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Improving productivity and efficiency in banana processing: Advancements and challenges in matooke peeling techniques

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Abstract

The processing of green bananas into various food products involves several critical post-harvest operations, with matooke fruit peeling being one of the most crucial steps to ensure quality, safety, and overall integrity of the derivative products. This study presents a comprehensive review of matooke peeling techniques, analyzing traditional, thermal, and mechanized methods, while also exploring the theoretical principles and operational concepts underpinning these processes. Parameter evaluation of crop-related physical and mechanical properties of the banana fruits is provided to identify key factors influencing the effective design of an efficient mechanized peeling system. These parameters, including fruit size, geometric mean diameter, peel thickness, moisture content, angle of repose, and shear stress, are shown to significantly impact peeling efficiency and system performance. The review emphasizes the potential of mechanical peeling as a viable solution for the full mechanization of matooke processing, eliminating the drudgery and contamination-prone manual intervention within the process. The success of the mechanized systems is highly contingent on the precise understanding and integration of these crop-specific characteristics. Based on these insights, the paper proposes a crop parameter-based design for an automated peeling system aimed at improving productivity, enhancing hygiene standards, reducing labor costs, and ensuring consistent peeling quality. This mechanized approach is positioned as a reliable, efficient, and cost-effective solution for small, medium and large-scale matooke processing, with good potential for value addition and significant advancements in the processing industry.

1.0 Introduction

In Uganda, agriculture plays a pivotal role in the economy, with 80-90% of the population relying on farming for their livelihoods. The agricultural sector contributes significantly to the country's Gross Domestic Product (GDP), accounting for 43% of the total (Uganda, 2023). Uganda is considered a predominantly agrarian economy, as over 70% of its labor force is engaged in agricultural activities (UBOS, 2019; Ssennoga *et al*., 2019). Among the various crops cultivated, bananas, particularly green bananas locally referred as matooke, are of paramount importance, providing food security for approximately half of the Ugandan population. Banana has a special place in the daily diet of millions of people around the world for sustenance and nutrient enrichment (Mohapatra *et al*., 2010). Around 75% of Ugandan farmers grow bananas (Lee, 2023). She also holds the distinction of leading in Africa and being the second highest global producer after India with an estimated annual production of 9.77 million tonne (Gumisiriza *et al*., 2017). Accounting for the highest per capita banana consumption globally, individuals consume between 220 and 400 kg per year, contributing to roughly 30% of their daily caloric intake (Lee, 2023; Nalunga *et al*., 2015). Thus, the banana crop is a critical source of food and income, as its asynchronous fruiting allows for a continuous supply. The Ugandan government recognizes the importance of banana cultivation and has prioritized it for food security and economic development (Lee, 2023). Furthermore, bananas provide more than just food; their by-products are widely utilized for animal feed, ropes, mats, and medicinal purposes (kilwinger *et al*., 2019). Bananas are used in special diets to ease digestibility, and where low fat, minerals and vitamin content are required (Bi *et al*., 2017). These special diets are used for babies, the elderly and patients with stomach problems, gout, and arthritis. Green bananas possess anti-diarrheal action. It is traditionally used to cure intestinal disorders (Aurore *et al.,* 2009, Bezerra *et al.,* 2013). In 2005, the Ugandan government launched the Presidential Initiative on Banana Industrial Development, which led to the establishment of a banana processing factory aimed at producing Matooke flour and other banana-based products (Kilwinger *et al*., 2019). However, despite efforts to promote these processed products, they have struggled to gain widespread acceptance in the domestic market, highlighting challenges related to consumer perceptions, processing and utilization of Matooke (Lee, 2023; Marimo *et al*., 2022)

Fruit bunch de-clustering/de-fingering and peeling are among the first postharvest operations carried out on matooke fruit irrespective of the targeted product (Marimo *et al*., 2022). This process of banana peeling is essential both for local consumption and for value addition in the banana processing industry. Traditionally, peeling is a manual process that requires significant human labor, which is both time-consuming and physically demanding. This method is highly dependent on skilled labor to ensure efficiency and precision. Attempts have been made in the use of thermally assisted means to achieve peeling, but not without its drawback of poor product quality. While mechanized peeling machines are available in more developed nations such as the United States and China, these systems are often expensive, have high power consumption, and entail substantial operational and maintenance costs (Nong *et al.,* 2009; Guo *et al*., 2020).

The peeling operation has been largely dominated by the injury prone manual methods which fails to meet the ever-increasing demand for matooke product as largely consumed in East Africa. Consequently, over reliance on the traditional methods of peeling matooke characterized by inefficiencies, drudgeries, low productivity and safety issues has drawn significant attention towards mechanization of the process.

