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RESEARCH ARTICLE

DEVELOPMENT OF A SMALL SCALE WASHING MACHINE FOR ROOT CROPS

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Abstract

A small scale washing machine with a rotating drum and a continuous pressurized water stream was developed and evaluated for root crops washing at farm after harvesting process. The performance of the developed washing machine was evaluated in potato tubers washing under three different drum speeds of 10, 20 and 30 rpm, three different batch loads of 12, 24 and 36 kg and four different retention times of 2, 4 ,6 and 8 min. Results revealed that the proper washing performance in terms of washing efficiency (93.07%), bruising percentage (5.33 %) and microbial washing efficiency (85.8 %) was achieved when the machine was operated at 20 rpm rotor drum speed, 36 kg batch load and 4 min retention time. At such proper operating parameters, the machine productivity was 0.43 Mg/h and the consumed specific energy was 3.96 kWh/Mg. To promote the developed washing prototype in small farms implementations, the potato washer production cost was estimated by 6.25 USD/Mg (100 EGP/Mg), which was less about 2.8 times than that of the manual washing process of 17.37 USD / Mg (278 EGP / Mg).

Introduction:-

Root crops like potato, carrot, radish, beet, sweet potatoes and other similar produces need to be cleaned immediately before transferring to the market. In addition, the harvested root crops should be cleaned before weighing and grading as harvesting process leaves soil and foreign materials stick to the harvested root crops. Washing of root vegetables is a vital step in most post-harvest processing operations, which enhances their attractiveness and improve their marketing value. Despite its substantial importance, the washing process of harvested root crops in all small farms is usually carried out manually which is very tedious, time consuming and expensive process (Meshram and Ikhar, 2018). For instance, potato tubers manual washing usually takes from 0.5 kg/min to 0.7 kg/min or 33 minutes for a person to wash a 20-kg bag of potato (Batara et al., 2015).

The performance of the washing process depends basically on the quality of the used water in the washing process because the water might be a source of microbial contamination (Siddique et al., 2017). Thus, Moreover, the washing efficiency of root crops can be determined using water turbidity measuring device (AI-Katary et al. 2010). Turbidity is defined by the International Standards Organization (ISO) as the reduction of transparency of a liquid caused by the presence of a dissolved matter. It is measured using the techniques of turbidimetry or nephelometry and is expressed (Nephelometric Turbidity Units). The direct relationship between turbidity data and suspended solids concentration depends on many factors including particle size distribution, particle shape and surface

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condition, refractive index of the scattering particles and the suspension medium (Lawler, 1995). Therefore, potable water with a turbidity of ≤5 NTU (Davis et al., 2002) can be used for the washing process. The turbidity of drinking water should not be more than 5 NTU (Nephelometric Turbidity Units), and should ideally be below 1 NTU (World Health Organization, 2004). Besides removing all debris, soil and crop residues from the surface of the harvested root crops, the washing process generally reduces the microbial load by 100-1000 fold. This prevents pathogens from being transferred from the rind or skin to the inner part of the harvested fruits or vegetables (Laanen and Scott, 2004).

The performance of the washing could be evaluated based on the mechanism used in the washing process. In general, the performance of the crop washer could be estimated in terms of mechanical washing efficiency, microbial efficiency and bruising percentage. The speed of the rotating parts of the washer has a significant influence on such performance. For instance, the results of the study conducted by (Narender et al. 2018) in carrot crop washer showed that the mechanical washing efficiency, microbial efficiency and bruising percentage were varied from 72.80 to 78%, 88 to 92% and 5.80 to 8.50%, respectively at 25 rpm of the rotor drum speed. In evaluating the overall productivity of the washing machine, it is also very critical to consider the fuel consumption as well because it affect the suitability of adopting this process directly on the farm after harvesting and whether it will augment the profit of the producers or not. Therefore, to achieve an efficient wash to be 98 % and washing productivity of 2.75 Mg/h for carrot washer with lowest fuel consumption, the suitable rotational speed of the washing drum should be between 20 to 21 rpm at 1500 rpm speed of tractor (Rashed et al., 2018). The washing process could be accompanied with some other post-harvest operations such as peeling. For instance, a batch type ginger washing-cum-peeling machine was developed and tested in the bleached dry ginger production line. This machine has two hard nylon brush rollers that rotated at 200 rpm in opposite direction to peel the rhizomes surfaces. The pressurized water aids in peeling and washing process to remove the soil from the rhizomes surface and about 59% of the total peels. The machine productivity was 13.86 kg/h with about 2 % loss of edible material. The developed machine can be used in small production units (Kumar et al., 2019).

