Challenges and Future Directions in Cacao Bean Hulling and Grinding Process Technology: A Review

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https://doi.org/10.5109/7323258

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 10, pp.164-170, 2024-10-17. International Exchange and Innovation Conference on Engineering & Sciences
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Challenges and Future Directions in Cacao Bean Hulling and Grinding Process Technology: A Review

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Abstract: *Cacao bean processing involves intricate stages of hulling and grinding to produce cocoa liquor, a fundamental ingredient in chocolate production. This review evaluates current technologies for cacao bean hulling and grinding, assessing their performance in terms of hulling efficiency, purity, and recovery index. Challenges identified include variability in performance metrics and the need for improvements to meet industry standards for purity and recovery index. Future directions focus on optimizing equipment through physical and mechanical properties, simulation using DEM, and automation and integrating hulling and grinding processes for efficiency gains and adopting automation to enhance precision and consistency. These advancements aim to advance cacao processing methods towards sustainability, higher quality standards, and increased production efficiency.*

Keywords: hulling, grinding, liquor, nibs, hull

1. INTRODUCTION

Cacao beans, the seeds of the Theobroma cacao tree, are the fundamental ingredient in chocolate-making [1]. Initially, the harvested cacao pods are split open to extract the beans, which are then fermented for several days to develop their complex flavors. After fermentation, the beans are dried [2], roasted, and cracked to remove their outer shell, exposing the nibs within. These nibs are then ground into a dense, paste-like substance called chocolate liquor [3], which includes both cocoa solids and cocoa butter. Through further processing, such as conching [4] and tempering, the chocolate liquor is refined into smooth, flavorful chocolate.

In products derived from cocoa beans, the inclusion of cocoa shells is unwanted as it can have a negative impact on both the manufacturing process and the ultimate product quality. It constitutes approximately 12% to 20% of the cocoa seed, though this percentage can vary significantly, similar to other plant-based foods, influenced by factors such as climate, cocoa variety, and processing conditions, among other variables [1], and also it represents 2.1%-2.3% of the cacao pod [2], [3], and therefore, the cocoa product's shell content serves as a crucial quality parameter [4]. This residue is a rich source of carbohydrates (178.0 ± 0.9 g/kg) and proteins (150 ± 2 g/kg) while having a low lipid content (20.2 ± 0.3 g/kg) [5].

2. CACAO HULLING PROCESS

To meet legal standards and produce a high-quality product, thorough shell removal is essential since the shell can introduce unwanted contaminants from external sources. These contaminants do not enhance the flavor and taste of the product and can even cause undesirable off-flavors. Additionally, shells are tough and fibrous, making grinding difficult and potentially causing equipment wear. Efficiently separating shells from nibs also impacts process efficiency, as losing small nib particles with the shell is financially undesirable. Ideally, the shelling process should ensure clean separation, with most of the shells being removed while leaving the nibs largely intact. [5], [6], [7].

The cracking is the process of breaking the cacao beans and the winnowing is the cacao hulls and nibs' separation after cracking, these mechanisms in a cacao bean huller serve as a critical process for the initial transformation of raw or roasted cacao beans into their essential components. The breaking component applies

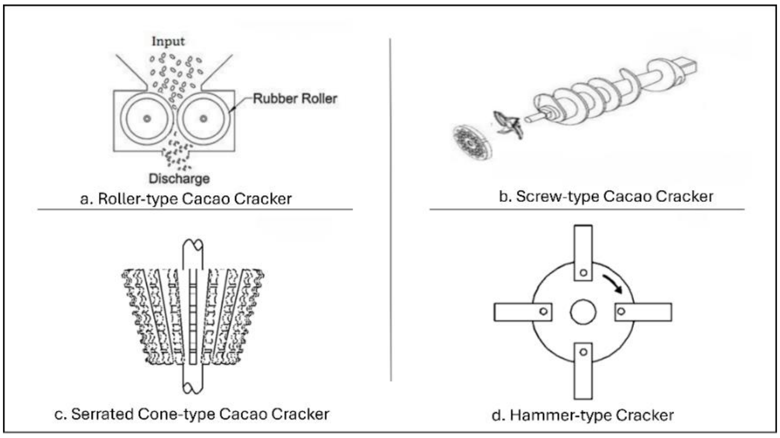

Fig 1. Cacao cracking mechanism

mechanical force to the cacao beans, effectively shattering the tough outer hull to reveal the valuable cacao nibs. Subsequently, the winnowing mechanism involves the separation of the lighter husk fragments from the heavier cacao nibs.