Given these challenges, there is a pressing need for affordable and efficient technologies that can enhance the banana peeling process. for supporting the dominating small-scale processors and households. In addition to the risk of injury, especially among women and children involved in the process, the prevalent manual peeling often results in wastages (loss of edible flesh) from unskilled operators, leading to significant economic loss when considered on a large-scale production. This underscores the potential benefits of developing and testing mechanical peelers that can help reduce labor while maintaining high-quality, fresh produce. Despite their potential advantages, mechanical peelers can be prone to material loss, due to variations in banana size, peel texture, and shape (Akankwasa *et al*., 2021; Nasirumbi *et al*., 2023; Madalla, 2023).

Mechanical peeling, when designed effectively and taking into account, the physical characteristics of the crop (Shirmohammadi *et al*. 2012), offers several benefits, including enhanced efficiency and improved product quality. As consumer preferences for hygienic, high-quality, fresh products continue to rise, the banana processing sector is increasingly leaning towards mechanical peeling methods. Mechanical peelers are known for their ability to preserve the integrity of the edible portion of the banana while minimizing waste (Kumar *et al*., 2019). Understanding the physical and mechanical properties of the fruit, such as size, shape, geometric mean diameter, peel thickness shear strength and toughness which are dependent on variety and age of maturity (Zhang *et al.,* 2005; Shirmohammadi *et al*. 2012), is crucial in optimizing the design of processing equipment and improving performance. Thus, ongoing development in the design and automation of banana peeling machinery is essential for enhancing efficiency and meeting the growing demands of the banana processing industry (Nalunga *et al*., 2015; Guo *et al*., 2020).

2.0 Banana Processing: Peeling Methods

Bananas, comprising over 100 varieties globally, are categorized mainly under five genome groups: AA, AB, AAA, AAB, and ABB (Maseko *et al*., 2024). These cultivars differ significantly in fruit color, pigmentation, shape, size, and plant stature, which influence their suitability for various processing and consumption purposes (Singh *et al*., 2016). Traditionally, they are generally classified into five types dependent on its food use: cooking, brewing, roasting, dessert, and multi-purpose. In Uganda, farmers often grow multiple types, with the cooking variety particularly the East African Highland Banana (EAHB), Musa spp., group AAA-EA, making up over 90% of banana cultivation (Edmeades & Smale, 2015; Mulugo *et al*., 2022; Ochola *et al*., 2022). Figure 1 shows some common varieties in in Uganda.

Playing a significant role in household diets, with over 97% of household's regular consumption, bananas are processed into a range of products. While some are consumed directly when ripened as *menvu* (yellow bananas), others are cooked when unripe (*matooke amanyige*), fermented into alcohol, or processed into flour for snacks and biscuits.

Figure 1 Some common banana varieties in Uganda (a) Kibuzi, (b) M30 (c) NARITA 2, (d) Nakitembe (Marimo *et al*., 2022).

Despite extensive information on banana species and their traits, there remains a knowledge gap in aligning cultivar differences with appropriate processing technologies, particularly for starch extraction, pulp and peel phenolic compounds utilization; and ensuring its optimal food applications. The physical and chemical differences among cultivars also affect their thermal and functional behavior during processing, rendering conventional methods such as those used in flour production often inadequate (FAO, 1990). Adapting processing techniques based on a clear understanding of cultivar-specific characteristics can improve efficiency and product quality (Guo *et al*., 2020; Edeh, 2020).

With green banana in focus, the processing involves a sequence of operations, as illustrated in the process flow diagram (Figure 2), leading to various products like steamed-mashed matooke, katogo porridge, banana chips, and flour.

Notably, peeling is a critical post-harvest step that precedes all other unit operations (Figure 2). The peeling operation removes the green skin from the banana fingers (Marimo *et al.* 2022). Any technique used in the peeling process significantly influence the peeling yield, product quality and overall output. Thus, peeling bananas is an essential operation for both local consumption and value addition within the banana processing industry. The final product quality from numerous culinary applications is often dependent on how effectively the peeling is done. In addition to enhancing product quality and improving aesthetic appeal, proper peeling is crucial to nutritional value preservation and post-harvest losses reduction; which are significant challenges in the agricultural sector of many banana-producing regions, particularly in East Africa (Hailu *et al*., 2013).

Manual, thermal and mechanical means have been employed in matooke peeling operations. This stage of banana processing is still carried out manually due to the lack of specialized equipment or machines for such purposes.