Owing to all previous problems associated with manual washing operations for root crops, introducing affordable washers are extremely important for the small farms to obviate cost constraints. Therefore, the present study aims to develop a small scale, movable and affordable washer prototype for root crops suitable not only for small farms but also can be used in small and medium processing units. The study involved evaluating some engineering parameters that affect the performance, efficiency and cost of the developed prototype.

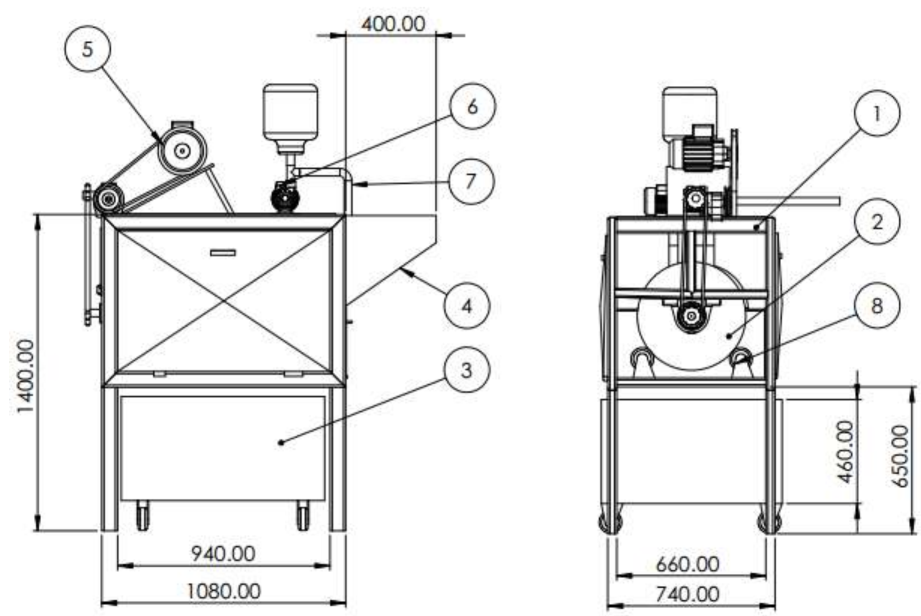
Materials and Methods:-

Configuration of the washer prototype:

In the present study, a small scale mechanical washer prototype was developed and evaluated for washing the potato tubers (Spunta variety) at the Agricultural Engineering Research Institute (AEnRI), Dokki-Giza, Egypt in 2019. The potato washer prototype consists mainly of six parts: the main frame, hopper, rotary washing drum, water supply system, water drainage basin and power transmission as shown in (Figs. 1, 2 and 3). The main frame was made of hollow square stainless steel rods of 2 mm in thickness with a cross section of 40×70 mm). The frame dimensions were1400×740×1080 mm for height, width and length, respectively. The main frame was directly connected with a large hopper to accommodate the potato feeding. The hopper was constructed from stainless steel sheets of 1.5 mm in thickness and fabricated in a rectangular shaped cross section at the top of 400×700 mm and a trapezoidal at the bottom. According to (Gamea et al., 2009), the potato repose angle was 35^{o}, so that the hopper base inclination angle on horizontal level was designed at 35^{o}. This facilitates the free flow by gravity of the fed potato from the hopper to the washing drum.

