure the stages of ripeness in fresh fruit bunches harvested from oil palm trees [57].

Fruit counting is another area where thermal imaging has shown its usefulness. The promise of a new active thermal imaging approach for automated fruit counting applications has led to its proposal for precise fruit counting in thermal movies. Another useful method for optimizing harvest time is an active thermography approach that can distinguish between ripe and unripe crops. Thermal imaging has also been used to differentiate between different pineapple cultivars, suggesting it might be a useful method for identifying and classifying pineapple varieties.

The efficiency and accuracy of this technology have been further improved by integrating machine learning techniques with thermal imaging-based maturity evaluation. Using these techniques, we can build reliable classification models that can distinguish between ripe fruits. To sum up, thermal imaging is an effective technique for identifying when the fruit is ripe; it is non-destructive, quick, and dependable, so it can optimize harvesting and storage methods, reduce post-harvest losses, and guarantee that customers get high-quality products.

Pest and disease detection

Using the unique thermal fingerprints of diseased or infested produce due to changes in their metabolic activity, thermal imaging provides a non-destructive and promising method for fruit pest and disease detection. To help identify impacted fruits, thermal imaging cameras can catch these temperature shifts and provide pictures that show slight temperature discrepancies. In order to reduce crop losses, mitigate disease transmission, and identify pests and diseases early, this strategy is crucial. Researchers have used thermal imaging to precisely monitor the surface temperature of apples kept in cardboard and plastic containers within the field of temperature monitoring [58]. As an example of the efficacy of thermal imaging for tracking temperature changes under various packing circumstances, this research attained remarkable estimated errors of 0.410 for plastic containers and 0.086 for cardboard containers. Optimizing post-harvest treatment operations is another area where thermal imaging has shown its worth. The ideal parameters for the apparatus were determined using thermal imaging in research that investigated cactus pear cauterization [59]. Thermal imaging can direct post-harvest treatment choices; for example, the researchers found that cauterization at 200 °C produced the longest shelf life.

In addition, thermal imaging has been used to improve fruit identification in orange trees. In order to evaluate the distribution of heat transfer on packing surfaces for fruit juices, researchers used thermocouples in conjunction with infrared cameras [60]. Fuzzy logic outperformed LPT in image fusion indices, and the researchers also created a way to fuse thermal and visual images. This provides further evidence that thermal imaging may be usefully used with other image modalities to enhance fruit recognition and attribution.

Packaging and supply chain

There has been a recent uptick in the use of thermal imaging technologies for better food processing and logistics. By supplementing current methods and offering a more complete picture of product conditions, this technology provides thorough temperature monitoring capabilities. Research by [61] shows that thermal imaging can monitor and trace the movement of commodities in the food supply chain, which might simplify monitoring operations and reduce the need for physical sensors like RFID/WSN. Because it doesn't involve physical touch, this non-contact technique is safer, less expensive, and more efficient than the old ways of doing things.

The use of thermal imaging to assess temperatures using pallet coverings is another area that has been investigated. The emissivity of the item being imaged determines how accurate the thermal pictures will be. Nevertheless, thermal imaging provides a non-invasive way to measure temperature distribution and find any cold or hot patches in pallet loads [62]. Maintaining items within their ideal temperature range during transit and storage relies heavily on this knowledge. Thermal imaging has also shown its use in assessing and improving packaging techniques for items with a high risk of spoilage, such as fruits. It is feasible to identify temperature gradients and variations that may suggest insufficient packing or ventilation by monitoring the surface temperatures of the fruit and the container simultaneously. This data is priceless for making informed decisions about the materials and designs of packaging that can keep contents at the correct temperature and humidity levels while in transit. Thermal imaging makes it much easier to compare how well various packing materials and designs keep perishable goods at their ideal storage temperatures. With this skill, experts in the food sector and related fields can find and choose packaging options that maximize fruit freshness and minimize spoilage.