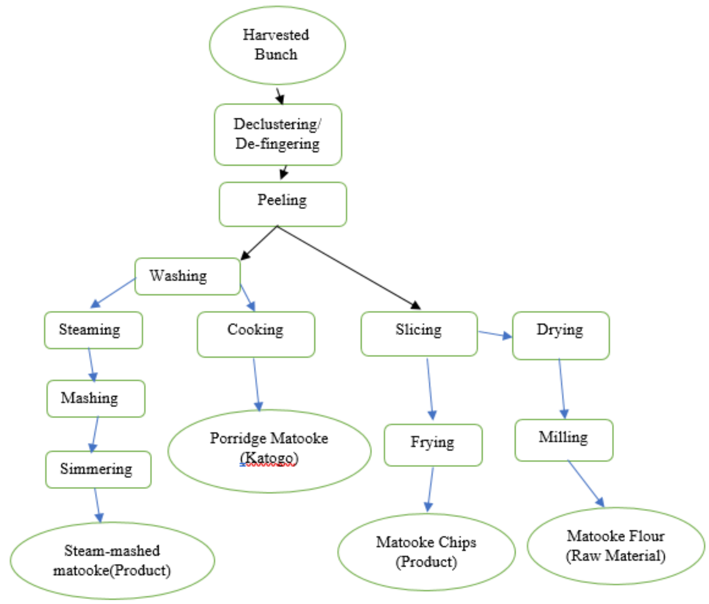

Figure 2: Matooke processing into different products.

2.1 Manual Peeling Method

Traditional banana peeling is a manual process, performed largely by hand. In this approach, a knife is manually used to remove the banana peel as shown in Figure 3. It is currently the most prevalent method of peeling bananas by small-scale or local processors in hotels, restaurants, and homes as it is adjudged to yield the best result (Osei, 2020). However, this process is quite laborious, time-consuming, injury-prone with physical strain. Though inexpensive, manual peeling depended significantly on the skills of the operator and is fraught with inefficiencies, low speed and loss of edible flesh since inexperienced workers often remove more flesh than necessary, resulting in significant product wastage (Emadi *et al*., 2007). Hence, it is largely characterized by low productivity.

Investigation by Marimo *et al*., (2022), revealed that the peeling productivity which relates the amount in kilograms of peeled bananas in an hour by a single operator vary from 18.4kg/hour/operator to 35kg/hour/operator with a mean value of 28.9kg/hour/operator. They further observed that the productivity

Figure 3 Manual peeling method

also depended on the varieties under study as certain characteristics of each specie influenced the output. Given the low output, the reliance on manual peeling methods has failed to meet the increasing demand for processed matooke, particularly in East Africa, where matooke as a staple food is in high demand (Nalingo *et al*., 2015). Thus, the expertise-dependent technique, relying disproportionately on women and children is a less-than-optimal method in terms of peeling consistency, productivity and safety (Seifu*.,* 1999).

The inefficiency and low productivity of manual method limits banana processing to small-scale operations, unable to keep pace with consumer needs, thereby calling for more advanced technologies to enhance productivity.

2.2 Thermal Peeling

Thermally assisted peeling methods, such as hot water or steam-based techniques have been utilized. These methods involve exposing the bananas to heat to loosen the skin, making it easier to peel (Smith and Harris, 1986; Garcia and Barrett, 2006; Srikaeo *et al*., 2011; Paengkanya *et al*., 2021). Thermal peeling can be performed using either wet heat (steam) or dry heat (such as flame or hot gases).

(i) Flame (Dry Heat) Peeling

In this process, bananas are subjected to direct exposure to flame for approximately one minute or placed in rotary tube peelers with hot gases. The heat causes steam to accumulate beneath the banana peel, which then causes the peel to burst, allowing for easy removal (Weaver *et al*., 1980).

(ii) Steam (Wet Heat) Peeling

This method uses superheated steam at around 10 atmospheres of pressure to soften the banana peel and underlying tissues. When the pressure is released suddenly, the steam beneath the skin expands, causing the peel to burst and crack, which facilitates its removal (Drooge *et al*. 1999).

Steam peeling is generally adopted due to its high automation capabilities, precise control over processing times, minimal peeling waste, and lower environmental impact (Smith & Harris, 1986; Floros, 1988). However, the thermal technique is not without drawbacks; while it reduces the physical effort involved, prolonged application of heat results in cooking which impacts the texture and appearance of the banana and diminishes the quality of the final product (Paengkanya *et al*., 2021; Lee, 2023). The dry heat methods can lead to the risk of burning the banana's surface, and any remaining peel fragments can negatively affect the fruit's appearance (Floros, 1988). In addition, the use of heat can alter the taste and cause nutrient degradation, thereby reducing the overall value of the processed product.

Furthermore, the application of thermal methods is often not cost-effective for small-scale banana producers due to the high energy consumption and the need for specialized equipment (Salunkhe, & Kadam, 1995). The operational and maintenance costs of such systems can be prohibitive for rural farmers and small processors, thus, limiting their widespread adoption.