The Philippine Agricultural Engineering Standard (PAES) has established standards for cacao hullers, which are categorized based on specific designs illustrated in Fig 1. Fig 1a depicts a roller-type cacao cracker made of steel or rubber bonded to an inner metal drum core, used for breaking cacao beans. The screw-type cacao crackers, shown in Fig 1b, feature a feeding auger and stationary perforated discs or a cracking plate. Figure 1c illustrates a serrated cone-type cacao cracker, where cacao beans pass through a cone-shaped steel structure with serrations. Lastly, Fig 1d presents a hammer-type cacao cracker that crushes the beans by impact, using several hammer bars (fixed or swinging) mounted radially on a horizontally rotating shaft [8].

3. CACAO GRINDING PROCESS

After the hulling process of cacao beans, the next step is the grinding process, meticulously orchestrated for size reduction. This process converts the cacao nibs into cocoa liquor, which serves as the foundational material for subsequent molding procedures.

Cocoa liquor is called Tablea in the Philippines, it is a product obtained from grinding the cacao nibs and solidified. The main product currently manufactured and traded in Mindanao's local market is tablea, which is cocoa liquor formed into tablet shapes. Tablea is composed of roasted, ground, and shaped nibs derived solely from 100% pure, fermented cacao beans, with no additional ingredients or additives. The production process of tablea usually begins with the conversion of cacao beans into nibs, followed by their transformation into liquor [9]. Chemically, cocoa liquor is a blend of mono- and di-triglycerides, proteins, cellulose, starch, water, minerals, polyphenols, phospholipids, and various other organic compounds in minor quantities. It is a highly complex substance that contains several components capable of absorbing significant amounts of water [10]. The primary constituents of cocoa powder include proteins, which make up 11.5% of the cocoa liquor mass, cellulose at 9%, starch at 6%, polyhydroxyphenols at 6%, and water at 5% [11]. Further process of tablea by pressing would obtain cocoa butter [12] and cocoa powder, and by refining, conching, and mixing with other ingredients would obtain chocolate. Tablea is widely used in making champorado, a sweet rice porridge enjoyed for breakfast or as an afternoon snack. Recently, it has also become a popular ingredient in various desserts and pastries, including cakes, pies, brownies, and ice cream.

The Philippine Standards for cacao grinding are illustrated in Fig 2, which includes flat burr, conical burr, blade-type, hammer-type, and auger-type grinders. A flat burr grinder (Fig 2a) uses a pair of flat disks with grooves on their faces; one disk rotates while the other stays stationary, and the nibs are ground into liquor primarily through shearing action. The conical burr grinder (Fig 2b) features a conical grinding surface that grinds cacao nibs more slowly and quietly than a flat burr grinder, typically found in low-speed and gear-reduction grinders. A blade grinder (Fig 2c) employs a metal blade that whirls to chop up the cacao nibs. The hammer-type grinder (Fig 2d) crushes cacao nibs through impact, with multiple hammer bars (fixed or swinging) mounted radially on a horizontally rotating shaft. The auger-type grinder (Fig 2e) has a feeding auger and stationary perforated discs, and the shaft axis of the grinding unit can be either vertical or horizontal [13].

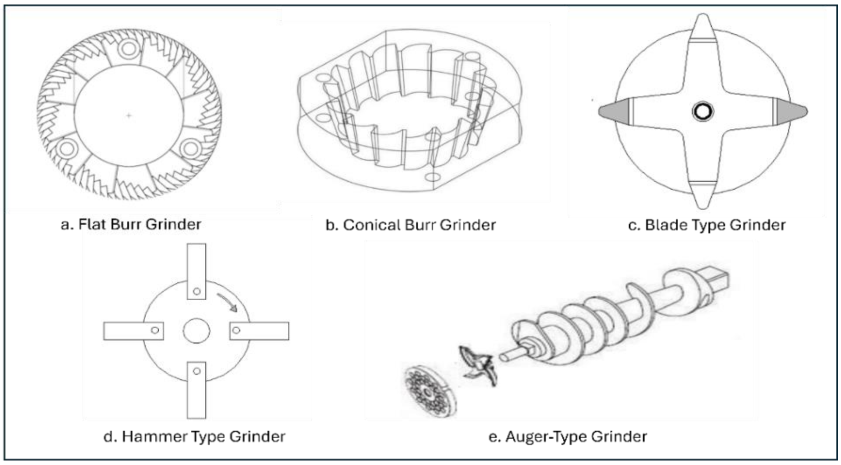

Fig 2. Cacao grinding mechanism.

