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WASHING OF AGRICULTURAL PRODUCE: A REVIEW

Emmanuel Olatunji Olutomilola
Department of Industrial and Production Engineering/Mechanical Engineering Department, Federal University of Technology, Akure, Ondo State, Nigeria
E-Mail: eoolutomilola@futa.edu.ng

ABSTRACT

Washing has now become very crucial to human survival today having become part and parcel of our daily activities due to the outbreak of coronavirus infectious disease 2019 (COVID-19) pandemic in the world. In Nigeria, efforts are geared towards developing indigenous/homebased technologies for processing Nigerian agricultural produce into value-added, easy-to-transport and storable products due to food insecurity occasioned by the ravaging effects of COVID-19, alarming postharvest food losses, climate change and population upsurge. Nigeria is believed to have the capacity to feed the world, if appropriate technologies could be developed and deployed to her agriculture and postharvest handling/processing of farm produce. Thus a review of past researchers' works on washing of farm produce is needful, being a very significant unit operation in food processing. To this effect, research papers and relevant materials were sought, obtained and reviewed from search engines and scientific databases. Hereby presented is a review of published researchers' works; and research gaps on mechanized washing of agricultural produce across the globe, with a view to provide useful/helpful information to Nigerian indigenous technology developers and food processing industries as Nigeria strives to make it a policy to grow what she eats and eat what she grows. A machine, capable of washing leafy and non-leafy farm produce in the production line of a food processing plant, is also proposed/suggested. Through the information contained in it, this research is expected to serve as an impetus for researchers in this study area.

Keywords: COVID-19; food security; farm produce; postharvest processing; crop washing review.

1. INTRODUCTION

It has been researched that farm produce, especially fruits and vegetables, have in them what it takes to fight seasonal health issues/challenges and build our immune systems against diseases, viruses (such as COVID-19), induced stress etc. [1]. A typical example of this is the use of plantain for managing diabetes, which is a risk factor for COVID-19 and one of the two leading causes of morbidity/death in COVID-19 patients [2, 3, 4, 5, 47]. Postharvest handling and processing of farm produce into value-added and storable products is very important to food security in this period of food insecurity occasioned by alarming postharvest food losses, population upsurge, climate change and the ravaging effects of COVID-19 pandemic outbreak in the world.

Postharvest washing of agricultural produce, a vital unit operation in food processing, produces attractive, hygienic and safe food [6, 7]. According to Olutomilola *et al*. [8], hygiene is known to be very crucial to human health and survival. Washing, a way of maintaining hygiene, has now become very crucial to human survival on earth and has become part and parcel of our daily life due to COVID-19 pandemic outbreak. Washing is a very important unit operation in processing of farm produce into value-added and storable products [9]. Washing of farm produce before consumption or before further processing is very crucial to human health/wellness and existence having established that it helps to remove soil, dirt, chemical residues and other impurities, attached to them, which might cause food poisoning, foodborne illnesses and other health hazards [10, 8].

According to Buchholz *et al*. [11], washing helps to reduce or eliminate potentially hazardous microorganisms and their toxins, but it has been reported that washing farm produce in water alone will only reduce microbial populations by 90% to 99%. Maffei *et al*. [7] also stated that the effectiveness of crop washing in removing debris/impurities and reducing microbial load is limited, while reduction of certain microorganisms via washing to a specific safety level cannot be assured. This claim is further accentuated by COVID-19 pandemic outbreak precautionary measures such as washing of hands up to the elbow with soap under running water for twenty (20) seconds and the use of alcohol-based sanitizer. This also confirms that water alone or still water will never be able to thoroughly wash or clean farm produce; the water has to be agitated or set in motion and contain food grade sanitizing substances. It has also been researched that inadequate washing/cleaning of farm produce would adversely affect their quality, shelf lives, market values, and lead to foodborne illness, spoilage and mold growth during storage [12, 8]. Washing of farm produce is adjudged a surface treatment and a value-addition operation which can minimize microbial contamination, ensure food safety and prevent other food hazards [13].

In many parts of the world, especially in Nigeria, washing of farm produce is mostly manual [14]. Manual washing of farm produce is very tedious, laborious, time-consuming, unhygienic and characterized with very low output [6, 8]. By virtue of the time and energy involved in manual washing, it is not suitable for medium and large scale processing of crops [15]. Thus, mechanizing the washing of farm produce is a necessity for ease of operation, improved productivity, improved marketability, availability of healthy food, and maintenance of hygiene, which is very crucial to healthy living [14]. However,

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Grandison [10] stated that: "Increased mechanization in harvesting and postharvest handling of farm produce has led to increased contamination with mineral, plant and animal contaminants, while there has been a general increase in the use of sprays, leading to increased chemical contamination. Microorganisms may be introduced from irrigation water, manure, fertilizer or contamination from feral or domestic animals, or from improperly cleaned equipment, wash waters or cross-contamination from other raw materials."

Moreover, farm produce are usually subjected to physical, chemical, and microbiological stresses during harvesting, postharvest handling or processing [1]. Thus, there is a need to review the mechanized and other techniques of washing agricultural produce as some food-borne illnesses have been reported in association with fresh agricultural produce [7]. Hence, the aim of this study is to review and document published researchers' works on mechanical washing of agricultural produce across the globe, which can be helpful to Nigerian food processing industries, and point out research gaps in the study area. This is to help optimize or improve on washing technology/techniques of farm produce, as a part of mitigating food insecurity and unemployment in Nigeria.

