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A REVIEW ON CROP-SLICING RESEARCH

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ABSTRACT

Nigeria is experiencing food insecurity and an alarming rise in food prices because of disturbing postharvest crop losses and other factors. One way to solve the aforementioned problems is the hygienic processing of crops into storable forms, which is in line with United Nations Sustainable Development Goal 2. Crops commonly come in varying forms that may necessitate slicing (a fundamental unit process) before consumption, further processing, or handling. In spite of substantial efforts to develop crop-slicing machines, significant research gaps remain in the field. This study presents the review of crop-slicing research across the globe and untapped research opportunities in the study area as part of the measures to improve the technology up to component standardization level to mitigate food: losses; price hikes; and insecurity. Validated and standardized models as well as experimental setups for designing and evaluating crop-slicing machines are still lacking. Slicing-machine design using established crops' characterizations remains an untapped research opportunity. An automated, flexible, or reconfigurable crop-slicing machine that can slice any crop (regardless of geometry) with the provision to select the desired slice thickness to be cut is necessary. Optimal crop slicer speed, and the relationship between slice thickness, machine throughput, and efficiency, still remain unknown.

Keywords: crop processing; slicing machine; review; food security; postharvest losses.

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1. INTRODUCTION

Crops, particularly fruits, and vegetables, are said to be helpful in combating seasonal health problems and fortifying the immune system against induced stress, diseases, viruses (e.g., COVID-19), and other factors [1], [2]. This claim is bolstered by the discovery of some crops with health-promoting, disease-prevention, curative or therapeutic properties that could allow them to be used as functional foods or nutraceuticals in addition to providing basic nutrition [3], [4], [100], [101]. Because crops are perishable, they are typically processed into durable products to mitigate their distressing postharvest losses [5]–[8], curb gluts, and serve as market diversification means [9]. This ensures that crops, particularly those suitable for use as functional foods or nutraceuticals, are readily available and accessible at a consistent and reasonable price. This has the potential to improve food security and stabilize food prices, both of which have been major challenges in Nigeria [10].

1.1 What is and Why Slicing?

Drying, before storage, is a well-known practice or method of preserving farm produce in order to eliminate or reduce their postharvest losses and ensure year-round availability and accessibility – noting that crops could best be dried when sliced [5], [11]. Slicing, also known as chipping, is the practice of cutting crops or food materials into flat shapes of a specific thickness in order to expose the largest surface area for speedy drying or frying [12]. It is a value-addition operation. After harvest, slicing is a frequent and critical operation in the processing of crops to make them storable, transportable, marketable, and value-added [13]. According to research, crop-slicing improves drying by increasing surface area, which causes fluids to migrate to the cut surface via capillary action [14], [1], [15], as depicted by Equation (1) [16]. Thus, crops must be thinly sliced to allow for efficient heat transfer, moisture migration, and moisture removal [15]. This will also help to mitigate or eliminate the casehardening effect that is usually associated with the drying or frying of crops.

$$M_{RR} = \frac{H_{tc}A_s}{H_L}(T_{db} - T_{wb}) \quad (1)$$

Where: M_{RR} stands for moisture removal rate from crops (kg/s); H_{tc} stands for volumetric heat transfer coefficient (W/m^3 °C); A_s is the crop's surface area (m^2); H_L stands for latent heat of vaporization (J/kg); T_{db} stands for drying air temperature (°C); and T_{wb} stands for temperature of wet bulb (°C) [16].

According to Asonye *et al.* [13] and Olutomilola [10], postharvest sizes of many crops usually necessitate size reduction before usage, consumption, or further handling. Slicing is commonly done to cut raw crops to predefined geometries suitable for further processing [17], [18]. As a result, the sizes and shapes obtained usually require lesser time and energy for drying/frying [19], [13]. Findings showed that the ability of crops to serve as functional foods or nutraceuticals may be affected by postharvest processing such as slicing, among others [4]. Oftentimes, cutting methods as well as size reduction practices are increasingly being named as chief contributing factors to product performance, acceptability, and improved storage [1], [20].

Crop slicers can be manual or motorized, with cutters typically arranged in a particular pattern [21], which can have a significant impact on the product's value. As a result, raw crop-slicing must be reconsidered to advance the unit process technology and align with Goal 2 of the United Nations (UN) Sustainable Development Goals (SDGs), as the world is confronted with a plethora of diseases, viruses, and health-related issues such as COVID-19, diabetes, and so on. However, because Olutomilola [10] reported on plantain slicing, it is not discussed in detail in this study. This study focuses on existing machines for cutting other raw crops into chips or thin slices.

2. STATE-OF-THE-ART OF CROP-SLICING PROCESS

Crop-slicing is primarily done with handheld tools in many parts of the world since antiquity and continues to be done so today, particularly in Nigeria [10]. This slicing method is known to have numerous flaws, which led to the development of mechanical crop slicers [22]–[24]. Despite significant efforts to develop crop-slicing machines, there are still significant research gaps in the field. There are no developed, validated, or standardized models for designing and evaluating crop-slicing machines. It should be noted that crop-slicing machine development in Africa, particularly in Nigeria, has not yet reached component standardization level, allowing for spare parts catalogues [25], [10]. The experimental results required to advance crop slicing process to this level are still missing [12]. This has been a foremost challenge in the postharvest processing of crops and a research gap that needs urgent attention as food security is under serious threat. For ease of maintenance and future design, it is obligatory to take research in this area to the indicated level. It will also be a significant step forward for Nigeria and other African nations to develop globally accepted standard books for the machines developed for slicing their home-grown crops for further handling [10]. Such books can then be used to select components for the machines as they are being designed.

According to research, crop-slicing machines with the ability to measure force and torque while slicing are still lacking. An untapped research opportunity is to design crop slicers using established characterizations of food crop materials and to evaluate their performance using standardized experimental procedures [12]. Establishing a relationship between food or material properties, process parameters, cutting blade design or properties, and cutting or process output quality remains an open research window that needs to be filled [12]. This will actually align with some of the UN SDGs. The previous information provided shows the relevance of this research at this time when there is food insecurity caused by disturbing postharvest crop losses, climate change, the devastating effects of coronavirus infectious disease 2019 (COVID-19), and other factors [2], [26]. This research has the potential to improve slicing techniques, allowing the production of higher-quality by-products from farm produce. The aim of this research was to review crop-slicing research across the globe in order to identify untapped research opportunities as part of the ways to improve the technology up to the level of standardization of the machines involved in order to mitigate food insecurity in Nigeria.

3. METHODOLOGY

To make this study successful, relevant keywords and keyword combinations were used to retrieve research papers from search engines (such as Google and Google Scholar) and scientific databases up to December 2022. The need for this study was also established or accentuated through researchers' works.