4. EXISTING CACAO HULLER AND GRINDER MACHINE

The cacao bean huller developed by PhilMech shown in Fig 3, the design and development of cacao huller using response surface methodology consists of four main components: a cracker, a grader, a winnower, and a prime mover. Roasted cacao beans are introduced into the cracking rollers, where two rotating metal rollers crack them. The resulting cracked beans, comprising nibs and hulls, are sorted by size using a perforated sheet. Larger nibs and hulls remain on the upper sieve, while smaller ones fall into another sieve to separate fine nibs and hulls. The mixture then goes through a blower, where the lighter hulls are removed from the system, leaving the nibs to exit through the nib output chute [14].

Fig 3. Cacao huller, 2022

Nguyen et. al [15] designed a breaker and winnower system utilizing centrifugal force (Fig 4). In operation, roasted cocoa beans are introduced into the centrifugal breaking device (2) from the feeding hopper (1), where they are stored and supplied for the breaking process. After breaking, a combination of shells and nibs is transported by the elevator (3) to the screen (5). The screen (5) categorizes the nibs into different sizes and directs them to the cleaning unit (4), where the shells are removed. Once separated, the nibs are collected for further processing.

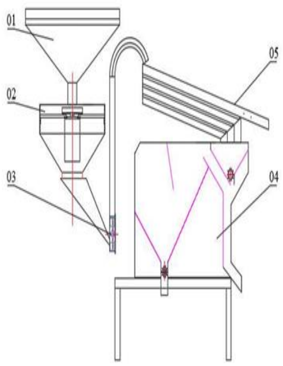

Fig 4. Breaker and Winnower, 2019

The grinding tooth-based breaker, recently adopted in Vietnam's cocoa processing system and depicted in Fig 5, has gained popularity. In operation, cocoa beans are fed into the inlet hopper (1) of the breaker, where they move to the beans agitator (2) and then proceed to the breaking section (3). The resulting mixture of broken shells and nibs is then processed through a screen raking system (4), ensuring a smooth flow of the product across the screens [15].

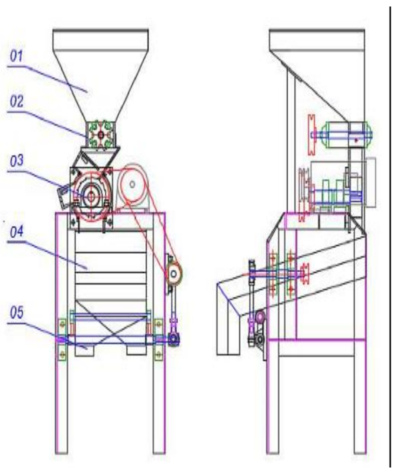

Fig 5. Cacao huller using grinding and crushing principle.

The cacao bean winnower shown in Fig 6 is developed [16], a small-scale winnower machine includes the following components: (a) A feeding mechanism featuring a 100mm stainless steel funnel and a peeler equipped with a blade-shaped rotor-stator, (b) an electric motor operating on 220V single-phase power, with 350 rpm and direct transmission, (c) a pipe for suctioning cocoa shells, (d) a channel for exhausting cocoa nibs, (e) a channel for exhausting cocoa shells, and (f) a fan and cyclone system. The machine operates by breaking cocoa beans using the peeler, separating them into nibs and shells. It features a dual-channel exhaust system designed to efficiently separate cocoa nibs from shells, optimizing both performance and space utilization.

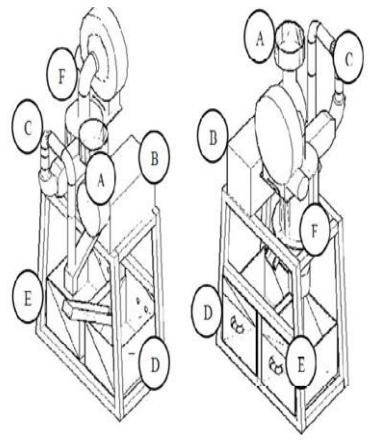

Fig 6. Cacao huller, 2016

The Indonesian Coffee and Cocoa Research Institute has developed and experimented with a rotary cutter-based machine designed to break and remove the shells from roasted cocoa beans (Fig 7). The breaking unit (c) is powered by a ½ HP motor (f) operating on a single-phase electrical system at 110/220 V and a speed of 1440 rpm. The transmission system for rotating the breaker unit employs a pulley and a single V belt (e). A centrifugal blower (i), serving as the separator unit between the cotyledon and the shell, is characterized by specifications including an airflow rate of 0.5 m3/min, a pressure of 780 Pa, a power of 370 W, and an electrical supply of 220 V. The components of the machine are as follows: (a) roasted cacao beans, (b) knife, (c) breaker, (d) frame, (e) V-belt transmission, (f) electrical motor, (g) screen, (h) shell outlet, (i) centrifugal blower, and (j) nibs outlet [17].