2.3 Mechanical Peeling

Mechanical peeling involves the use of specialized equipment to remove the peel from bananas, offering an efficient method for processing large quantities of the fruit. This mechanized technique is suitable for commercial-scale operations, as it significantly reduces manual labor with improve productivity up to 1000kg/hr (Kumar *et al*., 2019; Osei, 2020). Mechanical peelers are categorized based on their peeling mechanisms, which can vary widely from abrasive devices, drums, rollers, knives and milling cutters (Shirmohammadi *et al.* 2012). Some peelers are manually operated, while others are fully automatic or electrically powered (Guo *et al*., 2020). The common types of mechanical peelers include abrasive devices, drum-based peelers, roller systems, knife or blade peelers, milling cutters, rotary peelers, and electric peelers. These devices are designed to streamline the peeling process, ensuring consistent and high-quality results (Grotte *et al*. 2001; Akinmoladun *et al*., 2020; Olajide *et al*., 2021).

(i) Peeling tool: Nipah Banana Peeler

BANALOP was invented to peel the green Nipah banana skin to expedite the process of banana chips processing. The design is developed to assist workers for easy peeling process of the green bananas which resulted in higher productivity. The tool comprises of two mechanisms which are the slitter and peeler. Slitter which is able to cut the edge of green banana without penetrating the pulp and by following the longitudinal curvy line for easy peeling process. Separator which separates the skin easily without major loss in the pulp and shorten the peeling process.

Figure 3 Nipah Banana Peeler

(ii) **Mechanized Peeling Machines**

Lenscott (2004) invented a green banana safety cutter, that consist of a safety cutter for peeling green bananas wherein a handle portion is provided adjacent to a head portion which carries a peeling element with dual opposing peeling blades. The dual opposing peeling blades are relatively widely spaced apart at approximately 5/6" to allow the peeling element to cut through the tough, thick skins of a green banana. The cutter is also provided with an elongate retractable cutting blade which is used to first cut off either end of the green banana to allow it to be easily peeled. The green banana peeler is preferably provided into two halves secured by a bolt which allows either, the peeling element and/or the retractable blade to be changed by the user when they become dull or worn.

Ganguly *et al*., (2014) described a method and equipment for peeling bananas without applying force to the fruit, in which the equipment includes a biting part and two endless belts rotating in opposite directions with turning parts parallel to each other. In Figure 4 is a bevel gear assembly banana peeling machine developed to achieve automatic feeding and peeling as the fingers are conveyed withing the assembly.

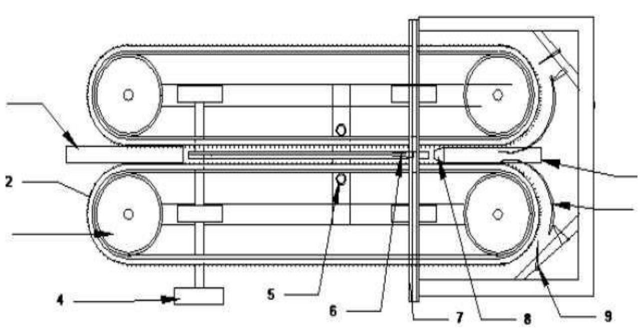

Figure 4 Bevel gear assembly banana peeling machine

The advent of mechanized peeling systems has been seen as a solution to the challenges associated with manual peeling. Mechanized peelers, which use various mechanisms such as blades, rollers, or air jets, have been developed to automate the peeling process. In developed countries, such as the United States and China, mechanized peelers have become integral to large-scale banana processing industries. These systems offer increased speed and consistency compared to manual methods, thereby reducing labor costs and improving product quality (Singh *et al*., 2019). However, despite their efficiency, these systems are often expensive, have high power consumption, and entail significant operational and maintenance costs. These limitations make mechanized peeling systems less accessible to small-scale processors in developing nations, where bananas are predominantly grown and processed.

2.4 Performance and Comparative Analysis of the Peeling Methods

It is important as part of the objective of this review work to weigh the strengths and limitations of the existing peeling methods, offer a roadmap for future areas of focus while identifying some factors that favor the mechanized peeling systems. Evaluations are carried out based on the key performance parameters, comparing the performance and effectiveness of each method. With limited data on green banana peeling as provided by Marimo *et al*., 2022 and adapting from the related studies of the performance evaluation of cassava peelers by (Abdulkadir, 2012; Edeh *et al*, 2018; Oyedele *et al.,* 2019). some performance parameters were adopted for the evaluation. Table 1 presents the analysis of the peeling techniques for easy comparison. The performance of each peeling method was accessed based on technical and energy requirements, peeling efficiencies, flesh losses, throughput capacities and potentials for mechanization/commercialization.

The peeling efficiency was estimated as percentage weight of of fingers after peeling to the weight of fingers before peeling. This is given by equation 1 (Marimo *et al*., 2022):

$$\eta_P = \frac{w_{ap}}{w_{bp}} \times 100 \quad (1)$$

Where η_P is the peeling efficiency (%), w_{ap} is the weight of fingers after peeling (kg) and w_{bp} is the weight of fingers before peeling (kg).