4. PAST RESEARCH WORKS ON CROP-SLICING MACHINES

4.1 Slicing of Fruits

Aziz *et* al. [27] developed a machine for slicing pineapple. It is made up of six horizontal bladed discs that are fixed and screw-tightened to the machine (Figure-1). Each of the six discs has a pineapple placed on its blades. The machine has six discs that can cut pineapple fruits that are pressed on the blades by the downward movement of a flat disc actuated by a load cell. The cut fruits are collected in a tray or tank beneath the machine. The machine can process 360 fruits in an hour. However, no information about the machine's efficiency or the thickness of the slices produced was provided.

Figure-1. Pineapple cutting machine [27].

Tavanandi *et al.* [28] developed a machine for cutting lemon, comprising of a rectangular tray-like hopper, cutting knife, power transmission, outlet chute, and frame. The tray, which is slightly tilted and loaded with lemon fruits, has a feeding tubular chute through which the fruits can drop directly into the cutting unit, where they are cut into desired sizes and finally collected in the collection unit for further handling. The machine was reported to have a capacity of 5000 lemons per hour and a power consumption of 0.11 kW. However, the machine's efficiency was not specified.

Wagh and Pardshi [29] developed a manually operated lemon cutter, comprising a feeding hopper, an operating handle, a spring-loaded pressure plate, four cutting blades, an outlet chute, a collecting container, a stand, and a plywood base. Each lemon is manually placed in the hopper. As the cutting blades, attached to a spring-loaded stud and manually operated by a lever handle, are pressed against the lemon, it is cut into four flakes. The flakes are then collected in a container that is located directly beneath the hopper. The machine's average capacity, cutting efficiency, and material loss were calculated to be 45.34 kg/h, 98.96%, and 0.98%, respectively.

Olutomilola's [10] study on plantain size reduction revealed that the handheld tools developed for slicing plantain pulps by Berger [30], Sheffield [31], Kovacs [95], Lo and Huang [32], and others could only be used for domestic processing of food. Their use was also reported to be laborious, time-consuming, unsanitary, hurtful, and associated with high labor costs [33], [23], [34]. The manual plantain-slicing machines reported by Lupoli [35], Obeng [36], Augustin [37], Tawi [38], Oke and Ogundare [39], and Dirisu *et al.* [40] were also known to be time-consuming and limited to domestic and micro-scale food processing.

Some flaws and research gaps were also discovered in the motorized plantain-slicing machines reported by Kachru *et al.* [41], Hiong [42], Friday [43], Sonawane *et al.* [44], Kalaivani *et al.* [45], Okafor and Okafor [46], Ismail *et al.* [47], Obayopo *et al.* [48], Ugwuoke *et al.* [49], Adesina *et al.* [50], Akande and Onifade [51], Onifade [52], Rajesh *et al.* [22], Osueke *et al.* [53], Ayodeji [54], Ipilakyaa *et al.* [55], Usman and Bello [56], Bello *et al.* [20], Bello *et al.* [57], Magpili *et al.* [58], Chilakpu and Ezeagba [59], Oyedele *et al.* [98], Ezugwu *et al.* [60], Wankhede *et al.* [61], and Pawar *et al.* [62]. The machines' application can only be limited to small-scale crop processing. Because they are all manually fed, they may contribute to the spread of diseases, viruses, and other health issues through food. As a result, they are not suitable for use in food processing plants and may jeopardize product quality. They also do not give the operator the option of selecting the thickness of the slices to be cut [10]. Moreover, no relationship was established between slice thickness, machine throughput and efficiency. These are research possibilities worth investigating.

4.2 Slicing of Vegetables

Ogbobe *et al.* [63] developed a manually loaded motorized okra slicer. Loaded okra crops are sliced as they pass through a vertical cutting disc rotated through a belt driven by an electrically powered shaft. The okra slices are then discharged for collection via an inclined chute located beneath a rotary cutting disc. The machine's throughput capacity, as well as slicing efficiency, was reported to be 42.8 kg/h and 95%, respectively, when producing slices of uniform thickness with a 0.13 and 0.14 standard deviation and variance, respectively. However, slice thickness variation was not taken into consideration in the machine.

A manual machine for slicing vegetable was developed by Awili *et al.* [64]. Vegetables are introduced into the slicer via a rectangular hopper and sliced as they pass through a bladed cutting drum rotated by a hand-operated handle. The vegetable slices are then received and gravity-fed into a collector via a chute. As revealed by its evaluation results, rotating speed had a significant effect on slice geometry, and on the slicer's capacity and efficiency. It was concluded that the higher the rotating speed, the greater the machine's slicing capacity and the lower its slicing efficiency.

Kamaldeen and Awagu [5] developed a wooden machine for slicing tomato. The slicer is manually operated and consists of a movable rectangular compartment (equipped with knives), a stationary rectangular slicing compartment, and a supporting frame. Loaded tomatoes in the slicing compartment are cut into 20 mm thick slices as the knife compartment is manually pushed against them. The slicer's throughput capacity and efficiency were given as 32.5 kg/h and 70%, respectively. Kamaldeen *et al.* [65] improved on the machine developed by Kamaldeen and Awagu [5] by changing all of its components from wood to metal and incorporating a rectangular trough beneath the cutting chamber for collecting tomato slices. The operating principle of the former is identical to that of the latter. The machine's slicing efficiency was reported to be 90.10%. However, the slices produced by the two slicers appear to be too thick for drying. As a result, there must be provision in the machine made for varying slice thicknesses to be cut for various purposes or applications.

Shekhawat *et al.* [66] provided a very brief report on a machine developed for slicing and shredding vegetables. It was reported that the machine could be adjusted to slice or shred vegetables at various speeds. It is to be noted that there was no information provided about its capacity, efficiency, and other parameters that are critical to the development as well as to the evaluation of a crop size reducer. Shittu *et al.* [67] developed a motorized tomato slicer in which tomatoes are manually fed through eight vertical feeding cylindrical ports and then fall by gravity toward horizontal blades in the cutting compartment. Tomatoes are cut by the shearing action of the horizontal reciprocating movement of the blades, which are stationed in the slicer's cutting compartment. Tomatoes slices are then conveyed to a collection tray via the sweeping action of the flange beneath the slicing blades. The slicer could also work for plantains because its operating principle is similar to that of a plantain slicer, but it is characterized by low slicing efficiency (60.34%), too thick slices (20 mm) for plantain pulps, and a high percentage of damage or loss (28.40%). Its reported average output capacity is 468.23 kg/h. It should be noted that the slicer can only handle tomatoes with a diameter less than or equal to 60 mm, implying that it cannot handle or accommodate tomatoes or plantain pulps that are bigger than 60 mm in diameter. Hence, the slicer could be improved to eliminate the aforementioned drawbacks.

Nagaratna *et al.* [68] developed a machine for slicing aloe Vera leaves. Its principle of operation is akin to that of the ginger-slicing machine reported by Silva and Jayatissa [69]. Aloe Vera leaves are manually placed and arranged on a horizontal belt conveyor and fed to spring-loaded feed-rollers, which also feed them against an assembly of vertical rotary knives housed in a mesh-like tray. The feed-rollers assist in gathering, griping, and pushing the aloe Vera leaves into the machine's slicing unit. The feed-roller helps the machine accommodate a variety of leaf sizes and geometries. As the sliced leaves fall off the knives, they are collected in a tray beneath the knives (Figure 2). The machine's slicing efficiency and capacity obtained were 90.46% and 648.21 kg/h, respectively. However, the machine's slicing segment should be completely enclosed for the safety of the operator and for hygienic processing to ensure the quality of the output product.