Challenges and Future Perspectives in Fruit Pulping and Processing: Automation, smart technology, and the valorization of by-products have all contributed to great advancements in the fruit pulping and processing business. Problems still exist, however, and striking a balance between accessibility, efficiency, quality, and sustainability is especially difficult. In the future, these problems will be tackled by new methods and technology, which will also determine the course of the sector. The following is an in-depth analysis of the main obstacles and potential solutions, with an emphasis on fruit pulping and processing by-products, quality issues, and value-added goods.

1. Challenges in Fruit Pulping and Processing

a. High Initial Costs of Advanced Technologies

- **Challenge:** Huge sums of money are needed to acquire modern technology like as aseptic systems, high-pressure processing (HPP), supercritical CO2 extraction, and equipment that can be connected to the internet of things (IoT). For instance, small and medium firms (SMEs) or processors in developing countries cannot afford an HPP machine, which may cost between half a million dollars and two million.
- **Impact:** Reduces uptake, especially among SMEs in tropical fruit-producing nations like Nigeria and India. This limits the potential to scale and compete in international markets.
- **Example:** The high expense of automated pulping lines forces small mango processors in Africa to depend on manual or semi-mechanized processes.

b. Technical Expertise and Skilled Labor

- **Challenge**: Operating and maintaining advanced systems (e.g., AI-driven quality control, enzymatic extraction) demands specialized skills. Training workers to handle IoT sensors, PLCs, or biorefinery equipment is resource-intensive.
- **Impact:** In regions with limited access to technical education, processors struggle to adopt smart technologies, leading to inefficiencies or equipment misuse.

- **Example:** In rural Brazil, lack of trained technicians delays maintenance of automated citrus pulping lines, causing downtime.

c. Regulatory Compliance and Food Safety Standards
- **Challenge:** Stringent regulations (e.g., FDA, EFSA, Codex Alimentarius) require rigorous microbial safety, nutrient labelling, and traceability. Compliance involves costly testing, certification, and documentation, especially for value-added products like functional foods or by-products like pectin.
- **Impact:** Small processors may fail to meet export standards, limiting market access. Non-compliance risks product recalls or bans.
- **Example:** Manual pulping operations in Southeast Asia often struggle to meet EU microbial standards for mango pulp exports.

d. Sustainability and Environmental Concerns
- **Challenge:** While modern systems reduce waste, energy-intensive processes (e.g., freeze-drying, HPP) and water usage in washing or pulping raise environmental concerns. Additionally, improper disposal of residual waste (e.g., wastewater, non-valorized pomace) persists in some regions.
- **Impact:** High carbon footprints and water consumption conflict with global sustainability goals, pressuring processors to adopt greener practices.
- **Example:** Large-scale pineapple processing in Thailand generates significant wastewater, straining local water resources if not recycled.

e. Market Competition and Consumer Perception
- **Challenge:** Value-added products (e.g., fruit purees, functional beverages) face competition from synthetic or cheaper alternatives. Consumers may perceive highly processed products as less "natural," impacting demand for items like fortified pulps or by-product-based snacks.
- **Impact:** Processors must invest in marketing and certifications (e.g., organic, clean-label) to build trust, increasing costs.
- **Example:** Peel-based fiber products struggle to compete with synthetic fiber supplements due to consumer skepticism about waste-derived foods.

f. Supply Chain and Raw Material Variability
- **Challenge:** Inconsistent fruit quality (due to seasonal variations, ripeness, or post-harvest losses) affects pulp yield, quality, and nutritional content. Supply chain disruptions, such as transportation delays or climate-related crop failures, exacerbate this issue.
- **Impact:** Processors face challenges in maintaining consistent product specifications, especially for export markets requiring standardized pulp.
- **Example:** Erratic mango harvests in India due to monsoon variability disrupt pulp production schedules.