2. METHODOLOGY

Google, Science Direct and Google Scholar search engines were consulted for relevant research articles, review articles and other related materials up to December 2020, using combination of words as follows: "crop washing, washer"; "crop washing machine"; "farm, agricultural produce washing, washer"; "farm, agricultural produce washing machine". This was done to be able to achieve this research's aim. The importance/relevance of this study, farm produce and washing of crops to this COVID-19 season was also established through researchers' works.

3. TECHNIQUES OF WASHING CROPS

Manual and mechanical methods are the two known ways of washing crops. There are principles guiding the washing of farm produce. Washing is adjudged a separation in which certain differences in physical properties of food and contaminants are exploited [10]. Traditionally, there must be relative motion between crop surfaces and the cleaning object or between two crop surfaces in water. The water must be fit for drinking, contain antimicrobial agents or other food grade sanitizing substances to avoid contamination and foodborne health issues. This ensures that the crop is 100% clean and fit for consumption or further processing. Mendenhall *et al*. [16] stated that cleaning effectiveness and timeliness depend on the kinetics involved in cleaning by affirming that cleaning rate depends on the mechanical action used, soil kind, soil moisture and nature of the support between the soil and crop surface. According to Olutomilola *et al.* [8], washing of crops can be done through moving water, water flood, water spray/jets, rotating drum, paddle conveyor washer, belt conveyor, eccentric drum washer, and hand washing methods. It is to be noted that the mechanical action used in each method will determine how efficient the washing will be, while bearing in mind that washing operation must comply with food processing and safety policies. However, in this study, agricultural produce washers reviewed are classified or grouped into five: cabinet with sprayer-type, stirrer-type, roller-brush, rotary barrel/drum-type, and conveyor-type crop washers.

3.1 Cabinet with Sprayer-Type Crop Washer

This washer type makes use of only water jet cleaning action while crops to be washed are manually placed on stationary mesh-tray. The washed crops are manually removed by pulling out the mesh-tray. This washing method is observed to be too limited due to the fact that there is no relative motion among crops as well as between the crops and the containing/confining walls. It is evident that thorough washing of leafy vegetables can never be achieved using this washer type.

However, Mendenhall *et al*. [16] critically evaluated and modified a household dishwasher by incorporating new holding rack and waterjet system into it to produce a cabinet-like machine for washing fruits and vegetables (Figure-1). The crops, placed on tray mesh, are washed as water jets from nozzles impinge on them. Its test results showed that cleaning degree varied with crops' distance from nozzles, location and orientation but was not affected by the type of nozzle and soil on the crops. The study suggested that washing time should be sufficient enough to allow thorough cleaning of crops. Hence, optimum washing time should be established for any crop washer in order to ensure thorough cleaning of farm produce before consumption or subsequent processing. Research should therefore be tailored towards this direction.

Walker *et al*. [17] evaluated a washer for removing California red scale from citrus fruits. The red scale is removed as the fruits are subjected to high-pressure water sprays from the machine. Its efficacy was tested in removing the red scale from the fruits by comparing different pressures and durations of treatment. The washer was found to be effective as it was able to remove the scale from the crop up to 98%.

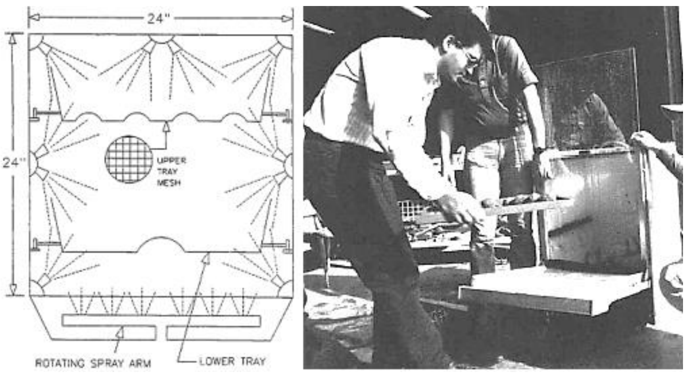

Figure-1. Vegetable washer [16].

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3.2 Stirrer-Type Crop Washer

This type of washer makes use of stirrer, rotor, paddle or any similar tool to agitate the water in which crops to be washed are immersed. Sometimes, washing water and crops being washed are agitated together depending on the nature and properties of the crops. However, care must be taken in employing this later method so as not to damage the crops.