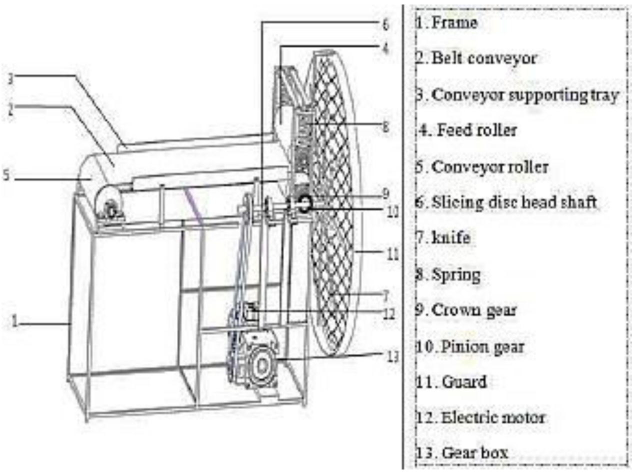

Figure-2. Aloe Vera leaf-slicing machine [69].

Anyanwu *et al.* [70] developed a motorized machine for slicing fluted-pumpkin (*ugu*) leaves. It consists of a belt conveyor system, a slicing unit, a support frame made from metal sheets, a power transmission assembly, two pairs of bearings, and two hollow metallic rods (Figure 5). The slicer's design and working principle are akin to the one reported by Nagaratna *et al.* [68]. The slicing unit houses a set of three vertical cutting blades fastened to an electrically gear driven shaft. When a kilogram of the leave is manually placed on the conveying belt, they are chopped to the desired size in 9 minutes after being introduced into the cutting chamber. The sliced leaves are then discharged through an inclined rectangular chute sited under the slicing unit housing. The machine's efficiency was stated to be 73.2%. Although automation was stated as an objective and identified as necessary, Ganyani and Mushiri's [71] research in this field focused primarily on the design, finite element analysis (FEA), and cost reduction of a vegetable cutting and slicing machine. However, the machine's cutting principle is similar to that reported by Anyanwu *et al.* [70].

4.3 Slicing of Root and Tuber Crops

A motorized machine was developed by Simonyan *et al.* [72] for slicing ginger. Its test results showed that higher moisture content resulted in higher slicing efficiency. At 30% moisture content (db), 76.8% slicing efficiency was obtained, while 64.6% slicing efficiency was obtained at 22% moisture content (db). It was also discovered that damaged material percentage decreased as moisture content increased, as 23.2% material damage was recorded at 30% moisture content (db) and 35.4% material damage was recorded at 22% moisture content (db).

Aniyi [73] developed a ginger slicing machine, which consists of a feed hopper, slicing unit/mechanism, drive mechanism, housing, and frame. Ginger rhizomes are gravity-fed into a rectangular cylinder of the slicing unit via the feed hopper. The ginger rhizomes are sliced as a piston pushes them against fixed cutting blades at one end of the cylinder, directly opposite the piston's travel. The cutting efficiency and percentage of material lost were 77% and 23%, respectively, at a 30% moisture content of the ginger. The cutting efficiency and percentage of material lost were 65% and 35%, respectively, at 22% moisture content. It became clear that the higher the crop's moisture content, the greater the cutting efficiency obtainable. This means that moisture content is in direct proportion with cutting efficiency but inversely proportional to material loss or damaged percentage.

Bolaji *et al.* [74] developed a motorized but manual-fed machine for cutting cassava into chips. It includes a feeding chute, chipping unit, power unit, discharge chute, and supporting frame. A tuber is fed into the chipping unit one at a time via the feeding chute, which houses vertical blades that are rotated by an electric motor-powered shaft. The tuber is cut into chips on reaching the rotary blades. The chips exit the slicer as a result of gravity and vibration via an inclined chute positioned below the blades. The machine's performance was assessed using five different motor speeds (300, 350, 400, 450, and 500 rpm). It was also discovered that the geometry of chips, chipping capacity, and efficiency was significantly influenced by motor speed. As a result, higher speeds will result in higher machine chipping capacity and lower chipping efficiency. The highest capacity (245 kg/h) was obtained at 500 rpm, while the highest chipping efficiency (92.6%) was obtained at 300 rpm. However, the machine's best performance was recorded at 400 rpm, with an 86.5% chipping efficiency and a capacity of 240 kg/h.

Chatthong *et al.* [75] developed a manual-fed motorized machine that cuts ginger into chips and strands (Figure-3). The machine is divided into two sections: chipping and strand cutting. The chipping compartment is composed of two vertical rotary blades that cut ginger into thin chips as they are fed into it horizontally via a rectangular trough located in front of the blades. The chips are released into a collector through a rectangular chute located beneath the blades, which conveys them away on a belt conveyor. The strand-cutting compartment consists of two grooved horizontal rollers. Ginger rhizomes are cut into thin strands or lines as they pass between the two rollers. A container placed below the rollers collects the ginger strands. The slicer could also cut other crops such as carrots, potatoes, etc. The machine's capacities in slicing the ginger into chips and thin strands were given as 81.8 kg/h and 17.9 kg/h, respectively. However, neither the machine's efficiency nor the thickness of the chips and strands was reported.

Figure-3. Ginger chipping/shredding machine [75].

Adejumo *et al*. [76] developed a manually fed motorized machine for cutting cassava into chips, which works in the same way as the machine described by Bolaji *et al*. [74]. Its performance was assessed using knife and groove chipping discs at 300, 350, 400, and 450rpm, with chips of 3-5 mm thick considered well chipped. The knife cutting disc had higher chipping efficiency, whereas the groove had higher throughput capacity. The reported mean chipping efficiency and throughput capacity were 74.91% (±18.86) and 451.35 kg/h (±49.59), respectively. It was also reported that optimum chipping efficiency occurred at speeds ranging from 300 to 400 rpm. At a 5% level, the variance analysis revealed no significant differences in the chipping efficiency with respect to speed except for the cutting disc type.

Ehiem and Obetta [14] developed a motorized slicer for yam that consists of two feeding chutes, a slicing unit, a power transmission assembly, and a frame. A yam tuber is vertically fed by hand into the slicing section via a chute, where it is cut into slices of a thickness of 7 mm as it moves against horizontal blades rotated by a shaft driven by an electrically powered v-belt drive. A channel collects the slices beneath the housing of the blades. The average slicing efficiency, throughput capacity, and percentage of non-uniform slices were given as 52.3%, 315 kg/h, and 47.65%, respectively. Slicing efficiency increased as the yam tuber diameter approached the diameter of the feeding chute. However, the machine's efficiency is found to be too low and the slices appear to be too thick for chips. As a result, there is room for improvement on the machine.