The peel quality was taken as percentage thickness of the finger peeled by a machine to the ideal thickness to be peeled by the machine or the peels removed manually.

Throughput Capacity is the ratio of the peeled mass to the time taken in peeling (kg/hr).it is expressed in equation 2 (Oyedele *et al.,* 2019):

$$\text{TP} = \frac{w_T}{t_p} \quad (2)$$

Where TP is the throughput (kg/hr), w_T is the weight of fingers in kg and t_p is the peeling time in hours.

Specific energy consumption is the energy require to peel a kilogram of fingers and is given by equation 3 (Edeh *et al.*, 2018). Energy efficient system requires minimal specific energy possible to operate.

$$\text{SE} = \frac{\text{E}}{w_T} \quad (3)$$

Where SE is specific energy (J/kg) and E is the energy required for peeling in Joule, J

Flesh loss was estimated as the percentage ratio of the weight of flesh (pulp) removed by the machine to the total flesh weight.

$$fl = \frac{w_{frm}}{w_T - w_p} \times 100 \quad (4)$$

Where *fl* is flesh loss (%). w_{frm} is the weight of flesh removed by machine and w_p is the weight of peels removed manually.

Table 1 Comparative Performance of Peeling Techniques

	Method	Requirements: Technical	Requirements: Energy	Peeling Efficiency	Fless/ pulp Loss	Productivity/ Throughput	Mechanization Potential
1	Manual Peeling	Skill-dependent. Labour-intensive. Physical strain	High man-power	High	Minimal	Low (28.9 kg/hr)	None
2	Thermal Peeling	Heat-dependent. (excessive heat causes cooking) Automation potential	High	High	None	Moderate (scalable)	Limited (high energy demand/ cost)
3	Mechanical peeling	Technically involving. Automation potential	Moderate	Moderate (Improvement capability)	Appreciable	High (700-1000kg /hr)	High

From the technical perspective, it is ideal to achieve 100% peeling efficiency, even when the manual method present high potential, it is bedeviled with a very low productivity. The thermal technique on the other hand as observed earlier, though has good automation and control potentials, its energy requirement is huge making it energy/cost ineffective in addition to poor product quality. The mechanical method though characterized with high flesh loss and mechanical damage but it's potential for improved efficiency and mechanization is very promising. Despite existing research efforts and innovations, a universally adaptable solution is still lacking. Thus, the urgent need to develop an efficient mechanical peeling system, locally manufactured and maintained; and capable of automatically handling fruit fingers of varying sizes, shapes, and weights

3.0 Banana Properties and Engineering Considerations in Equipment Design

The major challenge of peeling lies in the significant variation in fruit size, shape, weight, texture, geometric mean diameter (GMD) and moisture content across different varieties, limiting the efficiency of any mechanical peeling systems. Therefore, to design an effective processing equipment, it is essential to understand the physical, mechanical, and engineering properties of the crop to be processed (Adetan *et al*., 2003; Kumar *et al.,* 2019; Edeh, 2020). Investigating these properties can enhance the performance of the peeling equipment. Alli & Abolarin (2019) in their work argued that the output of any peeling equipment depended largely on the crop physical properties such as variety, stage of maturity (age) and moisture content. Consequently, consideration of these factors guarantees designs that minimize fruit damage, reduce waste, improve processing speed, and enhance product quality. Higher peeling productivity and efficiency have also been linked to banana varieties. Ease of peeling, amount of sap, and finger size/length are variety attributes; Hybrids such as NARITA 21 and NARITA 2 were described as having 'peel hard-to-detach from pulp', 'too much or a lot of sap', 'small fingers after peeling (Marimo *et al*., 2022).

3.1. Physical Properties and Impacts on Equipment Design

The physical properties of bananas, such as size, shape, density, and texture, are fundamental in the design of processing equipment (Shirmohammadi *et al*. 2012). These properties dictate how the fruit interacts with various mechanical components during processing, influencing decisions around the geometry, material selection, and motion design of the equipment. Table 2 presents investigated properties of some selected varieties.

Size and Shape

Bananas vary in size and shape, which significantly affects their handling during processing. For instance, the design of peeling machines, conveyors, and cutting tools needs to accommodate the curved and cylindrical shape of bananas. Systems such as rollers, pneumatic handlers, and specialized gripping mechanisms are developed to handle bananas without crushing or deforming them (Bi *et al*., 2021). Studies highlight that mechanized peelers should be designed to accommodate the varying dimensions of crops to avoid skin or pulp damage. Olukunle & Akinnuli, (2013), posited in their work, that variation in shape and sizes of material to be peeled can pose challenge in mechanizing the peeling process.