Magar *et al*. [6] and Kenghe *et al*. [18] reported the development and performance evaluation of the prototype of a mechanical stirrer-type washer that is capable of washing fruits as well as some vegetable, root and tuber crops. The washer operates based on the principle of turbulent flow of water created by different rotors within the washer's cleaning unit. Crops, manually placed in removable rectangular boxlike mesh, are washed as they come in contact with the vortex created in the cleaning unit. Water turbulence, which is made available from the sides and bottom of the mesh, effectively washes the crops without any mechanical damage (Figure-2). With 200 mm water depth, the effects of three rotor types (A, B and C) and speeds (1466, 1476 and 1486 rpm) on the washer's capacity and performance index were evaluated using mango, potato and tomato crops. 1486 rpm proved to be the optimum rotor speed for the machine as it gave the highest efficiencies, capacities and performance index for each rotor type in washing mango, potato and tomato. Moreover, rotor C gave the highest capacities and performance index, followed by rotor B while rotor A gave the lowest for each speed in washing potato, tomato and mango. Also, the highest throughput capacity and washing efficiency recorded were 892.11 kg/h and 98.18% respectively, with 3.26 performance index, in washing potato when rotor C and speed 1486 rpm were used. It can be said that the machine's rotor speed is directly proportional to its throughput capacity and performance index, since increased rotor speed led to increased throughput capacity and performance index of the machine. These observations suggest that rotor type and speed can significantly influence the performance of any crop washer that operates with the same principle. The ratio of the costs of washing mango, potato and tomato manually to that of washing the said crops with the machine were reported to be 4.26:1, 5.89:1 and 7.58:1 respectively. The average cost of washing with the machine was found to be Rs.24.80 ($0.34 USD) per ton, while the machine's cost was reported to be Rs.14,650 ($200.33 USD). However, the machine's cost could be further reduced by reviewing its selection of materials. This machine is observed not to be suitable for use in a food processing plant due to much of manual involvement.

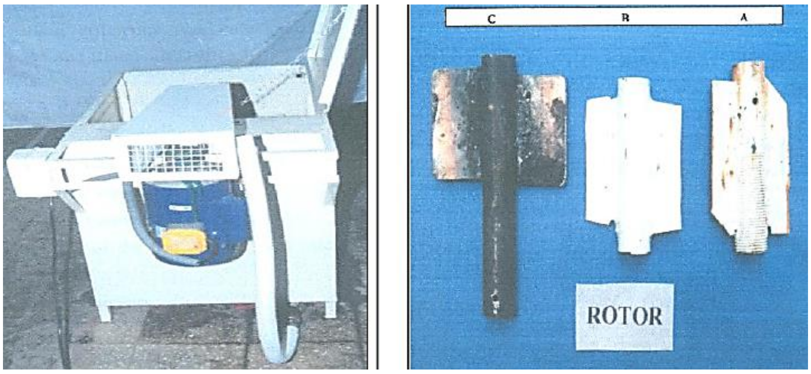

Figure-2. Stirrer type fruit washer [6].

Akinnuli *et al*. [19] reported the design and simulation of a machine for shredding and washing leafy vegetables. Vegetables are manually fed via its feed hopper and aided by gravity into the shredding unit, which also conveys them via a delivery chute into a washing basket (housed by a washing drum in the washing unit). The shredded vegetables are cleaned as the water inside the drum is agitated/stirred by three-dimensional pedals. The basket is then manually removed in order to collect the washed vegetables. The washing principle of the machine seems to be similar to that of the ones reported by Magar *et al*. [6] and Kenghe *et al*. [18]. However, the machine's capacity was reported to be 83 kg/h. In agreement with the claim of Buchholz *et al*. [11] that washing crops with water alone will only reduce microbial populations by 90% to 99%, the researchers recommended that antimicrobial agents (such as chlorine and quaternary ammonium compounds) be added to the washing water so as to prevent contamination and microbial reactions.

Olayanju *et al*. [20] developed a machine that uses ceramic composite as abrasive surface for concurrent peeling and washing of cassava tubers. Performance evaluation showed that the peeling efficiency, performance quality, and throughput capacity increased, while mechanical damage and peel retention decreased as the weight of tubers fed into the machine increased from 3.5 to 15.5 kg. Moreover, peeling efficiency, performance quality, and throughput capacity decreased while mechanical damage and peel retention increased as the weight of tubers fed into the machine decreased from 15.5 to 3.5 kg. It can therefore be inferred that the quantity of tubers fed into the machine can significantly influence its performance at any point in time. It is to be noted that a control and monitoring device could be incorporated into

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the machine to notify the operator of when the tubers have been properly/thoroughly peeled, washed and ready for discharge. This would save energy and time, and boost production capacity. Moreover, optimum speed and load (quantity of tubers to be fed) should be established for the machine and other crop washers.

Okunola *et al*. [21] developed a vertical, motorized machine for dehulling and washing locust bean seed. The machine, with components arranged vertically, consists of dehulling unit, washing unit, used water receiver, frame, an electric motor and a stirring shaft on which fan-like blades are radially arranged (Figure-3). Fed, via feeding chute and as the shaft rotates, the locust beans are dehulled by abrasion, conveyed to the washing unit beneath the dehulling unit and washed as the stirrer in the washing unit stirs the beans solution to dislodge the coats from the seeds by density variation principle. The coats, as they float, are collected by lowering the outer concentrate of the washing unit with hand operated handle. The machine's evaluation, which was based on the seeds' boiling time on an electric cooker, showed that its efficiency increased linearly with respect to increase in boiling time, while the throughput capacity and moisture content decreased with respect to increase in boiling time. The machine's average throughput capacity was reported to be 108 kg/h; dehulling efficiency ranged from 59.7 to 68%; while the cleaning efficiency ranged from 83.4 to 87.4%.

