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Design and implementation of sequential fruit size sorting machine[1]

Projeto e implementação de uma máquina sequencial de classificação por tamanho de frutas

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HIGHLIGHTS:

It is very desirable for farmers and traders to promote the marketing of a machine that is capable of sorting different fruits.
The machine is very useful for mechanical sorting, thus it can replace manual sorting.
Providing simple and cheap fruit sorting technology reduces packaging and transportation costs.

ABSTRACT: This study aimed to develop a simple and easy to construct fruits size sorting machine. The sorting machine was designed to sort oranges, apples, and yellow plums in small, medium, large, and extra-large size groups based on physical and mechanical properties including axial dimensions, arithmetic mean diameter, sphericity, mass, volume, projected area, and frictional characteristics (coefficient of static friction) against two structural surfaces of the sorting machine (galvanized iron and rubber). The maximum sorting efficiency of the machine was 98% at 20 rpm for plums. Whereas the minimum fruit sorting efficiency of the machine at 25 rpm was 76% for apple fruits. The sorting efficiency of the machine increased with increasing sphericity ratio of fruits. The sorting machine productivity was 280, 250, and 212 kg h^{-1} for sorting oranges, apples, and plums, respectively. It is recommended that the machine should be operated at three slope angles of the sorting unit 20º, 15º, and 10º for oranges, apples, and plums, respectively. These angles correspond to the coefficient of static friction of the tested fruit.

Key words: development, oranges, apples, plums, postharvest technology

RESUMO: Este estudo tem como objetivo desenvolver uma máquina classificadora por tamanho de frutas simples e de fácil construção. A máquina de classificação foi projetada para classificar laranjas, maçãs e ameixas amarela em grupos de tamanho pequeno, médio, grande e extra grande, classificando de acordo com as propriedades físicas e mecânicas, incluindo dimensões axiais, diâmetro médio aritmético, esfericidade, massa, volume, área projetada, e características de atrito (coeficiente de atrito estático) contra duas superfícies estruturais da máquina de triagem (ferro galvanizado e borracha). A eficiência máxima de triagem da máquina foi de 98% a 20 rpm para frutos de ameixas. Enquanto a eficiência mínima de classificação de frutos da máquina a 25 rpm foi de 76% para frutos de maçãs. A eficiência de classificação da máquina aumenta com o aumento da proporção de esfericidade dos frutos. A produtividade da máquina de triagem foi de 280, 250 e 212 kg h^{-1} para a triagem de laranjas, maçãs e ameixas, respectivamente. Recomenda-se operar a máquina em três ângulos de inclinação da unidade de classificação 20º, 15º e 10º para laranjas, maçãs e ameixas, respectivamente. Esses ângulos correspondem ao coeficiente de atrito estático da fruta testada.

Palavras-chave: desenvolvimento, laranjas, maçãs, ameixas, tecnologia pós-colheita

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Introduction

At present, the total area used for fruit cultivation in Egypt is about 700,854 hectares. Orange is the major citrus species crop in Egypt, with a cultivated area reaching 133,236 ha and representing about 69% of the total cultivated citrus area. This area produces approximately 2.9 million tons, representative of about 69% of the total citrus production and about 30% of the total Egyptian fruit production for exports (Abobatta, 2019).

Plum (*Prunus salicina* L.) is a popular fruit and is considered to be among the most important fruits in the world. The total cultivated area of plums in Egypt is about 1097.9 ha. According to data from the Ministry of Agriculture, Egypt, a total of 13,941 tons were produced in 2015, with an average yield of 13.42 t ha^{-1}. Most of the fruits are sorted before storage and preparation for presentation in the markets. These operations are one of the most significant costs in the fruit value chain, representing up to 40% of the apple production costs (Wunderlich et al., 2007). Fruits are mostly sized based on their diameter because it is the most significant factor (Lu et al., 2018). Rajapaksha et al. (2021) reported that at present, to some extent, sorting is carried out manually by wholesale and retail traders, especially at the supermarket level. No mechanical grading and sorting facilities are generally used or available on a commercial scale. Sorting based on size and quality is essential prior to the marketing of fruits and vegetables grown in commercial holding (Monicka et al., 2021). Ahmadi et al. (2020) reported that the sorting operation can be carried out by hand or mechanically. The shortage and cost of the labor force have contributed to the development and adoption of sorting machines for many fruits. Persons engaging in postharvest crop handlings such as farmers cannot use highly technical and costly sorting techniques (Joshi & Awate, 2016). Accordingly, this study aimed to design and implement a simple and easy to construct fruits size sorting machine.

Materials and Methods

The sequential sorting machine was fabricated in the workshop of the Faculty of Agricultural Engineering, Al-Azhar University, Assiut Branch, Egypt. All the experiments were carried out during the period from May 1, 2021, to June 24, 2021. All measurements were done using a random sample of 100 orange fruits (Valencia), Anna apples, and yellow plums. The samples were chosen randomly from a market and the measurements were taken on the same day. These three types of fruits were chosen because they are very different in size and thus indicate the extent of the machine's ability to sort various fruits despite the great variation in their diameter.

The design features of the sorting machine

Figures 1A, B, and C show the sorting process by the sequential sorting machine for plums, apples, and oranges, respectively.