Banana Curvature

This is the profile of the banana from the stalk to the apex. Knowledge of the curvature will assist in determine the peeling profile to be made by the peeling tools (Ganguly *et al*.,201)

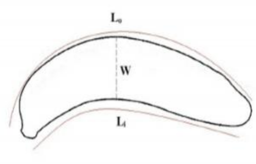

Figure 5 Matooke finger profile

Where:
L_1 is the curvature which the finger makes as it grows, in degree.
L_0 indicates the arc length, in mm.
W_o indicates the width (diameter) of the banana finger, in mm.
The above-mentioned parameters help in designing the cutting tool.

Geometric Mean Diameter

The geometric mean diameter (GMD) is a measure of the central tendency of particle sizes in a population of particles (Mohsenin, 1980; Simonyan & Ehiem,2012). Edeh, (2020) argued that morphological disparities in cassava tuber during evaluation was accounted for by mean value of GMD. Hence good knowledge of GMD across varieties and finger size will help in the design of the flexibility of the peeling tools to accommodate varying sizes of the matooke finger.

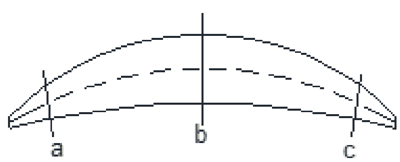

Figure 6 Matooke finger (a) major, (b) intermediate and (c) minor diameters

It is given by equation 5.

$$GMD = \sqrt[3]{(a \times b \times c)} \quad = (a \times b \times c)^{\frac{1}{3}} \tag{5}$$

Where: a = major diameter, mm

b = intermediate diameter

c = minor diameter

Generally,

$$\text{GMD} = \sqrt[n]{a.b.c \ldots dn} \tag{6}$$

where a, b and c are different diameters at different points, n is the number of points on which diameter is taken.

Sphericity

This parameter evaluates the degree of roundness of the fingers and it is determined using the expression given by Koocheki *et al*. (2007) in equation 7.

$$\varphi = \text{GMD}/a \tag{7}$$

where φ denotes sphericity (a dimensionless parameter)

Density and Texture

The density and texture of bananas, especially matooke (which tends to be firmer and less sweet than dessert bananas), also play a role in how the fruit behaves under mechanical pressure. The firmness of the fruit affects its resistance to peeling forces, slicing, or mashing. Understanding these properties helps in designing equipment that applies the appropriate force without damaging the fruit. Banana slicers or mashers need to account for the firm texture of matooke, ensuring that the cutting or mashing tools can handle the toughness without excessive force, which could lead to bruising or squashing (Shewfelt., 1993).

Moisture Content and Durability

The moisture content of bananas influences their shelf life and the way they should be processed. For instance, in peeling operation, the higher the moisture content the easier with which the fingers are peeled (Marimo *et al*., 2022). The moisture content influences the operation of the cutter. Similarly, drying or ripening equipment must consider the water retention capacities of matooke. The moisture content of the fruit also impacts the efficiency of drying equipment, as bananas with higher moisture content require longer drying times, influencing the design of dehydration units. Such designs often include specific air circulation patterns, heat sources, and moisture removal rates tailored to banana properties (Bi *et al*., 2021).

The moisture content of the banana fingers also varies with species and age; and influences the peeling efficiency. It is calculated using the formular in equation 8 (Del Nobile *et al*. 2007).

$$M_C = \frac{m_o - m_d}{m_d} \times 100\ \% \tag{8}$$

Where M_c is the moisture content (%) of the banana fingers, m_o is the initial mass (kg) and m_d is the final mass (kg) of the banana fruit.

Peel Thickness

Peel thickness varies with variety and maturity of crop (Edeh, 2020). It also varies along its length. The banana peel is formed by 3-5 longitudinal planes and the joint of these planes forms a ridge. The thickness of peel is more at these ridges than at other places. Determining and establishing the peel thickness of matooke across species will assist in the design of the depth of cut of the peeling tools

Pulp to Peel Ratio

This influences the peeling rate, and overall quality of the process like peeling efficiency, peel removal, pulp quality, machine performance and others. High dry matter content makes the banana fingers subtle, smooth to touch, easy to peel (Marimo *et al.,* 2022). Pulp to peel ratio is thus given by equation 9:

$$PP_r = \frac{w_{fl}}{w_p} = \quad (9)$$

Where PP_r is pulp to peel ratio, w_{fl} is the weight of flesh/pulp (kg) and w_p is the weight of the peel (kg).

3.2 Mechanical Properties and Equipment Design

The mechanical properties of matooke, such as it's angle of repose, tensile strength, compressive strength, and elasticity, are critical in determining the feeding hopper/discharge spout design and types of forces that can be safely applied during processing. During peeling, undesirable mechanical loads such a compression, impact, shearing and vibration are imposed on products (matooke fingers) resulting in fruits bruising (Kumar *et al.,* 2019).