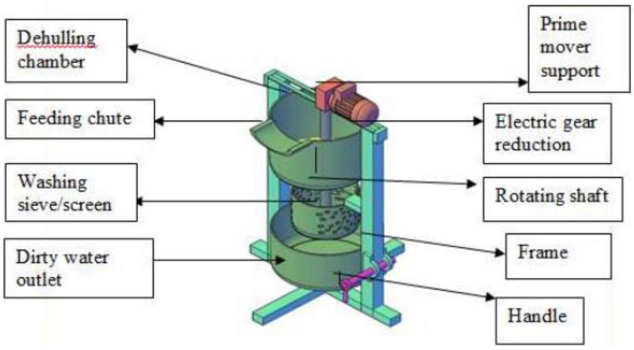

Figure-3. Locust bean seed dehulling/washing machine [21].

3.3 Roller-Brush Crop Washer

A roller-brush washer employs rollers incorporated with brushes to provide scrubbing action for cleaning the surfaces of crops under continuous water supply. Researchers have also documented some developed washers of this type. Choi *et al.* [22] developed a root crop washing machine, which is incorporated with two horizontal and parallel roller-brushes that are manually operated at 6 rpm by crank and rolling in opposite directions. The clearance or space between the two brushes is made adjustable to accommodate different sizes of root crops. Crops are manually fed and are washed as they come in-between the two roller-brushes (which provide scrubbing action) under continuous supply of water jets. It was observed that the washer effectively cleaned the crops' surfaces with no major or visible damage to the crops.

Adegbite *et al*. [14] developed and evaluated the performance of a continuous-type fruit washer. Fruits are manually fed through the feed hopper into the washer's washing chamber onto roller brushes that are partially immersed in water (Figure-4). Fruits are washed as they are conveyed by the roller brushes from the hopper to the discharge chute. The cleaning action is affected by the roller brushes and the brushes located above them. The washer's mean washing efficiency and capacity were reported to be 89.73% and 326.63 kg/h respectively for tomato, as well as 90.16% and 480.57 kg/h respectively for orange. A critical evaluation of the washer shows that it would not be able to wash other crops that are not round or spherical in shape unless it is improved upon.

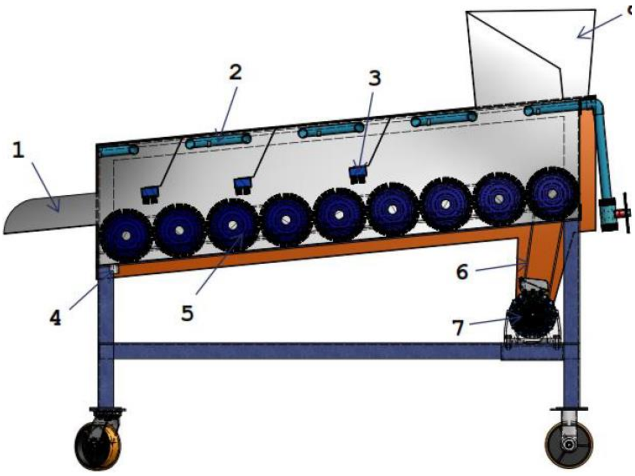

Figure-4. The fruits and vegetables washer [14].

Kumar *et al*. [23] developed a batch type machine (which consists of two hard nylon brush rollers that rotate at 200 rpm in opposite direction) for washing and peeling ginger in the production line of bleached dry ginger. 3 kg of fresh harvested ginger rhizomes were manually fed into the machine at every 12 minute interval while the output was manually collected after each batch of operation. Gingers are washed as they are lifted and tumbled on brush rollers in the presence of water jets. The water jets help to remove soil and other foreign materials from their surfaces, while removing about 59% of the total peels during the process. The throughput capacity, loss of edible material, mean washing and peeling efficiencies of the machine were reported to be 13.86 kg/h, about 2%, 98.57% and 58.97% respectively. In the production line of bleached dry ginger, the machine reportedly saved 42.3% of labour and 46.7% of the time required for manual washing and peeling. The machine is said to be useful for small processing centers, commercial kitchens and restaurants that need to peel about 3.4 kg of ginger per day.

Sahu and Anwar [24] gave a brief report about a machine that was developed at ICAR-Indian Institute of Sugarcane Research (IISR), Lucknow for cleaning and washing sugarcane before crushing while processing it in order to extract its juice for jaggery production. The machine consists of six rollers, which are said to move with different speeds and in different directions for obtaining better rubbing and scrapping actions. Two of the rollers serve as feeders while the remaining four serve as scrappers by incorporating wire brushes on them for removing impurities and other foreign materials from the sugarcane stalks under continuous water supply. However, no information was given about the evaluation of the machine's cleaning and washing performance.

3.4 Rotary Barrel/Drum-Type Crop Washer

This washer type consists of a rotating barrel/drum, inside which crops are washed under continuous supply of high-pressure water spray. Washers of this type can conveniently/successfully serve in the production lines of plants that process farm produce into value-added, easy-to-transport and storable products. Hence, lots of researchers have worked on this washer type.