As the washing process depends fundamentally on the friction and rubbing between potato surfaces and the inner surface of a rotating drum in the presence of pressurized water stream, the core of the potato washer prototype is the rotating washing drum and pressurized water supplying system. The rotating washing drum has a dimension of 480 mm for diameter and 1000 mm for length. The drum is rotating around a horizontal axis supported on one ball bearing (30 mm ID) from the closed drum side, but the other opened drum side was loaded in two wheels. The drum inner surface circumference was covered with a square perforated plastic guard (100×100 mm). The plastic guard was rested above of 24 wooden slats on internal surface of the circular frame. Between each two wooden slats, a blank space (250 mm) was left to allow waste discharge using pressurized water from drum to the drainage basin. For potato unloading after washing operation, the outlet opening was installed below the hopper. In general, water is pressed from a centrifugal water pump of 0.75 kW at 400 kPa maximum pressure (2.5 m^3 / h flow rate) to a galvanized iron pipe (12.7 mm diameter) inside the washer drum. This pipe has 10 nozzles with 100 mm spacing between each two nozzles; the hole of each nozzle is 3 mm diameter. The waste water was discharged from the drum to collecting basin (900 × 800 × 460) made of galvanized steel sheet of 1.5 mm in thickness. The basin base was provided with a hole of 25 mm in diameter attached with on/off valve for waste water effluent. The washer drum is driven by a 1.5 kW, single phase electric motor connected to gear box to reduce the speed from 1450 to 29 rpm (50:1). To adjust the drum speed levels to obtain 10, 20 and 30 rpm (0.25, 0.5 and 0.75 m/s), the motor power was transmitted to the gear box using different changeable sizes of pulleys and V-shaped belts. To prevent the slippage, two sprockets and chain were used to transmit the available power from the gear box to the rotor drum axis.

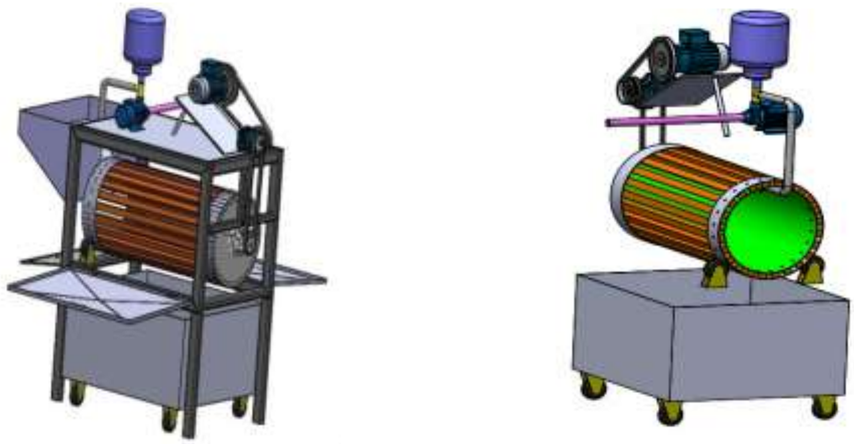
Fig. 1:- General view of potato washer.



Elevation Rear side view

1:Main frame	4- Potato hopper	7- Iron pipe
2: Washing drum	5- Power transmission	8- Two wheels
3: Water drainage basin	6- Water supply system	

Fig. 2: Schematic diagram of the potato washer prototype.



Side view Rotor drum connected with water supply unit.

Fig. 3:- Isometric views of the internal configuration of the washer prototype.

Performance evaluation of the washer prototype:

The performance of the developed washing machine was evaluated under three different speed levels of the rotating drum of 10, 20 and 30 rpm (0.25, 0.5 and 0.75 m/s), three different batch loads of 12, 24 and 36 kg and four retention times of potato inside the drum of 2, 4 ,6 and 8 min. Three replicates were performed for each trial using a sample of ten potatoes for each replicate making a total of 30 potatoes. The potatoes were perforated with a pin and different color dyes were poured on each sample and the marked potato sample was fed in the hopper with other potato samples. The washer performance was evaluated in terms of the washer productivity, mechanical washing efficiency, bruising percentage, microbial efficiency and the consumed specific energy. The washer productivity (Pr, Mg/h), was defined as the potato batch load (L = 12, 24 and 36 kg) divided by the total washing time (T) [loading time (T_l = 0.5 min) + washing retention time (T_r = 2, 4, 6 and 8 min) + unloading time (T_u = 0.5 min)]. One minute was allowed for loading and unloading time and the productivity was calculated according to (El-Ghobashy, 2012) using the following equation:

$$\mathrm{Pr} = \frac{\mathrm{L}}{(\mathrm{T_l} + \mathrm{T_r} + \mathrm{T_u})} \times \frac{60}{1000} \qquad (1)$$