g. Limited Adoption of By-Product Valorization
- **Challenge:** While by-products like pectin, seed oils, or biogas offer economic potential, their extraction and commercialization require specialized infrastructure and market development. Many processors lack the resources or knowledge to implement valorization.
- **Impact:** Significant waste (30-50% of fruit mass) remains underutilized, missing opportunities for revenue and sustainability.
- **Example:** In Africa, avocado seeds are often discarded despite their potential for oil or antioxidant extraction due to lack of processing facilities.

h. Accessibility for Small-Scale Processors
- **Challenge:** Small-scale and rural processors, particularly in developing countries, lack access to modern equipment, financing, or markets. Manual pulping remains prevalent, limiting their ability to produce high-quality or value-added products.
- **Impact:** Widens the gap between large commercial processors and small producers, hindering inclusive growth.
- **Example:** Rural banana processors in Uganda rely on sun-drying due to limited access to freeze-drying or aseptic technologies.

2. Future Perspectives in Fruit Pulping and Processing
a. Emerging Technologies
Nanotechnology
- **Potential:** Nano-encapsulation can protect nutrients, antioxidants, and flavors in pulp, enhancing shelf life and bioavailability. For example, nano-encapsulated vitamin C in orange pulp could retain 95% potency over months.
- **Applications:** Functional foods, fortified beverages, and by-product-derived nutraceuticals.
- **Impact**: Improves nutritional value and consumer appeal while enabling premium pricing.

3D Food Printing
- **Potential:** Fruit pulp can serve as a base material for 3D-printed foods, such as customized snacks, desserts, or nutritional bars tailored to dietary needs.
- **Applications:** Personalized nutrition (e.g., high-fiber mango bars for diabetic patients) and novel food formats.
- **Impact:** Expands market opportunities for value-added products, especially in health and wellness sectors.

Biotechnology and Synthetic Biology
- **Potential:** Engineered enzymes or microbes could enhance pulp yield, nutrient extraction, or by-product valorization. For instance, genetically modified pectinases could increase pectin yield from citrus peels by 20%.
- **Applications:** Efficient extraction of bioactive compounds, biofuels, or fermented products.
- **Impact:** Reduces processing costs and waste, boosting sustainability.

Advanced Robotics and AI
- **Potential:** AI-driven systems can optimize pulping parameters in real-time, predict yields, and detect defects with greater precision. Robotics can handle delicate fruits (e.g., berries) with minimal damage.

- **Applications:** Fully automated processing lines, quality control, and predictive maintenance.
- **Impact:** Increases efficiency, reduces labor costs, and ensures consistent quality.

Green Processing Technologies

- **Potential:** Innovations like solar-powered pulpers, waterless processing, or energy-efficient HPP systems reduce environmental impact.
- **Applications:** Small-scale processing in off-grid regions, sustainable large-scale operations.
- **Impact:** Aligns with global sustainability goals, lowering carbon footprints and operational costs.

b. Circular Economy and Zero-Waste Models

- **Perspective:** Integrated biorefineries will process all fruit components (pulp, peels, seeds, waste water) into value-added products, by-products, and energy. For example, a mango processing facility could produce pulp, pectin, kernel oil, and biogas in one system.
- **Implementation:** Modular biorefinery designs for scalability, supported by public-private partnerships.
- **Impact:** Minimizes waste, enhances profitability, and supports sustainable development goals (SDGs).

c. Personalized and Functional Foods

- **Perspective:** AI and data analytics will enable tailored pulp formulations for specific consumer needs, such as high-antioxidant berry pulps for heart health or fiber-rich guava pulps for digestion.
- **Implementation:** Integration of consumer health data with processing systems, supported by blockchain for transparency.
- **Impact:** Meets growing demand for personalized nutrition, creating niche markets for premium products.