Moos *et al*. [25] reported the development and performance evaluation of a mechanical carrot washer, which is a non-immersion, horizontal rotary barrel washing system. Considered for the washer's development, in comparison with manual washing, are carrot sizes to be washed, operator's safety, low operating speed (to prevent crop bruise and breakage), low water pressures and flow rates, retention of small pieces, ease of sample loading and unloading, time and cost savings. Supporting the barrel (equipped with a low–pressure spray wand) are roller drive wheels. Its performance evaluation showed water requirement, optimum operating speed and washing time to be approximately 11 to 15 liters, 10 to 12 rpm and 5 to 7 minutes respectively per maximum of 16 kg of carrot.

Sehgal and Arora [26] developed a motorized portable vegetable washer, which consists of a 760 mm long inner rotary drum of diameter 620 mm that is made of 1.5 mm thick stainless steel. Incorporated into the washer, for regulating the drum's rotational speed (up to 60 rpm), is a timer as well as an electronic device. Washing efficiency was reported to be from 90.2 to 95.5% in evaluating the machine's performance using carrot, potato, radish, turnip, ginger, okra, tomato and spinach.

Jayashree and Visvanathan [27] studied the mechanical washing of ginger rhizomes by evaluating the performance of a rotary drum washer at three peripheral speeds (45, 55 and 65 rpm) for three washing periods (5, 10 and 15 minutes), based on bruise index, mechanical washing efficiency, microbial washing efficiency and washed ginger colour. It was reported that microbial washing efficiency of 92%, washing speed of 55 rpm and duration of 5 minutes were considered as the washer's optimum washing conditions. Thus bruise index, mechanical washing efficiency and throughput capacity of 7.5%, 97.8% and 60 kg/h were respectively obtained under the said optimum washing conditions.

Ambrose and Annamalai [13] presented the development and performance trials of a manually loaded and operated rotating drum washer, which has the capacity of washing up to 10 kg of root vegetables at a time. For ease of operation, the washer's development was based on its direct users' anthropometric data. At its center is a hollow shaft with holes for releasing waterjets, which help to wash the crops inside as the washer rotates. The washer's washing and cleaning efficiencies were reported to be 97 and 91% for carrot as well as 96 and 90% for radish respectively. Ghuman *et al.* [28] reported the development and performance evaluation of a root crop washer, which is similar in design and operation to the washers reported by Stark [29], Ambrose and Annamalai [13].

Ugwu and Ozioko [30] developed and evaluated the performance of a motorized cassava peeling cum washing machine, which consists of two chambers: the peeling and washing chamber; and the chamber that encloses the peeling and washing chamber (Figure 5). Cassava tubers are manually fed via hopper into its peeling and washing chamber, which are simultaneously peeled and washed as the chamber rotates. The tubers are washed through the action of pressurized water jets and brushes incorporated into the peeling and washing chamber. Washed cassava tubers are then conveyed out of the machine with the aid of an auger shaft. Three different speeds (380, 420 and 460 rpm) and feed weights (15, 20 and 25 kg) were used to evaluate the performance of the machine. The highest efficiency (72%) was obtained when a speed of 420 rpm was used while the lowest (55%) was obtained when a speed of 380 rpm was used. It was then reported that speed can significantly influence the machine's performance while feed rate or weight cannot as evidenced by the fact that increasing the speed beyond and reducing the speed below 420 rpm will both reduce the machine's efficiency. It is to be noted that time was not considered in evaluating the machine's performance.

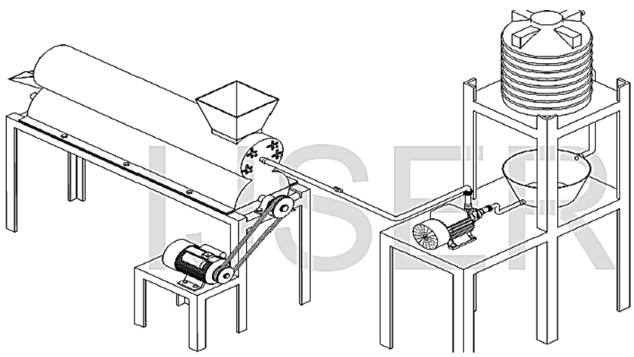

Figure-5. Cassava peeling cum washing machine [30].

Batara *et al*. [31] developed a wooden, small-scale rotary barrel-type potato washer, which is similar in design and operation to the one reported by Emers [32] as shown in Figures 6 and 7. As the drum rotates, potato tubers (manually fed into the washer) are washed as they travel from feeding to exit end, in the presence of continuous supply of water jets. The washer's performance, as affected by loading weight (10, 15 and 20 kg) and drum's rotational speed (9-10, 11-12 and 14-15 rpm), was evaluated. The highest throughput capacity (409.2 kg/h) was recorded at loading weight of 20 kg and rotational speed of 14-15 rpm. The highest cleaning efficiency (93.82%) was obtained at a loading weight of 10 kg and rotational speed of 14-15 rpm; while the lowest skin damage (3.51%) was achieved at 20 kg loading weight and 9-10 rpm speed. Having established that rotational speed and loading weight can significantly influence the washer's performance, speed of 9-10 rpm and loading weight of 20 kg were recommended for its operation in order to minimize skin damage. Hence, researchers' focus should be on establishing optimum trough loading for crop washers.

Figure-6. Barrel washer for cleaning root crops [32].

Figure-7. Potato washer [31].