Kartika and Arahanth [77] developed a handheld potato slicer with a handle, a set of five cutting blades, and a housing/frame for the blades. A potato tuber is held in one hand and sliced as it slides over the blades with the slices collected beneath the blades. During testing, the slicer was reported to produce slices with a thickness of 1.2 mm. However, the slicer's throughput capacity and efficiency were not disclosed. Jiang [78], [79] reported the design of a mini-household root vegetable slicer with small volume, high processing efficiency, good uniformity, stability, and safety. According to reports, the slicer consisted of a crop inlet, cutting, product outlet, and elevating system. The slice thickness was said to be from 0.5 to 5 mm. However, the slicer's working principle, capacity, and efficiency were not disclosed. It has, therefore, become evident that giving attention to the slicer's development is needful to assist small and medium-scale farmers in the postharvest handling of their farm produce.

Aji *et al*. [80] developed a motorized cassava slicing machine with an average throughput capacity of 318 kg/h (in terms of chips production) and a 95.6% efficiency. The machine is an assembly of a hopper, vertical chipping disc, cover, discharge chute, power transmission assembly, and frame. Cassava tubers introduced into the machine's hopper move by gravity and vibration towards the chipping disc, which is rotated by an electric motor-powered shaft. As soon as the disc is in contact with the tubers, they are cut into 10 mm thick slices. The slices exit the slicer through the inclined chute attached to the chipping disc cover for collection via gravity and vibration. However, the machine's working principle seems to be the same as that reported by Bolaji *et al*. [74].

Tony *et al*. [81] developed an automated vegetable cutting machine, consisting of a mechanical setup as well as an electrical circuit. The mechanical setup consists of a square hopper, a hopper tube, a 45° angle plate, a square cutting case, and a square cutting grid alongside the supporting frame. The electrical circuit consists of an AC–DC converter, two relay circuits, a microcontroller, an LCD display, and a keypad. The hopper, in conjunction with a sliding bar mechanism, aids in the regulation of vegetable entry into the cutting unit. One end of the bar is connected to a pneumatic cylinder's piston rod plate, while the other end is connected to a 45° angle plate. The cylinder reciprocates along the vertical length of a casing while the cutting grid remains stationary. A square-shaped netlike intermeshed stainless steel blade serves as the cutting grid. The air supply into the cylinder is reportedly controlled by a solenoid-actuated DCV that is controlled by a microcontroller. A pneumatic cylinder and a single bar mechanism control the entry of vegetables into the grid apparatus. The vegetables are fed via an inclined tube. Vegetables are sliced and placed on a tray beneath the machine. The microcontroller performs variable pressure settings for cutting various vegetables. However, no mention was made of the machine's performance, capacity, or efficiency.

Malomo *et al*. [82] evaluated the performance of a motorized cassava grater cum slicer, which consists of a grating unit, a slicing unit, a power transmission unit, and a frame. The slicing unit, which is the nidus of this work, has a similar cutting and operating principle to the machines reported by Bolaji *et al.* [74] and Aji et al. [80]. Moreover, the slicer's chipping efficiency, throughput capacity, and mechanical loss (or percentage of damaged cassava) reportedly ranged from 82.5 to 92.3%, 95.80 to 167.67 kg/h, and 6.00 to 20.00%, respectively, in evaluating two cassava species. However, the mechanical loss recorded ranged from 6 to 20%, which is too high; and no provision was made for varying chip thickness to be cut. Hence, these drawbacks must be addressed.

Oladeji [83] reported a cassava chipping machine, which could be operated manually or with the help of a 3.75kW gasoline engine. Its operating principle and that of the one reported by Aji *et al*. [80] are the same. When manually operated, 36.28 kg/h and 91.83% average working capacity and efficiency were recorded, respectively; while 346 kg/h and 87.09% average working capacity and efficiency were obtained, respectively when operated by the 3.75kW gasoline engine, in producing 2 mm thick chips from the machine.

A motorized machine was developed by Ayodeji *et al*. [84] for peeling and slicing yam tubers in a processing plant. The machine consisted of a loading unit, a peeling chamber, a brush-bearing shaft, an idle roller, and an auger shaft. Yam tubers are peeled as they are conveyed by an auger shaft and pressed by an idle roller against wire brushes attached to the periphery of a rotating horizontal shaft as they are fed into the peeling chamber via the loading unit. The peeling action is triggered by the tubers' rotary motion plus the relative motion of the brush-bearing shaft and the auger shaft. The peels are collected in a chute beneath the machine, while the peeled yam tubers are conveyed to the slicing segment as the brush-bearing and auger shafts rotate, where they are sliced by the reciprocating motion of an inclined mesh-like cutter. The slices are then transported to the next stage of the plant via an inclined chute. The machine's average slicing efficiency, materials lost due to slicing, and throughput were given as 94.62%, 5.38%, and 1.2 kg/s (4320 kg/h), respectively. However, there was no provision for adjusting the thickness of the slices. Food loss of 5.38% due to size reduction alone appears to be significant, which may exacerbate food insecurity in contravention of UN SDG Goal 2.

Awulu *et al*. [85] developed a manual cum motorized cassava slicing machine consisting of a hopper, chipping section, power transmission shaft, handle for manual powering, electric motor, inclined discharge chute, receiving box, and frame. The chipping unit consists of a rotating horizontal shaft, on which equally spaced eleven cutting blades are perpendicularly arranged. The shaft is either powered by a motor or a hand. Cassava tubers, introduced into the chipping unit via feeding hopper, are cut into chips (with a thickness ranging from 10 to 20 mm when motorized and above 20mm manually operated) as the blades impinge on them. The chips are then discharged into a receiving box via an inclined chute by gravity and vibration. The machine's performance was evaluated by varying the diameters of the pulleys to achieve three rotational or operational speeds (300, 350, and 400 rpm). It was discovered that as the operational speed increased from 300 to 400 rpm, the machine's efficiency decreased. It was also reported that the highest efficiencies (86.7% for motorized and 83.12% for manual operations) and the best chip geometries were obtained at 300 rpm with 209 kg/h throughput capacity. However, it is to be noted that there was no control over chip thickness.

Hatwar *et al*. [86] developed a potato slicer. Loaded potato tubers in the hopper travel through a vertical tunnel into a rectangular horizontal channel, where they are pushed by a leverage mechanism towards or against a rotating vertical bladed wheel, which cuts them into slices/chips of uniform thickness of 2 mm. It was reported to have 60 kg/h throughput capacity. However, no provision was made for varying or adjusting the thickness of the chips, and the machine's efficiency was not reported.