The mechanical washing efficiency (E_w, %), was using turbidity measuring device. Potato washing efficiency, was defined as turbidity value in water sample that washed by the machine (Tr_m, NTU) comparing with turbidity value in water sample that washed by hand (Tr_h, NTU). Each measured water sample was attributed to 1 liter pure water per 1 kg potato (AI-Katary et al., 2010) using the following formula:

$$\mathrm{E_w} = \frac{\mathrm{Tr_m}}{\mathrm{Tr_h}} \times 100 \qquad (2)$$

The microbial washing efficiency (E_m, %), was estimated using the surface microbial load in terms of total plate count (colony forming units, cfu) before and after washing of potato samples by serial dilution technique (Ranganna, 1986) and calculated as follows (Arora et al., 2007):

$$\mathrm{E_m} = \frac{\text{Initial microbial load} - \text{Final microbial load}}{\text{Initial microbial load}} \times 100 \qquad (3)$$

Mechanical bruising percentage (Br, %), the bruised potatoes (skin comes cut) that results from the washing machine in each batch was calculated as follow (Narender et al., 2018):

$$\mathrm{Br} = \frac{\text{Mass of bruised potato after washing}}{\text{Total Mass of potato after washing}} \times 100 \qquad (4)$$

The power requirement (kW) for potato washer was estimated using the clamp meter to measure the values of electric current intensity (I) and the difference of electrical potential (V). The total electric power requirement (P, kW) for the washing machine included both the power of washer with electric motor and the power of water pump. The total power required for the machine was estimated from the following equation (Chancellor, 1981):

$$\mathrm{P} = (\mathrm{I} \times \mathrm{V} \times \cos\theta) / 1000 \qquad (5)$$

Where:
P: Total power requirement for the potato washer, kW.
I: Electric current intensity, Amperes.
V: The difference of electrical potential, Voltage.
Cos θ: Power factor, equals 0.85.

The consumed specific energy (CSE) in kWh / Mg was computed according the following equation:

$$CSE = Power\ (P)\ /\ productivity\ (Pr) \quad (6)$$

Cost estimation of the washer prototype:
The cost per operation hour for mechanical washing process that included the fixed, variable and total costs was estimated as following (Suliman, 2007):

$$Fixed\ cost\ (EGP\ /\ h) = D + I + Si\ (0.045\ Pm)\ /\ hours\ of\ use\ per\ year \quad (7)$$
$$Variable\ costs\ (EGP/\ h) = Rm + E + Wc + La \quad (8)$$

where:
D: Depreciation costs, EGP/ year [$D = Pm - Sa / Lm$],
Pm: constructed cost = 18000 EGP (1125 USD),
Sa: Salvage rate when the machine is full 7 years = 0.1 Pm,
Lm: washing machine life= 7 years,
I: Interest costs, EGP / year [$I = (Pm + Sa / 2) \times in$],
in: Interest rate = 10 %,
Si: Shelter, taxes and insurance costs, EGP/ year = 0.045 Pm,
Yearly operation = 1500 hours / year.
Rm: Repair and maintenance costs, EGP / h (Rm=100 % of D),
E: Energy costs, EGP/ h [E=Total electric power requirement, (1.71 kW) × Electricity price, (0.65 EGP / kWh)],
Wc: Water costs EGP/ h [Wc= Total consumed water, ($2.5 m^3/h$) × water price ($6.5\ EGP/m^3$)] and
La: Labor costs, EGP / h [La = Salary of one labor, (7 EGP / h) × No. of labors (2)].

Total costs (EGP/ h) = Fixed costs (EGP/ h) + Variable costs,(EGP/ h) (9)
Total costs include profit (EGP/ h) = Total costs (EGP/ h) × Profit (1.20 %) (10)
Production total cost (EGP/ Mg) = Total costs include profit (EGP/ h) ÷ Productivity (Mg/ h) (11)

On the other hand, the costs of labors and water consumption in manual washing were calculated according to (Thapt, 2005) and (Batara et al,.2015) as follow:
Labor cost =35 (Labor / Mg) × 1 (h) × 7 (EGP / h) = 245 (EGP /Mg). (12)
Water cost =5 (m^3 / Mg) × 6.5 (EGP / m^3)= 32.5 (EGP /Mg). (13)
Total Costs of manual washing = 245+ 32.5=277.5 EGP /Mg. (14)

Results and Discussion:-

Washing machine productivity:
Fig. 4 shows that the washer productivity increased with increasing the batch load from 12 to 36 kg, but it continuously decreased with increasing the retention time from 2 to 8 min. The highest machine productivity of 0.72 Mg/h was obtained when the machine was loaded with 36 kg batch load and 2 min retention time. On the other hand, the lowest washer productivity of 0.08 Mg/h was recorded at 12 kg batch load and longer retention time of 8 min. In general, as confirmed from the previous results, the high washer productivity is usually associated with high batch load but low retention time.