Ogunlowo *et al*. [15] reported the development and performance evaluation of an automated system for simultaneous cleaning, peeling and washing of cassava tubers (Figure 8), which has the same working principle with the machine reported by Ugwu and Ozioko [30]. The machine's peeling and washing unit, enclosed by a stationary drum and slightly inclined, is a rotary drum into which are incorporated cutting blades that are 10 mm high and 2700 mm long with an auger of 2 mm thick flights. It was reported that the machine, which has 1.2 liters/kg water utilization, uses gravitational and pressurized washing techniques to clean cassava tubers. The machine also has the ability to recycle used water after being filtered. The study recorded 94% peeling efficiency, while nothing was reported about the washing efficiency of the machine.

Figure-8. Cassava cleaning, peeling and washing machine [15].

Siddique *et al*. [33] developed a motorized wooden, rotary drum carrot washer that is similar in every way to the wooden barrel washers reported by Emers [32] and Batara *et al*. [31]. Carrots are manually fed into the washer via an opening created at one of the drum's faces, while washed carrots exit through the other face. Carrots are washed as they rub against brushes (fitted into the drum) and against one another (occasioned by the rotation of the drum) under pressurized water supply; while used water drains-off through the slots created around the drum's circumference. A maximum of 98% and 1398 kg/h cleaning efficiency and throughput capacity were respectively recorded from the washer's performance evaluation. It was also observed that changing parameters like drum slope, length or diameter caused significant difference in the washer's performance as there were variations in its cleaning efficiency and throughput capacity with respect to changes in the aforementioned parameters.

Rashid *et al*. [34] developed a tractor operated carrot washing machine, which consists of an octagonal drum, a center pipe (with drilled holes for spraying water), power transmission unit and mainframe. Its principle of operation is not different from that of the one reported by Siddique *et al*. [33]. However, a throughput capacity and an average washing efficiency of 2750 kg/h and 98% were respectively obtained from its performance evaluation. Also, Ganesh *et al*. [35] reported the fabrication and performance evaluation of a dual-powered root vegetable washing machine that is not different from the one reported by Siddique *et al*. [33]. However, its maximum cleaning efficiency was reported to be 93.11%.

Narender *et al*. [12] evaluated the performance of a root vegetable washer using carrot, which is similar in operation, drive and in every respect to the one reported by Rashid *et al*. [34]. The major component of the washer is a drum that rotates at approximately 25 rpm. The mechanical washing efficiency, microbial washing efficiency and percentage of bruised material reportedly ranged from 72.80 to 78%, 88 to 92% and 5.80 to 8.50%, respectively; while its fuel consumption ranged from 1.8 to 2.2 liters per hour.

Meshram and Ikhar [36] developed the computer aided design (CAD) model of a rotary drum cleaner for washing vegetables, while Meshram *et al*. [37] reported its finite element analysis (FEA). Kanoje and Dhandre [38] presented a brief report on 3-D modeling of a manually operated vegetable and fruit washing machine. No information was given about its operation and evaluation, but its washing capacity, maximum cleaning efficiency and minimum material damage were reported to be 409.2 kg/h, 93.82% and 3.51% respectively.

Kumar and Azad [39] evaluated the performance of a rotary drum root crops washer, which is similar in design, principle and operation to the washers reported by Emers [32], Batara *et al*. [31] and Siddique *et al*. [33]. The feed rate and drum rotational speed were reported to be 400 kg/h and 20 rpm respectively. Its mechanical washing efficiencies were reported to be 80.46%, 78.79%, 76.7%, 74.18% and 63.73% in washing carrot, ginger, taro, shatavari and turmeric respectively. Its microbial washing efficiencies were found to be 79.64%, 76.16%, 70.58%, 66.94% and 59.7% in washing carrot, turmeric, ginger, taro and shatavari respectively. Its bruising percentages were obtained to be 8.41%, 7.82%, 6.93%, 4.12% and 3.6% in washing carrot, turmeric, ginger, shatavari and taro respectively. Moreover, residence times were recorded to be 2.11, 2.09, 1.55, 1.45 and 1.2 minutes in washing ginger, turmeric, carrot, shatavari and taro respectively. The differences observed in the evaluation parameters were attributed to differences in the crops' geometries. However, it was observed that the bruising percentage for each crop could be minimized by reducing the washer's rotational speed and feed rate.

El-Ghobashy *et al*. [40] developed a root crop washing machine that consists of a rotary drum in which crops are washed. The machine's design seems to be a modified and advanced version of the washers reported by Emers [32], Batara *et al*. [31], Siddique *et al*. [33], Kumar and Azad [39], but the principle with which it washes crops is the same as theirs. The core of the washer is a rotating drum provided with housing, feeding hopper, bearing at the center of feeding end, two support-rollers at discharge end and a pressurized water sprinkling system (Figure-9). Three drum speeds (10, 20 and 30 rpm), three batch loads (12, 24, and 36 kg) and four retention times (2, 4, 6 and 8 minutes) were used to evaluate the washer's performance. Proper/optimum mechanical washing efficiency (93.07%), microbial washing efficiency (85.8%), bruising percentage (5.33%), throughput capacity (430 kg/h) and specific energy consumed (3.96×10^{-3} kWh/kg) were obtained when the washer was operated at 20 rpm drum speed, 36 kg batch load and residence time of 4 minutes.

Figure-9. Washing machine for root crops [40].