Aji *et al*. [87] developed a motorized machine for peeling and slicing cassava tubers, which consists of a frame, an inclined rectangular feeding hopper, a cylindrical peeling unit incorporated with an abrasive peeling drum, a chipping unit, a power transmission unit, and rectangular discharge chutes for peeled and sliced cassava. Cassava tubers are fed manually via the hopper and peeled in the peeling chamber by the abrasive action of the rough surface of the peeling drum and are channeled by gravity via an inclined rectangular chute to the chipping unit where they are sliced into chips of 10 mm thick. The principle by which the machine slices cassava tubers appears to be similar to those reported by Bolaji *et al*. [74] and Aji *et al*. [80]. The machine's capacity, peeling, and chipping efficiencies were 6.72 kg/min, 33.73%, and 76.5%, respectively, at 1150 rpm. The cost of producing the machine was reported to be ₦46,100 ($150). This could be extremely dangerous for the machine's operator. As a result, this shortcoming must be addressed.

Silva and Jayatissa [69] developed a slicer for small-scale postharvest processing of ginger. The slicer has a slicing mechanism with a stainless steel rotary vertical cutting disc and a semi-automated conveyor feeding system (Figure 4). The conveyor feeder consists of a belt and a plate that holds ginger rhizomes while they are being sliced. A chiseled straight blade (made of stainless steel) with one side beveled is attached to the rotating vertical disc. Ginger rhizomes, placed on the conveyor belt at the feeding end and guided by an upper holding plate and conveyor railing, are conveyed at a constant speed towards the disc's bladed side by push-pins attached to the conveyor belt. The ginger rhizomes are sliced as soon as they reach the bladed side of the rotary vertical disc, which is powered by a gear motor via belt drive. The ginger slices are received on the un-bladed side via a slot created beneath the cutting blade. The machine's performance for a ginger variety with a moisture content of 71.26% wb was evaluated using two rotational speeds (400 and 480 rpm). The mean slice thickness, average slicing efficiency, material loss, and throughput were 9.6 mm, 87.9%, 2.8%, and 71.4 kg/h at 400 rpm, respectively, while they were 9.2 mm, 82.5%, 3.2%, and 81.1 kg/h at 480 rpm. It could be argued that the machine is more efficient at slower speeds and vice versa. However, the slices obtained appear to be too thick to allow for a faster drying rate.

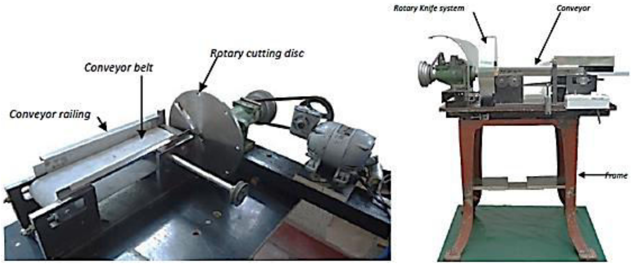

Figure-4. Ginger slicer for small-scale production [69].

Hoque and Saha [15] developed a manually operated potato slicer. It consists of four cylindrical vertical hoppers of varying diameters, two hexagonal hoppers, a handle for transmitting power to cutting blades via a shaft, valve-like grippers (to keep the crop from wobbling), a rotary base disc (to which three blades are attached), and supporting frame assembly. The bladed-disc is powered manually by a handle to which a shaft is bolted. Potatoes are sliced as they move against the cutting blades located beneath the hoppers into which they are loaded as the handle is rotated clockwise. The slicer's slicing efficiency, throughput, capacity, and non-uniform slices were 88.80%, 59.90 kg/h, 42.93 kg/h, and 11.22%, respectively, in cutting potatoes into slices with an average thickness of 3.07 mm.

Aremu *et al.* [88] fabricated and evaluated the performance of a potato slicing machine whose design and operation principles resemble (and appear to be a repeat of) the one reported by Aji *et al.* [80]. However, the machine's average capacity and average functional efficiency were given as 41.2 ± 1.20 kg/h and 63.77 ± 14.73% respectively, with no mention of slice thickness. A motorized machine was developed by Tanimola *et al.* [89] for slicing turmeric. It is composed of a vertical conical hopper, beneath which there is a horizontal cylinder that houses a piston, driven by an electric motor via a connecting rod. Turmeric rhizomes are sliced as the piston's reciprocatory motion pushes them against stationary blades. The sliced rhizomes are then received at the other end of the cutting blades. The machine's performance evaluation resulted in throughput capacity, slicing efficiency, and subpar slice percentage of 34.3 kg/h, 59.8%, and 40.2%, respectively. It was revealed that the amount of lost material, and non-uniform slices increased as the number of rhizomes introduced into the machine increased. This is a challenge needing urgent attention.

Win *et al.* [90, 91] developed a motorized potato-slicing machine with an average capacity and average efficiency of 223.2 kg/h and 83.4%, respectively. Its operating principle is similar to those reported by Bolaji *et al.* [74], Adejumo *et al.* [76], Aji *et al.* [80], [87]), and Anyanwu *et al.* [70]. A motorized machine for slicing yam tubers was also reported by Bello *et al.* (2020). One yam tuber at a time is manually introduced into the slicing via a chute and sliced as it falls vertically against a set of rotating blades. The slices are then directed to a chute beneath the cutting unit, where they are collected. The average throughput capacity, slicing efficiency, and subpar slice percentage were given as 315 kg/h, 52.3%, and 47.65%, respectively. However, the work on root and tuber slicing shows that more research is required to improve crop slicer performance.

4.4 Multi-crop Slicing Machines

In their study, Agbetoye and Balogun [19] developed a motorized multi-crop slicing machine. Crops, manually fed and guided into slicing unit/chamber in an inclined position, are transversely cut into slices of uniform thickness as they are picked and conveyed by an assembly of nine discs (separated by spacers) to an assembly of nine horizontally arranged knives, separated by spacers and joined together by a long bolt and nut. The slices are discharged by gravity and vibration through an inclined outlet chute, located beneath the machine. The machine's efficiency and throughput were investigated in slicing carrot, potato, onion and yam, which were grouped into small, medium and large sizes at 39 rpm, 41 rpm, 43 rpm, 46 rpm and 48 rpm machine speeds respectively. It was reported that 46 rpm favoured only the cutting of large size crops, with 48.9 kg/h and 95.4% throughput and slicing efficiency recorded for carrot respectively. The samples of the selected crops with medium and large sizes reportedly yielded good result for potato at 41 rpm with corresponding throughput capacities of 72.8 kg/h and 88.9 kg/h at slicing efficiencies of 97.9% and 94.8%, respectively. At 41 rpm speed, optimum result was also obtained for small and medium size onions with corresponding throughput capacities of 44.6 kg/h and 71.6 kg/h at efficiencies of 91.7% and 96.4% respectively. Moreover, 135.7 kg/h throughput and 96% slicing efficiency were obtained for yam at 41 rpm. With the exception of carrot, 41 rpm was obtained as the optimum speed at which the machine performed best for all the crops selected. It became clear that the slicer could cut root and tuber crops into slices with thickness ranging from 8 to 9 mm. As novel as the machine is, it is to be noted that there was no provision made in it for varying the thickness of crop slices at will or as desired by its operator. This has to be addressed.