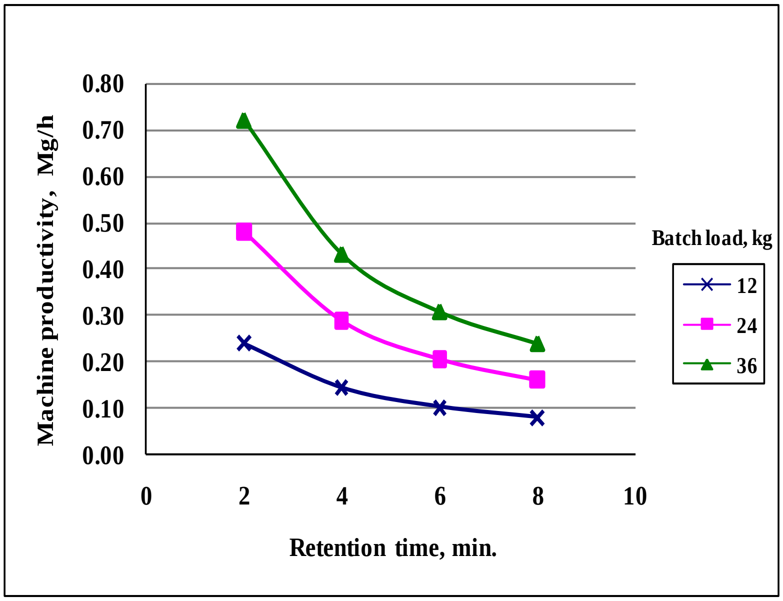


Fig. 4: Machine productivity as affected by retention time and batch load.

Mechanical washing efficiency:

Fig. 5 revealed that increasing batch load from 12 to 36 kg and retention time from 2 to 8 min increased the washing efficiency from 40.08 to 74.86, from 49.86 to 94.70 and from 59.24 to 97.55 % at 10, 20 and 30 rpm of rotor drum speeds, respectively. It is clear that increasing the retention time from 2 to 6 min has more effect on the washing efficiency compared with the little increase in retention time from 6 to 8 min.

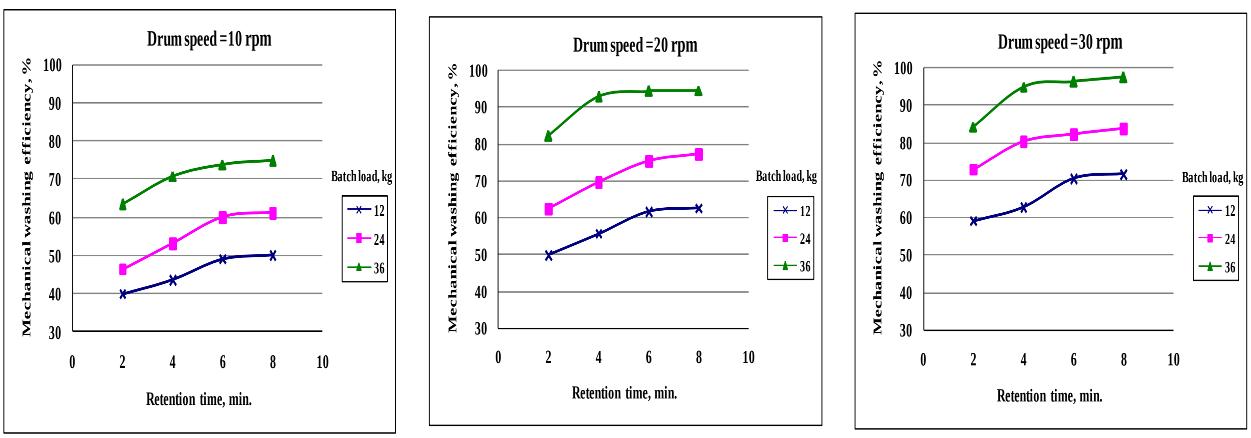


Figure 5:- Mechanical washing efficiency as affected by retention time, batch load and rotor drum speed.