3.5 Conveyor-Type Crop Washer

This is a continuous flow washing machine which may be general-purpose or specialized in nature/operation. It usually finds application in food processing plants. The conveyor can be belt, roller, chain etc. The use of this washer type is said to be safe, economical, reliable, versatile, practically unlimited in range of capacities and suitable for performing numerous processing functions in connection with its normal purpose of providing continuous flow of materials between operations [8].

Olotu *et al*. [41] developed a petrol engine powered-machine for continuous washing and separation of seeds from the fermented pulps of different crops like melon, locust bean, coffee, cocoa, etc. Its washing chamber is a stationary, horizontal drum that is made of a small cylinder and a perforated big cylinder. Brushes are fixed on spikes that are spirally arranged on a centralized shaft that runs through the cylinders' length for washing and conveying the seeds. The seeds are separated from their pulps, washed, conveyed along the cylinders' length and discharged via outlet chute into a collector as the spiked-shaft rotates, which rubs them against the cylinders' walls and against each other. The pulpy slurry, on the other hand, passes through the perforated holes on the big cylinder to a collector first before the seeds arrive/reach the collector. Average cleaning efficiencies, recovery percentages, output capacities and throughput capacities of 91.8% and 92.1%, 97% and 96.4%, 293.3 kg/h and 232.02 kg/h, 508.89 kg/h and 514.42 kg/h were obtained from the machine's preliminary test using melon and locust bean respectively. However, discharging the pulpy slurry and washed seeds through the same chute will reduce the washer's cleaning efficiency. Hence, a different outlet chute should have been designed/incorporated for discharging the pulpy slurry in order to prevent the seeds from having contact with the slurry after being washed.

The design, fabrication and performance evaluation of a fruit washing machine was reported by Oyeleke *et al*. [9]. Crops are washed as they are conveyed at a controlled speed from its feeding hopper to discharge chute by the action of water jets (at a regulated pressure) from sprinklers, which are strategically positioned to spray water at high pressure on the crops along and across the conveyor. Used water is drained into a tank via net, filtered and recycled for reuse. The machine's washing capacity and efficiency were reported to be 16.3 kg/h and 62.5% respectively in washing oranges, while its production cost was reported to be $300 USD. The

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machine may not be able to thoroughly clean some fruits because it gives no room for relative motion between the crops and the conveyor, and among or within the fruits.

Afolami *et al*. [42] developed a machine for washing yam in a *poundo* yam flour process plant, which consists of water sprinkling system, auger shaft, washing brushes, washing chamber, frame, water pump, water tank, water inlet and outlet channels (Figure 10). As they are conveyed by auger shaft, yam tubers are washed through the action of pressurized water jets and abrasion of brushes that are fitted to the sides of the machine's frame. Washing efficiency and throughput capacity of 77% and 28 kg/h were recorded from the machine's performance evaluation. It is to be noted that the recorded 28 kg/h capacity is too low for a process plant. Hence, an improvement design on the machine is necessary.

Figure-10. Yam washing machine [42].

Olutomilola *et al*. [8] reported the design and finite element analysis of a belt conveyor system for transporting, washing and preheating plantain pulps in a plant that processes plantain into flour. The washer is a modified design of and has the same operation principle with the one reported by Ayodeji [43] for washing raw pulps in a plantain flour process plant. The machine consists of a perforated belt conveyor with incorporated flights, a feeding hopper with opening/closing mechanism, rollers, water-storage/sprinkling system, a heater-blower device, and power transmission system. The machine is said to have the capacity of processing 250 kg of plantain pulps per hour or 2000 kg of plantain pulps per day. Plantain pulps are introduced into the system via a hopper. Turned by cam-like rollers under pressurized water-spray, the plantain pulps are washed and are preheated after washing in order to pre-dry them as they are conveyed by the belt conveyor (Figure-11). However, this machine may not be able to wash other crops because its design was solely based on plantain geometry or physical properties. As evidenced by the reviewed researchers' works, conveyor-type crop washing requires that optimum conveying speed and optimum water jet pressure/flowrate be determined or established for its optimum performance.

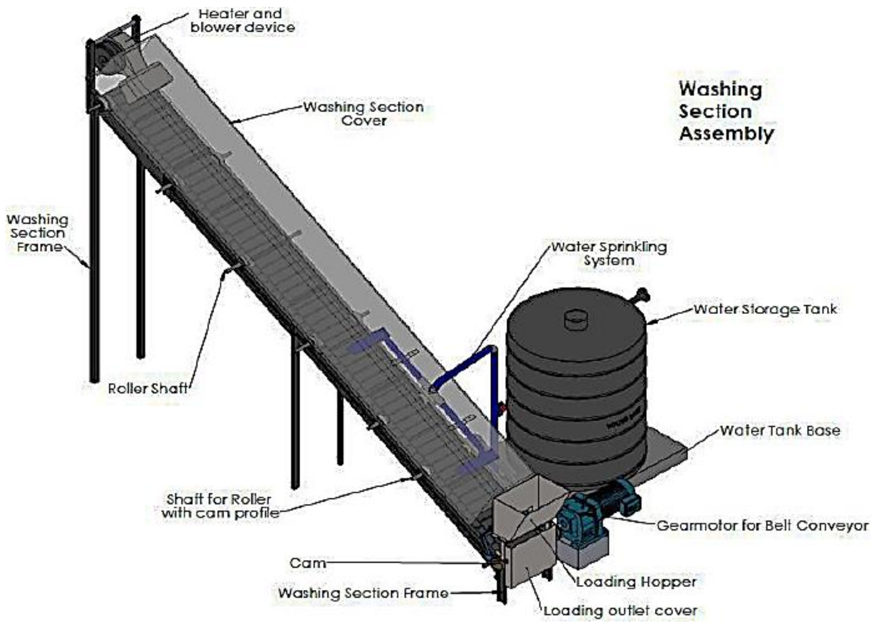

Figure-11. Plantain washing and preheating machine [8].