Bello *et al.* [57] researched a motorized small-scale multi-crop chipper, comprising of an in-feed chute, a cutter assembly and its housing, a power transmission assembly, and frame. The slicer appears to work on the same principle as the one described by Chatthong *et al.* [75]. Crops are fed into the slicer manually via an inclined semi-circular chute attached to the top of the cutter assembly housing. The crops are sliced as they move towards a vertical rotary blade attached to a shaft powered by an electric motor via a V-belt drive. The slices are then discharged and collected via an inclined rectangular chute attached to the cutter assembly housing directly beneath the cutting blade. The slicer was evaluated using garden eggs, cassava tubers, and plantain pulps. The machine had the highest slicing efficiency (89.72%) and the lowest slicing efficiency (48.05%) when slicing unripe and ripe plantain pulps, respectively, and the highest throughput capacity when slicing garden eggs. It is obvious that crop type, variety, or ripeness level can all significantly influence the slicing efficiency and throughput capacity of crop-slicing machines. Based on this discovery, databases or catalogues for future design may be created by conducting more research to further establish and validate the assertion.

5. CONSIDERATIONS FOR CROP-SLICING MACHINE DESIGN

According to Olutomilola [10], factors such as hygiene, minimal material loss, ergonomics, fabrication material properties, and so on are commonly taken into account when designing crop-slicing machines. Hygiene is key to the prevention of diseases, viruses, and other pathogens through food. In order for the food produced to be hygienic enough to prevent food-related health problems, the slicer's manufacturing must be meticulously planned and carried out. The slicer must be designed so that material loss is minimal or non-existent during operation. The crop slicer should be simple to use and should not endanger or harm its operator. The slicer's and operator's safety must be carefully taken into account. The crop slicer should be kept as simple as possible by minimizing its components. Throughput capacity, efficiency, damaged/lost material percentage, cutting blade speed, feeding mode/rate, cutting mechanism, power source, and product discharge method are all important factors to consider when designing crop slicers. The materials for fabricating the slicers should be readily available at a reasonable price.

Crop slicer design is heavily influenced by the physical, mechanical, and chemical properties of fabrication materials [92]. Density, luster, geometry, and colour are vital physical properties of the materials selected for fabricating the machine. Material thickness must be carefully chosen in order for the machine to be portable. Strength, toughness, machinability or manufacturability, and hardness or wear resistance, are mechanical properties that ensure that materials perform properly. Chemical properties (such as corrosion resistance etc.) are also essential for ensuring that materials in direct contact with water or crops do not react with them. This will aid in the prevention of material corrosion, which can result in food poisoning [93]. Furthermore, slicer cutting blades should be thin, sharp, and strong enough to shear crops while remaining corrosion-free when in contact with water or the crop. To avoid the problems mentioned above, food-grade stainless steel (SS 304) is typically recommended for the fabrication of food processing machine components that will be in contact with crops or water [93], [23].

5.1 The Main Structure of Crop-Slicing Machines

It is obvious in this study that a crop slicer should primarily consist of the inlet system, cutting system, power transmission system, material outlet system, a housing for all moving parts, and a machine frame or supporting system, with the possibility of additional components serving as accessories [79], [10]. Researchers working in this field should take note.

5.2 Cutting Blade Geometry and Speed

Cutting blade geometry such as blade sharpness, slicing angle, blade edge geometry, contact length, depth of cut, cutting speed, and blade shape were found to have significant effects on the slicing operation's energy consumption and overall efficiency [1], [13]. Cutting blade geometry can also affect product shelf life, quality, and the amount of damage recorded when a crop is sliced [1]. According to research, the cutting blade's sharpness is inversely proportional to the cutting forces, implying that the sharper the blade, the lower the cutting forces [12]. The preceding information demonstrates the impact of blade geometry on crop-slicing. Thus, cutting blade geometry must be carefully considered and monitored for effective slicing operations.

As revealed by this study, three blade types (straight, concave, and convex) are commonly used in the cutting units of crop slicers. Regardless of the speed used, the convex cutting blade is adjudged the best for any crop slicer in terms of throughput capacity, efficiency, material damage, or loss [45], [10]. This assertion is also supported by the claim that the use of curved blades, which permit continuous crop slicing, results in high productivity [94]. This implies that a crop slicer's cutting blade speed and geometry can have a significant impact on its performance and efficiency. It is crystal clear that researchers have not yet determined the optimal speed for the cutting blades of crop-slicing machines [10]. This must be done to allow for the standardization of the cutting speed. This is a research gap that needs to be filled right away.

6. CROP PROPERTIES AFFECTING SLICER DESIGN AND PERFORMANCE

According to reports, a slicer's design and performance are highly dependent on certain physical, mechanical, and other important engineering properties of crops [20], [13], [18]. Average diameter, fibre orientation, average length, texture, average width, shape or geometry, size, crop variety, load requirement to cut, maturity stage, mass, density, weight, moisture content, cutting load per unit width, rolling/frictional resistance, total cutting or breaking energy, shear stress, cutting force, rupture force, strength properties, penetrating force, energy requirement per unit area of the cut, breaking strength, and breaking deformation are examples of these properties [14], [13], [10]. This assertion is supported further by the model presented in Equation (2), which represents the energy required to perform a crop-slicing operation [12]. Equation (2) was created as a result of crop-to-cutting-blade interactions during slicing operations. These interactions determine the cutting forces involved, but they are very complex, and there are currently no validated theoretical models for them [94]. This is a research window that must be filled.

$$E_{ers} = E_{es} + E_{lvf} + E_{friction} + E_{rup} \tag{2}$$

Where: E_{ers} is the energy required for crop-slicing operations; E_{es} is the elastic energy stored; E_{lvf}

refers to energy lost to viscous flow; $E_{friction}$ is the energy due to frictional effects in the slicing operation; and E_{rup} is the energy required to rupture the crop in order to produce slices [12].

As revealed by this study, the following parameters are critical for evaluating the detailed performance of machines designed for slicing raw agricultural produce: throughput capacity (Equation 3); percentage of materials lost during the slicing operation (Equation 4); percentage of damaged or unacceptable slices or chips (Equation 5); and slicing efficiency (Equation 6). The parameters aid in determining the viability or effectiveness of slicing machines.

$$Q_{tc} = \frac{W_{Ic}}{t} \tag{3}$$

$$L_{mlp} = \frac{W_{Ic} - W_{ocs}}{W_{Ic}} \times 100\% \tag{4}$$

$$S_{dsp} = \frac{W_{DS}}{W_{Ic}} \times 100\% \tag{5}$$

$$\eta_{SE} = \frac{W_{ocs} - W_{DS}}{W_{ocs}} \times 100\% \tag{6}$$

Where: Q_{tc} is the throughput capacity (kg/h); L_{mlp} refers to percentage of material lost during slicing operation; S_{dsp} is the percentage of damaged slices; η_{SE} is the slicing efficiency; W_{Ic} is input weight of crop; t is the time taken to slice the crop; W_{ocs} is the total weight of crop slices; and W_{DS} is the weight of damaged slices.