Angle of Repose

Angle of repose is that angle beyond which material slides down the inclined plane. It is used to determine the angle of inclination for the feeding hopper to ensure that feeding is by gravity which totally eliminates a complicated or energy dependent feeding mechanism. The angle of repose and coefficient of friction of materials on different surfaces were found to be crucial in predicting the movement of materials within processing equipment (Gupta & Das, 1998; Nwankwojike, 2012; Edeh *et al*, 2019). Angle of repose is therefore given by the expression in equation 10.

$$Tan\theta_r = \frac{h}{d} \quad (10)$$

where, h = height of inclined plane, d = fixed horizontal distance of the inclined plane just before the specimen slides. It is also related to coefficient of friction as

$$Tan\theta_r = \mu \quad (11)$$

Tensile and Compressive Strength

Matooke is firmer than dessert bananas (Lee, 2023), and its tensile and compressive strengths are essential in designing machinery for tasks such as peeling and chopping. For peeling equipment, the applied force requires calibration to separate the peel without damaging the underlying flesh (Dowgiallo, 2005, Olutosin *et al.,* 2017). Amarasinghe *et al*., (2021) in their study suggested that the peel of matooke may have varying mechanical strength compared to dessert bananas, leading to modifications in peeling machine design. Similarly, when designing machines for banana slicing or dicing, the machine needs to be capable of withstanding the higher compressive strength of matooke and applying sufficient cutting pressure without causing unnecessary damage. However, there are sketchy data on the mechanical strength of green bananas; requiring detailed investigations.

Elasticity and Deformation

The elasticity of the banana's skin and pulp is another critical factor when designing equipment for tasks like pulping or mashing. If the equipment is too rigid or operates at too high a speed, it may result in over-deformation of the fruit, leading to loss of texture and quality. Equipment that incorporates adjustable pressure systems or soft materials (such as rubber rollers) can help mitigate these issues by accommodating varying degrees of elasticity in the fruit (Kumar *et al*., 2019; Watharkar *et al*., 2021). Additionally, the design of crushing and mashing machines must take into account the elasticity of bananas to ensure that the equipment does not over-compress the fruit, leading to excessive juice loss or mushiness.

3.3 Experimental Investigation of Matooke Properties

After identifying some of the physical and mechanical properties that influence processing equipment development, random experimental investigation was conducted on four local varieties of matooke fruit commonly found in the western part of Uganda. The varieties included *kibuzi, mbwazirime, muziba* and *enyonwonyo* (*mpologoma*). The average finger arc length, average finger mass, density, GMD, sphericity, angle of repose and peel thickness were among the parameters investigated across the varieties. Table 2 summarizes all the results of this investigation.

From Table 2, it was evident that the investigated properties varied across the species. The average finger length ranges from 156 mm to 246 mm with *muziba* species exhibiting the longest finger attribute in addition to having maximum GMD value. Having average fruit finger mass of approximately 0.22 kg and density of 1.38kg/m^3, *mbwazirime* showed the highest density of 1.69 kg/m^3 which suggested a compact pulp of firm texture with less moisture. With sphericity above 0.9 for all the varieties tested, matooke fruit is assumed cylindrical in shape hence any peeling tool to be developed could be modeled to trace a circular profile. It could also be seen that for all the varieties, the angle of repose of the unpeeled fruit finger is always higher than peeled fruit. This implies that the angle of inclination of the feeding hopper is higher than that of the discharge spout. With the range of peel thickness of 4.67 to 5.09 mm, *muziba* species showed thicker peels and this helps to guide in design of depth of cut without excessive flesh loss. It is however, recommended that more detailed and exhaustive investigation be conducted to have a robust data showing the general trends of variation of the properties across varieties, while determining the mechanical strength (stress-strain characteristics) required in processing operation.

Table 2 Properties of Some Matooke Varieties.

Variety	Av. Finger Length (*mm*)	Av. Finger mass (*kg*)	Av. Volume (m^3)	Density (Kg/m^3)	Diameter (*mm*)			GMD (*mm*)	Sphericity φ	Angle of repose (*Deg*)		Peel thickness (*mm*)
					a	b	c			unpeeled	peeled	
Kibuzi	156.38	0.2059	0.1405	1.4655	34.85	37.98	28.50	33.50	0.96	29.58	18.67	4.67
Mbwazirime	239.68	0.2329	0.1371	1.6993	38.73	40.03	35.95	38.16	0.99	33.25	28.87	4.92
Muziba	246.07	0.2170	0.1972	1.1006	45.60	47,55	42.35	45.17	0.99	35.93	26.66	5.09
Mpologoma (Enyonwonyo)	237.78	0.2330	0.1827	1.2753	44.90	45.60	42.25	44.23	0.98	29.00	24.82	4.96

3.4 Technical Specifications

Technical specification to be considered in the development of an efficient peeling machine included:

- Capacity: Improved system productivity (capable of peeling over 200 kg of Matooke per hour).
- Materials: Stainless/galvanized steel for the machine body to ensure strength, durability and hygiene.
- Peeling Mechanism: Design of an appropriate mechanism based on insight from the influence of crop related properties such as a combination of moving blades and friction systems to peel the bananas without damaging the pulp.
- Power consumption: Any effective system should have minimal specific energy consumption to keep the operational cost low.
- Dimensions: To be compact and suitable for small and medium-scale processors

3.5 Economic Implications and Affordable Technologies

There is a pressing need for more affordable and efficient technologies to improve the banana peeling process, particularly for small-scale processors and households that rely heavily on manual labor. A shift towards mechanized or semi-mechanized systems could increase productivity, reduce the physical toll on workers, and decrease waste, which has significant economic implications. By reducing wastage and improving efficiency, small-scale farmers and processors can achieve higher profit margins and contribute to local economies (Akankwasa *et al.,* 2021).

Additionally, reducing the reliance on manual labor can alleviate safety concerns associated with the process, particularly the risk of injury, which disproportionately affects vulnerable groups like women and children (Kumar *et al*., 2019). Given the high demand for matooke in East Africa, addressing these inefficiencies could lead to a more sustainable and profitable banana processing industry, benefiting small-scale farmers and processors.

4.0 Effective Equipment Design

To optimize banana processing equipment development, it is essential that the engineering design integrates the key physical and mechanical properties of bananas. The objective is to create equipment that maximizes processing efficiency while maintaining high product quality. Several critical factors must be considered to achieve this goal, including material selection, structural design, energy efficiency, and ergonomic safety.

4.1 Material Selection

The materials used in the construction of banana processing equipment must be carefully chosen to align with the fruit's inherent physical characteristics. Non-abrasive materials are critical to prevent damage to the banana peel during peeling or handling processes. Stainless steel and food-grade plastics are commonly employed due to their resistance to corrosion and ability to prevent contamination. Given the high moisture content of bananas, materials must also be highly durable to withstand prolonged exposure to moisture, ensuring the longevity of the equipment (Biale *et al*., 2019).

4.2 Ergonomic Design and Worker Safety

In small-scale processing settings, the ergonomic design of the equipment is paramount. Poorly designed machinery can lead to significant physical strain for workers, including back and arm injuries, as well as potential harm from sharp components such as knives or slicers. It is essential to incorporate ergonomic principles into the design process, such as adjustable equipment heights, safety guards, and easy-to-operate mechanisms. By prioritizing ergonomics, the design can minimize worker fatigue and reduce the risk of injuries, thereby enhancing both worker productivity and safety (Ssekiwoko *et al*., 2018).

4.3 Energy Efficiency and Power Consumption

Banana processing equipment should also prioritize energy efficiency, particularly in regions where resources are limited. By understanding the mechanical properties of bananas, engineers can design systems that apply force in a way that minimizes energy consumption while optimizing throughput. Mechanisms such as gears and pulleys should be carefully calibrated to match the banana's resistance, ensuring that energy is used efficiently and operational costs are kept low. The development of energy-efficient equipment will not only enhance the sustainability of banana processing operations but also make such systems more accessible to smaller-scale producers (Guo *et al*., 2020).

Ultimately, for the development of banana processing equipment to be effective, engineers must harmonize material selection, ergonomic design, and energy efficiency considerations with the fruit's physical properties. By doing so, they will create equipment that enhances operational efficiency, reduces costs, and ensures safety, all while maintaining the high quality of the processed bananas

5.0 Conclusions

As the banana processing industry continues to grow, particularly in regions like East Africa, it is imperative to design and optimize appropriate peeling equipment for better efficiency, productivity and sustainability.

While traditional manual peeling methods remain the norm, they are inefficient and prone to safety issues, wastage, and high labor costs. Thermal methods and mechanized peeling systems offered potential solutions, but their limitations, particularly in terms of product quality, accessibility and cost; highlight the need for more affordable and efficient technologies.

This review presented detailed insight on a comprehensive plan for the development of an efficient cost-effective green banana (matooke) peeling system based on good knowledge of the fruit physical and engineering properties that facilitates the selection and design of the suitable concepts. The mechanical concept will significantly improve processing efficiency and reduce labor costs while ensuring high hygiene standards from material selection and elimination of manual interventions. The system will be designed with scalability in mind to accommodate larger production volumes if needed. In confident, upon successful implementation, the system will meet the needs of matooke processors in Uganda and contribute positively to the overall banana processing industry.

Future research and development efforts should focus on low-cost, energy-efficient, and scalable peeling technologies that cater for the needs of small-scale processors. By doing so, the banana industry in East African regions particularly Uganda, could improve productivity, reduce waste, and support the livelihoods of local farmers. Therefore, proper integration of agricultural machinery and agronomy is the key to mechanized development of green banana peeling.

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Declaration of conflict of interest

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