Bruising percentage:

Figs. 6 and 7 revealed that the bruising percentage increased by increasing the rotor drum speed from 10 to 30 rpm. On the other hand it decreased with increasing the batch load from 12 to 36 kg at the retention time from 2 to 8 min. The highest value of bruising percentage of 13.92 was observed at 12 kg batch load, 30 rpm rotor drum speed and 8 min retention time. While the lowest value of 4.50 % was recorded at 36 kg batch load, 10 rpm rotor drum speed and 2 min retention time. When potatoes stay longer time inside the washer prototype, they will be liable to mechanical damage and bruising. Longer retention time and higher rotor drum speed usually result in more rubbing actions and more contact rate of potato between its surfaces and between potato surfaces with the inner rotating drum surface. The obtained results are in accordance with that obtained by (Narender et al. 2018). In contrary, the increase in the batch load to 36 kg resulted in lower bruising percentage but higher washing efficiency. This may be attributed to softer impacts among potatoes at the higher batch load instead of hard impacts resulting from the rotating drum that usually led to aggressive hits to the potatoes resulting in severe bruising at lower batch load.

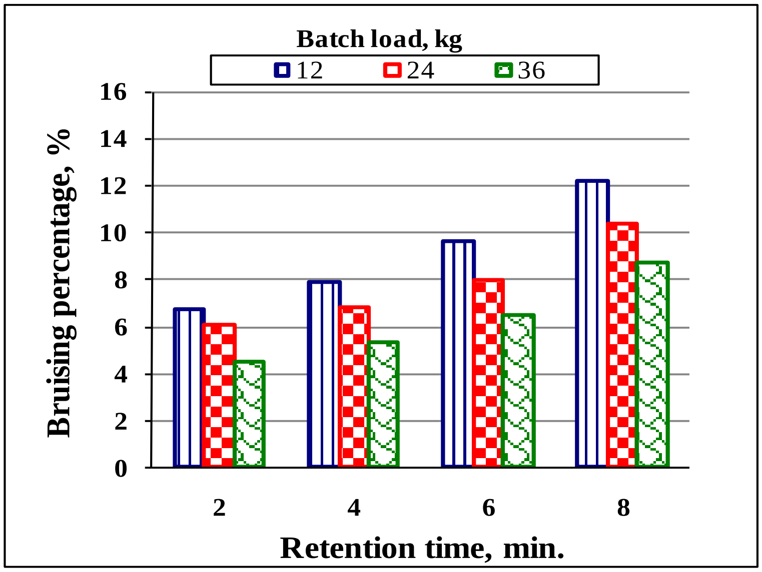


Fig. 6:- Relationship between bruising percentage and retention time at different levels of batch load.

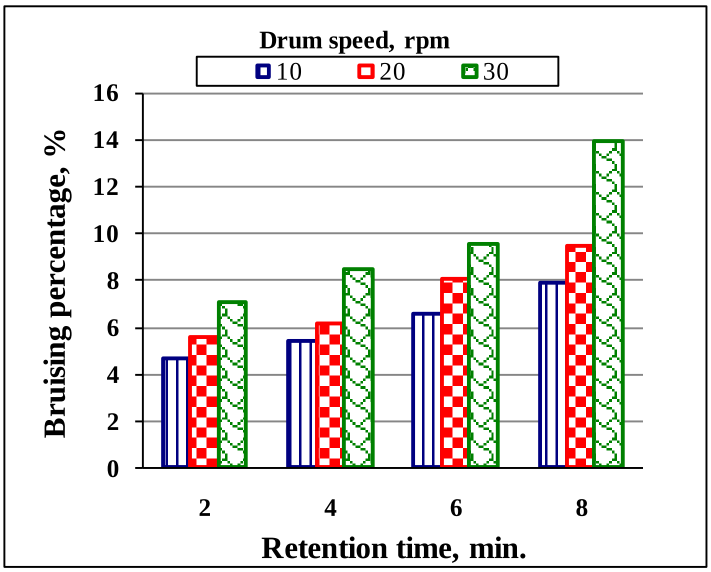


Fig. 7:- Relationship between bruising percentage and retention time at different levels rotor drum speed.