7. EVALUATION RESULTS OF SLICING MACHINES

Findings show that the procedures used to evaluate crop-slicing machine performance are not the same, as evidenced by the use of different cutting blade geometries and speeds. As a result, varying results are often obtained, leaving the industry unsure of which to adopt for use. Addressing this problem will require collaborative efforts. Table-1 a sum-up of researchers' evaluation results shows the lowest and highest values of slicers' performance evaluation parameters as revealed by the recent studies of Shete et al. [96] and Olutomilola [10].

High material losses are clearly one of the most serious issues with the slicers that have been developed thus far. Crop-slicing technology must be improved in order to minimize the volume of materials lost during the process, which can sometimes reach 47.7%. This percentage loss may adversely affect food security/chain, and it will exacerbate the problem of postharvest food losses, especially in Nigeria. This is substantiated by the quantity of damaged or atypical slices recorded or observed during and after the crop-slicing operation, which is sometimes up to 47.65% of the input. This is not cost-effective for the food processing industry. Moreover, the optimum cutting speed is yet to be determined/established for crop-slicing machines developed thus far, as revealed in Table 1.

However, validation of experimental or evaluation results of crop-slicing machines, in order to make them transferable to industry and usable for learning or teaching purposes, is still an untapped research opportunity [12]. These are grounds for redress. Experiment setups for evaluating crop slicers should therefore be developed, validated, and standardized.

Table-1. The lowest and highest values of slicers' evaluation parameters.

S. No	Parameters	Minimum Value	Maximum Value
1	Speed of slicing blade	39 rpm	1150 rpm
2	Slicing efficiency	36.38%	98.96%
3	Throughput capacity	17.9 kg/h	4320 kg/h
4	Percentage of lost materials	0.98%	47.7%
5	Percentage of damaged or nonstandard slices	4.37%	47.65%

8. A GUIDE FOR RESEARCHERS IN THIS STUDY AREA

It must be noted that the materials selected for fabricating crop-slicing machines must not react with water or the crop in order to prevent corrosion, which could result in food poisoning [93]. As a result, stainless steel (SS 304) is typically advised for parts that will come into contact with water or crops [96], [23]. Furthermore, as a guide for researchers, Figure 5 shows a flowchart of the activities involved in developing any crop-slicing machine. As revealed by this study, the following procedures for developing raw plantain size reducers highlighted by Olutomilola [10] could be used in conjunction with Figure 5 to develop crop-slicing machines:

a) Establish the need for the slicing machine and outline the design considerations.
b) Identify the properties of the crops to be sliced that may influence the slicer's design and performance.
c) Study the traditional methods of slicing crops and conduct a thorough literature review of researchers' works on their mechanization in order to identify research gaps.

d) Create the machine's model using suitable computer-aided design (CAD) application software such as SolidWorks, Creo, AutoCAD, and so on.
e) Select appropriate materials for the machine's component parts. Ensure that food-grade materials are selected for components that will be in contact with the crops or water.
f) Design analysis of the machine's component parts should be done using appropriate equations.
g) Simulate and perform finite element analysis (FEA) on the final model developed.
h) Generate the machine's working drawing.
i) Itemize the fabrication procedures or processes for the slicer.
j) Purchase materials for the slicer's fabrication.
k) Fabricate the machine in accordance with the procedures outlined in (9) above, and develop the machine's control system.
l) İncorporate the developed control system into the machine.
m) Test and carry out a comprehensive performance evaluation of the crop-slicing machine.
n) With full understanding of how the machine works, artificial intelligence and bio-sensing technology may also be considered or incorporated at this level.
o) Produce spare parts for the machine to facilitate maintenance.
p) Produce a user manual for the slicing machine.
q) The slicer should be commercialized.

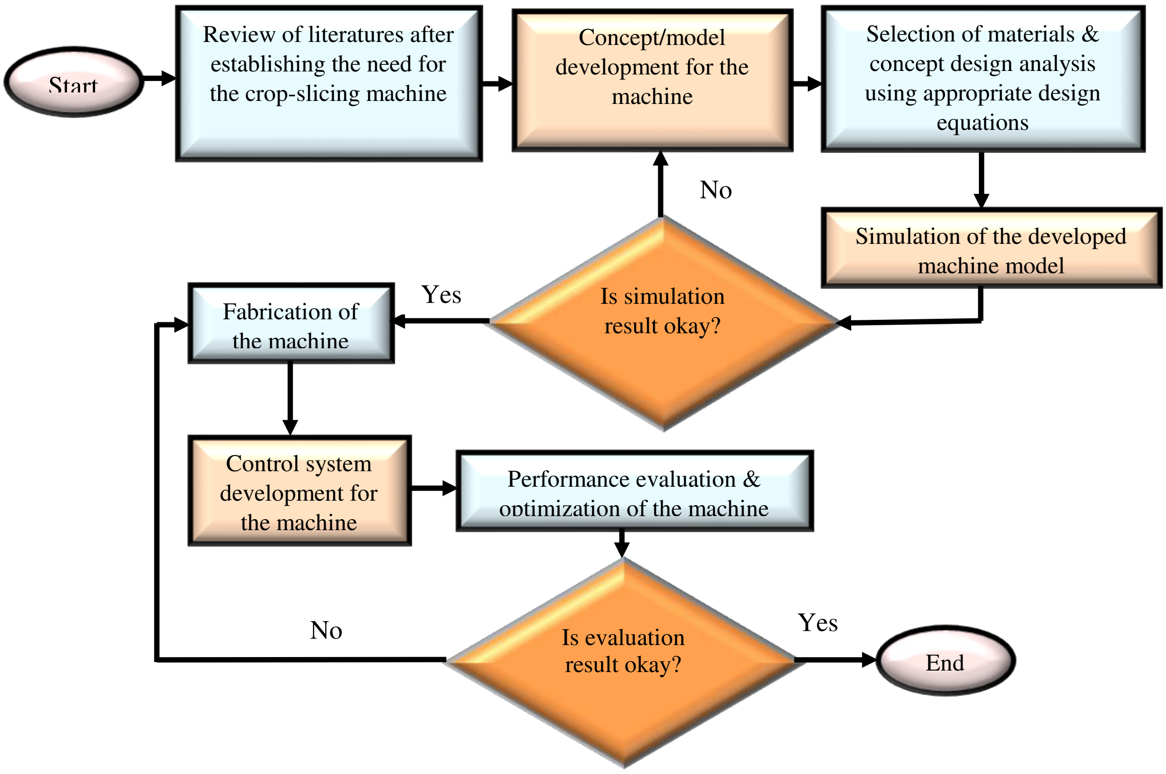

Figure-5. Crop-slicing machine development flowchart.