4. BASIC COMPONENTS OF A CROP WASHING MACHINE

The following are expected to be the basic components of a typical crop washing machine: loading, washing, power transmission, water handling, crop discharge, housing for moving parts and supporting units/segments. Hence, researchers in this area of study should take note.

a) **Loading unit:** This is the segment through which crops are fed into a crop washer.
b) **Washing unit:** This is the segment that houses the washing/cleaning mechanisms, and where washing/cleaning of crops takes place in a crop washer.
c) **Power transmission unit:** This is the unit that supplies the power required to perform the needed washing/cleaning action in a crop washer.

d) Water handling unit: This is the segment that is responsible for the supply of water required to effectively perform the needed washing/cleaning action in a crop washing machine. It is also the one that is responsible for handling used water.

e) Discharge unit: This is the unit through which crops exit a crop washer after completion of washing/cleaning.

f) Housing for moving parts: This is the part that covers all the moving components of a crop washer for the safety of its operator and anyone around during operation.

g) Supporting unit: This, also known as frame, is the part on which other components of the crop washer are mounted. It is the one that supports the weights of other components of the washer and firmly holds them in place.

5. EVALUATION OF CROP WASHERS

It will be helpful for researchers in this study area to note that mechanical washing efficiency (Equation 1), microbial washing efficiency (Equation 2), bruising percentage (Equation 3), retention/residence time, throughput capacity (Equation 4) and performance index (Equation 5) are performance parameters that are very crucial to detail/comprehensive evaluation of agricultural produce washers [18, 39].

$$\text{Mechanical washing efficiency} = \left(\frac{\text{Produce weight before washing} - \text{Produce weight after washing}}{\text{Produce weight before washing}} \times 100\right)\% \quad (1)$$

$$\text{Microbial washing efficiency} = \left(\frac{\text{Initial microbial load} - \text{Final microbial load}}{\text{Initial microbial load}} \times 100\right)\% \quad (2)$$

$$\text{Bruising percentage} = \left(\frac{\text{Weight of bruised produce after washing}}{\text{Total weight of produce after washing}} \times 100\right)\% \quad (3)$$

$$\text{Throughput capacity} = \left(\frac{\text{Total weight of produce washed}}{\text{Total time taken}}\right)\ \text{kg/h} \quad (4)$$

$$\text{Performance index} = \left(\frac{\text{Efficiency} \times \text{Capacity}}{\text{Operation unit cost}}\right) \quad (5)$$

6. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORKS

Having established that rotational speed and loading weight can significantly influence a crop washer's performance, researchers' focus should therefore be on establishing optimum trough loading and speed for crop washers [31]. As revealed by recent studies, crops' geometries can significantly influence the throughput capacity, mechanical washing efficiency, microbial washing efficiency, residence time and bruising percentage of a crop washer [39]. Hence, the geometries and other relevant properties of agricultural produce should always be considered in order to be able to design efficient/effective washers for them.

It has been observed that the time for mechanized washing of farm produce has to be sufficient enough to allow thorough cleaning of the materials. Thus, research should be tailored towards establishing optimum time for mechanized washing of each agricultural produce in order to ensure crops are thoroughly cleaned before consumption or subsequent processing. This should be done in the same way twenty (20) seconds was established for hand washing (up to the elbow) with soap under running water as one of the ways to prevent community transmission of COVID-19. This also confirms that still water will never be able to thoroughly wash or clean farm produce. Hence, the need to review mechanized washing of farm produce. The washers should therefore have timers where the time required for each crop to be washed can be selected. This will ensure availability of safe, quality and healthy food in this era of COVID-19 pandemic and beyond. However, the water/fluid used for washing crops should contain sufficient food-grade sanitizer(s) or disinfectant(s) in response to the critical issues raised by Buchholz *et al*. [11] and Maffei *et al*. [7].

Research focus should also be towards developing flexible/reconfigurable universal washing machines that would be capable of washing any type of crop and can directly be incorporated into plants that process raw agricultural produce into value-added and storable products as suggested by Olutomilola [44], Adeyeri *et al*. [45] and Olutomilola [46]. This will help to eliminate contamination that may come through much of human involvement in food processing as the world battles to get rid of COVID-19. This will also help to rule-out the possibility of food-transmission of viruses (such as COVID-19, Lassa fever, Ebola, etc.), diseases and other pandemic in the future. The washing machines should be designed for continuous flow since it is a major factor in food processing plants. However, the procedures highlighted by Olutomilola [46] for developing size reducers will also be found helpful in developing crop washing machines. Researchers in this study area should therefore take note.

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