d. Decentralized and Modular Processing

- **Perspective:** Compact, modular pulping units (e.g., solar-powered micro-pulpers) will empower small-scale processors in rural areas, reducing reliance on centralized facilities.
- Implementation: Affordable, plug-and-play systems with low maintenance needs, supported by microfinancing.
- **Impact:** Enhances inclusivity, reduces post-harvest losses, and boosts rural economies.

e. Policy and Financial Support

- **Perspective:** Governments and international organizations will incentivize sustainable processing through subsidies, tax breaks, or grants for adopting green technologies and by-product valorization.
- **Implementation:** Policies promoting circular economy practices, training programs for SMEs, and export incentives.
- **Impact:** Accelerates technology adoption, improves competitiveness, and supports small processors.

f. Consumer Education and Market Development

- **Perspective:** Educating consumers about the benefits of by-product-derived products (e.g., peel-based snacks, seed oils) and sustainable processing will drive demand.
- **Implementation:** Marketing campaigns, clean-label certifications, and QR codes linking to traceability data.
- **Impact:** Builds trust, expands markets for value-added and by-product-based goods, and encourages sustainable consumption.

g. Climate-Resilient Supply Chains

- **Perspective:** Technologies like blockchain, IoT, and predictive analytics will enhance supply chain resilience by tracking fruit quality, optimizing logistics, and mitigating climate-related disruptions.
- **Implementation:** Digital platforms for real-time monitoring, climate-smart agriculture for consistent fruit supply.
- **Impact:** Ensures stable raw material supply, reduces losses, and supports consistent production.

3. Comparative Summary: Challenges vs. Future Perspectives

Challenge	Future Perspective
High costs of advanced technologies	Modular, affordable systems; policy incentives
Lack of technical expertise	Training programs; user-friendly AI interfaces
Regulatory compliance	Blockchain for traceability; automated compliance
Environmental impact	Green technologies; zero-waste biorefineries
Market competition/consumer perception	Consumer education; clean-label certifications
Raw material variability	Climate-resilient supply chains; AI yield prediction
Limited by-product valorization	Biotechnology; integrated biorefineries
Accessibility for small processors	Decentralized, solar-powered micro-pulpers

4. Case Studies and Emerging Trends

- **India's Mango Industry:** Facing high costs, India is piloting solar-powered pulping units for SMEs, reducing energy costs by 30% and enabling by-product valorization (e.g., pectin from peels).
- **Europe's Berry Processing:** AI-driven HPP systems are producing antioxidant-rich berry pulps for functional beverages, with blockchain ensuring traceability to meet EU standards.
- **Africa's Rural Innovation:** Modular pulping units in Uganda are processing bananas and pineapples, reducing post-harvest losses by 25% and creating value-added snacks.
- **Global Trend:** Biorefineries in Brazil are converting citrus waste into pectin, essential oils, and bioethanol, achieving near-zero waste.

Conclusion

The fruit pulping business has always strived for efficiency, quality, and sustainability, and this has been reflected in the development of fruit pulping technologies, which have progressed from simple mechanical systems to complex automated ones. Despite their simplicity and low cost, traditional technologies sometimes fail to satisfy the requirements of constant quality control and large-scale manufacturing. On the other hand, advanced technology has completely transformed the fruit processing industry. Enzyme-assisted pulping, cold extraction, ultrasound-assisted systems, and smart automation have all contributed to this revolution by increasing production, conserving nutrients, and decreasing water and energy usage.

A big stride forward has been achieved with the integration of smart technologies, which allow processors to optimize every step of pulping via the use of AI-driven controls and real-time monitoring. Sustainability innovations are also bringing the fruit processing business in line with worldwide environmental targets via water-saving designs, waste valorisation, and energy efficiency.

Technologies that can adapt, scale, and be environmentally sensitive will be crucial for fruit pulping in the future due to rising customer expectations and stricter regulatory regulations. To overcome adoption hurdles and propel the fruit pulping sector towards the next level of innovation, ongoing research and cooperation amongst industries are crucial.

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