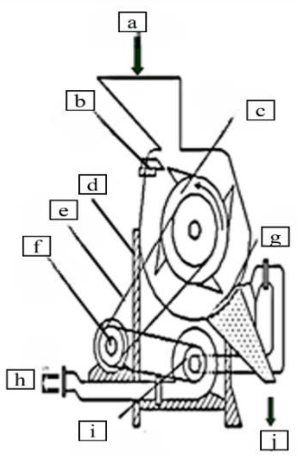

Fig 7. Cacao huller, 2005

Fig 8 shows the cacao grinder that is present in the Philippine market, where it has a hopper, a vertical burr-type grinder, powered by an electric motor. The problem of this grinder is the number of passes the cacao nibs will undergo, the bigger the sizes of the nibs, the more it will undergo.

Fig 8. Cacao grinder in the market

The Digital Kova grinder machine features a digital control panel shown in Fig 9, 31 grinding levels, a conical grinder blade, and a portable design. However, it has drawbacks such as low anti-pental, a small capacity, a 38 mm grinder diameter, and subpar materials. The new grinder machine offers practicality, ease of use, a digital panel, 31 grinding settings, a 500-gram storage capacity, better materials, and a 40 mm grinder diameter, although it is heavier and more expensive. The reverse engineering method for designing the new grinder involves disassembly, assembly, benchmarking, design using Fusion 360, and prototyping. The new design optimizes performance with a capacity increase to 9.42 kg/hour for medium fineness and 5.8 kg/hour for fine fineness, and improved hopper and storage capacities to 500 grams and 300 grams, respectively, enhancing user efficiency [18].

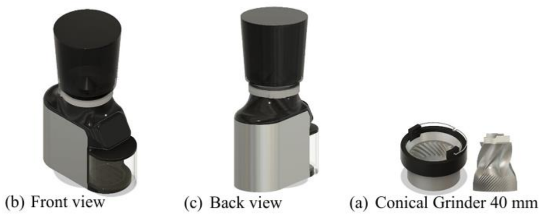

Fig 9. Digital Kova grinder machine

5. CHALLENGES

Based on Table 1, the evaluation of various cracking and grinding mechanisms reveals distinct performance metrics in hulling efficiency, cleanness/purity, and recovery index when compared to the Philippine standard values of 98% for purity and 85% for recovery index. The roller-type mechanism demonstrates a large nib purity of 97.13% and a small nib purity of 95.99%, with a nib recovery index of 0.845. While the large nib purity is close to the standard, the small nib purity falls short. However, the nib recovery index meets the standard of 85%. The centrifugal force type mechanism excels in cleanness with a value of 99.1%, surpassing the standard, but its nibs recovery rate of 78.3% is significantly below the standard. The impact type mechanisms show both a nibs recovery rate of 70.9% and cleanness of 95.8%, failing to meet the standards in both aspects. The rotor stator mechanism, with a winnowing capacity of 2.615 kg/hr, power transfer efficiency of 61.01%, and shell parchment percentage of 1.06%, lacks specific data on cleanness and recovery rate, making direct comparison to the standards unfeasible. Another impact type mechanism with a capacity of 268 kg/hr and varying product distributions also fails to achieve the required cleanness standard of 98%. In summary, the roller-type mechanism is the closest to meeting the standards, particularly in nib recovery index, while the centrifugal force type mechanism excels in cleanness but falls short in recovery rate. The impact type mechanisms and the rotor stator mechanism do not meet the required standards based on the available data.