A polynomial regression analysis relationship was formed to relate the change in mechanical washing efficiency (Ew, %) and bruising percentage (Br, %) as dependent variables with the change of rotor drum speeds (S), batch loads (L) and retention time (T) as independent variables. The interaction between different treatments shows a significant effect with (R^2 = 0.95 and 0.89) and stander error of (3.17 and 0.96) for Ew, % and Br, % respectively. The obtained regression equation was in the form of:

$$Ew = 8.5 + 1.12\ S + 1.19\ L + 2.10T \quad (15)$$

$$Br = 2.65 + 0.19\ S - 0.11\ L + 0.79\ T \quad (16)$$

Proper performance of the washer prototype:

Table 1 shows the highest, lowest and proper values of the evaluation parameters of the developed washer prototype in terms of mechanical washing efficiency, bruising percentage, microbial washing efficiency, productivity and consumed specific energy at various levels of retention time (T), rotor drum speed (S) and batch load (L). It could be noticed that the bruising at lowest value (4.5%) and proper value (5.33%) were close together, while the washing efficiency increased from 40.08 to 93.07 %. The proper washing efficiency was not selected based on the highest values but the interaction between the various levels of variables affecting both washing efficiency and bruising percentage of washed potatoes. Accordingly, adjusting the washing machine at 20 rpm drum speed (S2), 36 kg batch load (L3) and 4 min retention time (T2) gave the proper washing efficiency, bruising percentage and microbial washing efficiency of 93.07, 5.33 and 85.8 % respectively. Consequently, employing such proper operating conditions (S2, L3 and T2) provides a machine productivity and consumed specific energy of 0.43 Mg/h and 3.96 kWh/Mg respectively.

Table 1:- The potato washer performance as affected by various variables.

Washer performance	Lowest value		Highest value		Proper value	
Mechanical washing efficiency, %	S1	40.09	S3	97.55	S2	93.07
	L1		L3		L3	
	T1		T4		T2	
Mechanical bruising, %	S1	4.50	S3	13.92	S2	5.33
	L3		L1		L3	
	T1		T4		T2	
Microbial washing efficiency, %	S1	60.26	S3	92.79	S2	85.80
	L1		L3		L3	
	T1		T4		T2	
Machine washing productivity, Mg/h	L1	0.08	L3	0.72	L3	0.43
	T4		T1		T2	
Consumed specific energy, kWh/Mg	S1	2.30	S3	20.91	S2	3.96
	L3		L1		L3	
	T1		T4		T2	
S1, S2 and S3 : 10, 20 and 30 rpm drum speed respectively.						
L1, L2 and L3 : 12, 24 and 36 kg batch load respectively.						
T1,T2, T3 and T4 : 2, 4, 6 and 8 min retention time respectively.						

Operation costs of the washer prototype:

By operating the washer prototype at the proper performance conditions (S = 20 rpm, L = 36 kg and T = 4 min), the total hourly operating costs for potato washer was 43 EGP / h (equation 10). Also, the estimated production costs of the washer was 100 EGP/ Mg (equation 11), which is much lower than the manual washing cost of 278 EGP / Mg (equation 14). This means that the estimated cost of the potato washer was less about 2.8 times than the manual washing procedure.

Conclusion:-

The important results could be summarized as follow:

1. The potato washer prototype can be operated successfully at the proper operating parameters of 4 min retention time, 20 rpm rotor drum speed and 36 kg batch load, which attained the proper washing efficiency, bruising percentage and microbial washing efficiency with values of 93.07, 5.33 and 85.8 %, respectively.
2. The machine productivity and consumed specific energy of 0.43 Mg/h and 3.96 kWh/Mg were obtained at the previous proper washing machine performance.
3. The production costs of potato washer was 100 EGP/ Mg this is in comparison with 278 EGP/ Mg for manual washing operation (Or in other words manual washing operation was about 2.8 times higher than that of the mechanical washing).
4. The washer prototype suitable for small farms and can be recommended for use in small and medium production units (Egyptian sorting, grading stations, small food factories).

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