9. A LOOK INTO THE FUTURE OF CROP-SLICING

Following a discussion of the advancements in crop-slicing technology, the following future research prospects are acknowledged as depicted in Figure 6:

a) The design of crop-slicing machines using established characterizations of food crops, as well as using standardized experimental setups for evaluating their performance remains a research opportunity [12]. Crop-slicing machines must also be designed to be able to measure force and torque in the slicing process. Hence, crop slicer evaluation experimental setups must be developed, validated, and standardized in order to make results to be safe for use.
b) Experimentation is required to develop and validate theoretical models of the complex crop-to-cutting-blade interactions during slicing process [94].
c) Crop's moisture content was reported to be directly proportional to cutting or slicing efficiency, but inversely proportional to the material percentage damaged/lost and force needed to slice them, as typified by Equation (7). Further work are needed to refine and validate this claim for use in crop-slicing machine design. This may also result in the creation of tables or charts from which values for future designs can be selected.

$$M_{mc} \propto \frac{S_{CE}}{C_f, M_{lp}} \qquad (7)$$

Where: M_{mc} is the moisture content; S_{CE} is the slicing or cutting efficiency; C_f is the cutting force; and M_{lp} depicts material percentage lost.

d) It is essential to conduct research to develop, validate, and standardize models for designing and evaluating crop-slicing machines.

e) The reviewed works revealed that the chipping or slicing machine's speed can significantly influence product geometry, chipping/slicing time, throughput capacity, and slicing efficiency [74]. As a result, it is needful to monitor crops' moisture content, and slicing machine speed must be carefully chosen in order to obtain slices with desired or desirable geometries, which can significantly influence their market value. Optimum speeds should be established for the machines and their component parts should also be standardized, as suggested by Olutomilola [10], [2]. Extensive research is thus needed to ascertain the best crop-slicing speeds and crop-slicing energy requirements in order to develop mathematical models, tables, or charts from which values can be selected for the subsequent design of crop-slicing machines [13].

f) Extensive research is required to determine or establish the relationship between slice thickness, machine throughput and efficiency, which may lead to the development and validation of mathematical models, tables, or charts for use in crop-slicing machine design in the future.

g) It has also been discovered that researchers' primary focus has been on developing slicers for a single crop [25]. In view of this fact, more works are needed to develop multi-crop or universal crop-slicing machines, as proposed by Bello *et al.* [97] and Olutomilola [10]. The machine should be designed and equipped to handle crops of varying diameters, sizes, or geometry.

h) Findings also show that researchers in this field did not consider slice thickness variation, because the machines developed thus far have no provision for selecting slice thickness or where an operator could select the thickness of slices to be cut. This must be keenly addressed, while efforts should be directed towards developing crop-slicing machines that can serve in crop processing plants.

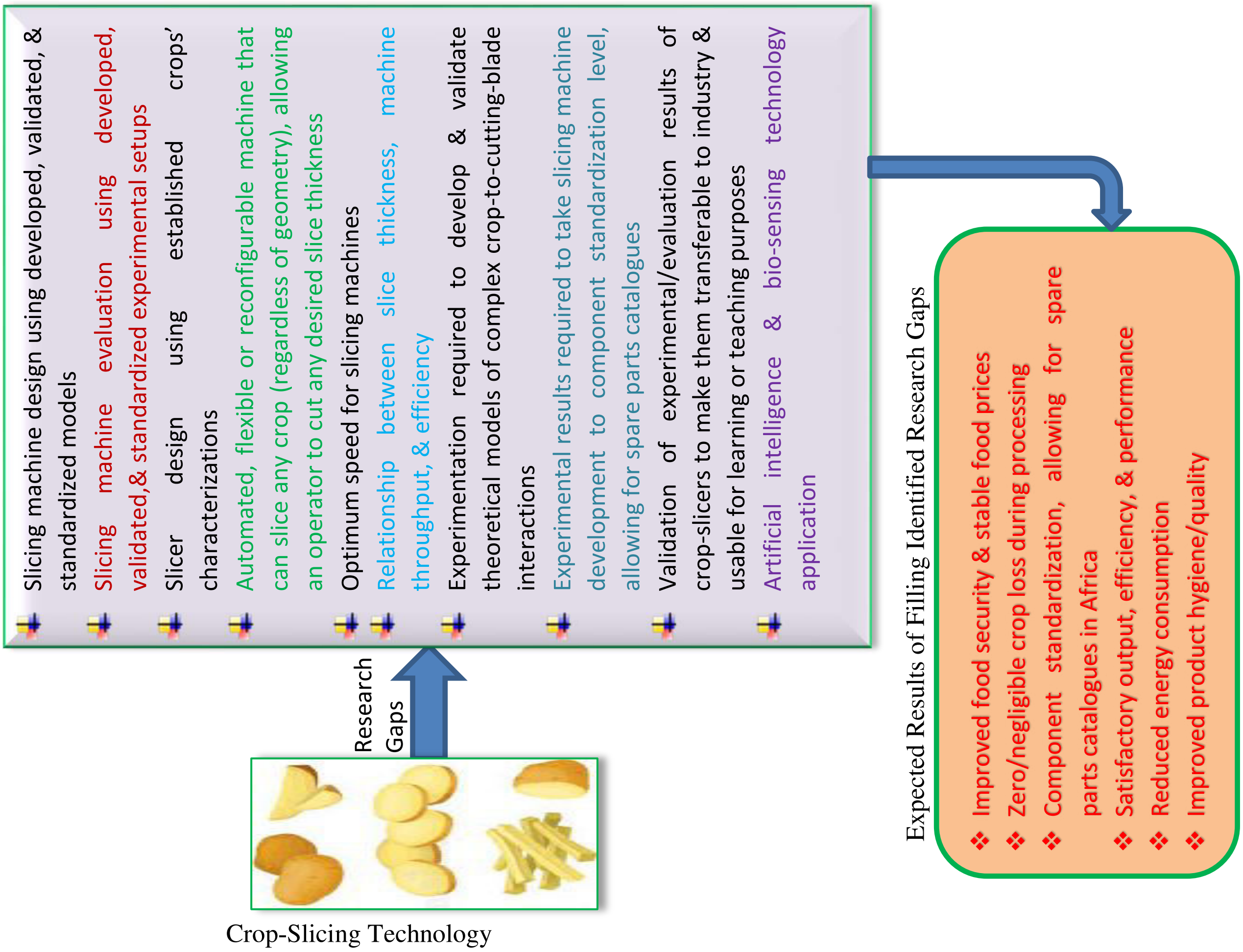

Figure-6. Crop-slicing research gaps and expected results of filling the gaps.

10. CONCLUSIONS

Researchers' findings in this field are deemed too premature to be used for design or further research. More work is thus required to substantiate their findings. Artificial intelligence (AI) and bio-sensing technology (BST) are yet to be considered in crop-slicing operations. This consideration may aid in achieving zero or negligible material loss, as well as satisfactory output, efficiency, or performance. Automation with AI and BST in crop slicers will, among other things, help reduce energy consumption and promote product hygiene [99]. This will also aid in the elimination of damaged or subpar slices, ensuring safe or usable results. Thus, this study will aid researchers in developing improved or smart machines for slicing agricultural produce in Nigeria, which is thought to have the capacity to take care of feeding the entire world [2], [11].

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