Table 1. Performance of the existing machines

Cracking/Grinding Mechanism	Performance	References
Roller-type	Large nib purity: 97.13% Small nib purity: 95.99% Nib recovery index: 0.845	[14]
Centrifugal force type	Nibs Recovery Rate: 78.3% Cleanness: 99.1%	[15]
Impact type	Nibs Recovery Rate: 70.9% Cleanness: 95.8%	[15]
Rotor stator	Winnowing Capacity: 2.615 kg/hr Power: 132 W Power transfer efficiency: 61.01% Shell parchment: 1.06%	[16]
Impact type	Capacity: 268 kg/hr Percentage product Outlet 1: 94.5% Outlet 2: 5.5% Particle Distribution: Outlet 1: 92% (cotyledon), 8% (shell in cotyledon) Outlet 2: 97% (shell), 3% (cotyledon in shell)	[19]

The evaluation of various cracking and grinding mechanisms for hulling efficiency, purity, and recovery index reveals significant challenges in meeting industry standards. These challenges underscore the need for further optimization and refinement of these mechanisms to achieve the desired standards, ensuring more efficient and effective hulling processes.

6. FUTURE DIRECTIONS

4.1. Physical and mechanical properties of roasted cacao beans

The physical properties of cocoa beans, similar to other grains and seeds, are crucial for designing and constructing equipment and structures for handling, transporting, processing, and storing the beans. These properties also play a role in assessing product quality. Equipment for cleaning, grading, separating, and conveying cocoa beans is designed and built based on these physical properties [20]. The angle of repose and the coefficient of static friction are key physical properties influencing the conveying characteristics of grains and seeds [21]. Significant moisture-dependent physical properties of biological materials include shape and size, mass, crushing strength, bulk density, seed density, porosity, angles of repose for filling and emptying, and coefficient of friction [22]. These properties have been studied for various seeds and nuts, including pumpkin seeds [23], neem nuts [22], soybeans [24], sunflower seeds [25], guna seeds [26], cumin seeds [27], and bambara groundnuts [20], dried cacao beans [28], [29], coffee beans [30], among others.

Cocoa is used to produce a variety of food and non-food products. Based on the desired final product, the dried beans can be either roasted or left unroasted before being cracked and ground for further processing. During these processes, the material is compressed between two hard objects moving towards each other, applying a force greater than its strength, causing it to break or rupture in multiple directions [31]. The energy used in this size reduction process is only partly absorbed and stored temporarily as strain energy. The material absorbs energy up to the point of rupture, which is the energy required to break it [32]. The deformation of the strained material is influenced by its energy absorption and storage capacities. When the absorbed energy exceeds the material's storage capacity, it breaks into fragments as the stored energy is released, creating new surfaces [33], [34]. Numerous studies found about the mechanical properties of various agricultural products including coffee beans [30], soybeans [35], maize and rice [36] [37], among others. Information on the physical and mechanical properties of roasted cacao beans is not available in the literature.

4.2. Emerging trend and innovation

4.2.1. Discrete element method simulations

Understanding how the direction of feeding impacts grain movement during the hulling process is crucial for grasping the underlying mechanisms and enhancing the efficiency of hullers [38], [39]. Fortunately, recent advancements in computer simulation technologies using the discrete element method (DEM) have enabled the detailed analysis of the movement of agricultural granular materials. Notably, progress has been made in studying particle movement during rice harvesting, cleaning, hulling, and milling processes [40], [41], [42], [43]. These studies may be considered for designing efficient hulling and grinding machines for cacao beans using DEM.

4.2.2. Automation of machine

The emergence of automation in technologies is revolutionizing industries by enhancing efficiency, accuracy, and productivity across various sectors. A programmable logic controller, load cells, and proximity sensors were used to design an automated husking and peeling machine for rice [44], and lotus seeds [45]. These studies can be considered for improving the efficiency of hulling and grinding cacao beans. Integrating these processes would be beneficial, as there are currently no available studies on this integration.

7. CONCLUSION

The evaluation of various cracking and grinding mechanisms for cacao bean processing highlights significant challenges in meeting industry standards for hulling efficiency, cleanness/purity, and recovery index. While the roller-type mechanism approaches the desired standards, other mechanisms such as the centrifugal force type, impact type, and rotor stator mechanisms exhibit notable deficiencies. These challenges necessitate further optimization and refinement of existing technologies to achieve the standards of 98% cleanness/purity and 85% recovery index, ensuring more efficient and effective hulling processes.

Future directions in cacao bean processing emphasize the importance of determining physical and mechanical properties. These aspects can optimize equipment design and operational parameters, thereby improving process efficiency and product quality. Additionally, modeling and simulation using DEM, automation, and integrating hulling and grinding processes into a single streamlined operation present opportunity to enhance precision, reduce material loss, and increase production capacity. Focusing on these areas can propel the cacao processing industry toward more sustainable, efficient, and higher-quality production methods.

8. ACKNOWLEDGMENT

The researchers would like to acknowledge DOST-ERDT for financial support.

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