The design feature of the machine includes two major characteristics: (I) Ability to sort two types of fruits. The first type is small-sized fruits such as plums and the second type is large-sized fruits such as oranges and apples, through a simple adjustment process for the sorting elements. (II) Uncomplicated design, easy to maintain, and made from local raw materials. The sorting machine was designed based on the measured physical and mechanical properties of the fruits. The machine sorts fruits in four categories of size (small, medium, large, and extra-large). In the case of adjusting the machine for the sorting of small-sized fruits, the four classes according to the diameter are as follows: less than 22 mm (first-class), greater than 22 mm and less than 30 mm (second class), greater than 30 mm and less than 38 mm (third class), and finally, greater than 38 mm (fourth class). In the case of adjusting the machine for sorting large-sized fruits, the four classes are: less than 60 mm (first-class), greater than 60 mm and less than 74 mm (second class), greater than 74 mm and less than 88 mm (third class), and finally, greater than 88 mm (fourth class).

Components of the sorting machine

Detailed descriptions of the essential parts of the machine are shown in Figure 2.

1. Fruit hopper

The hopper is the frustum of a square pyramid that was fabricated of galvanized sheet 1.0 mm thick, the height of the hopper is 500 mm, and the two bases have side lengths of 300 and 200 mm. The hopper opens and closes through a sliding gate.

2. Frame

The frame was formed from welded steel L-sections 30×30×3 mm in thickness. The frame is 1600 mm long, 600 mm wide, and 500 mm high. There are screws at the legs of the frame to control the inclination angle of the sorting unit.

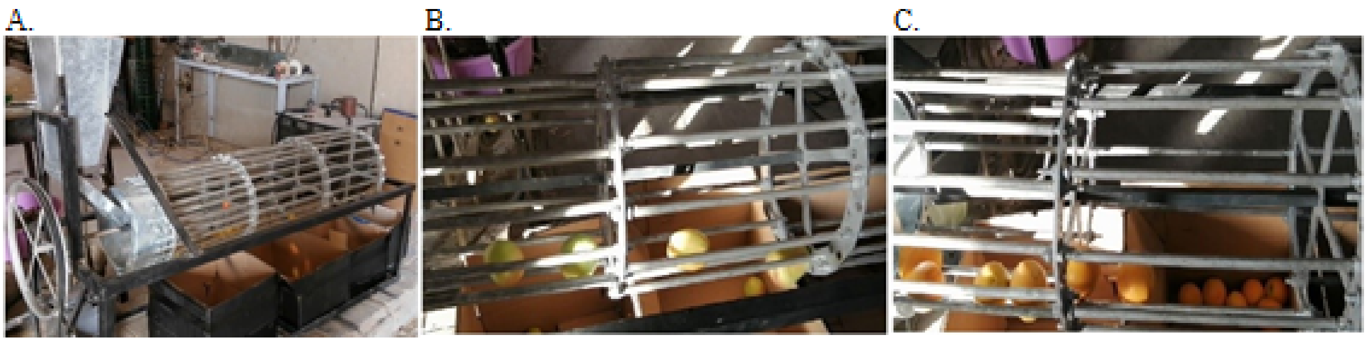

Figure 1. The machine during fruit sorting: (A) Plums, (B) Apples, and (C) Oranges

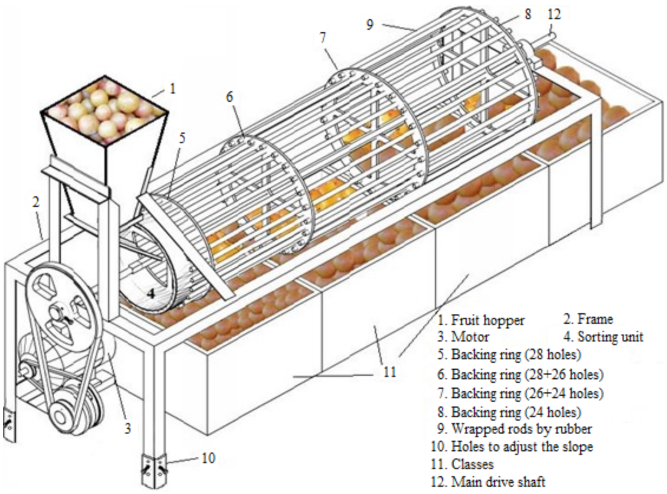

Figure 2. Essential parts of the designed sequential sorting machine

3. Motor

The machine is operated with an electrical motor (0.25 kW/0.34 hp, 1430 rpm, ElprnseElprromTroyanBulGaria, made in Egypt). The power required to rotate the sorting unit at the maximum experimental speed (25 rpm) was estimated as follows:

$$P = \frac{2\ \pi\ n\ T}{60\eta}$$

where:

P - power requirement in hp (horsepower = 745.7 W);

n - rotational speed of the main drive shaft of the sorting unit in rpm; and,

T - torque produced by the total load of the sorting unit weight and fruits in Nm.

4. Sorting unit

The sorting unit consists of three sequential sections. The sorting unit is fixed to the main drive shaft and based on the frame by a pair of bearings. Detailed dimensions of the sorting unit are presented in Figure 3.

The rods are wrapped in rubber to prevent any mechanical damage to the fruits during the sorting process; especially when adjusting the machine for the sorting of small-sized fruits. The clearances of the classes were 22, 30, and 38 mm, and were derived from 28, 26, and 24 rubber-wrapped rods, respectively. The rubber-wrapped rods are circumferentially distributed on the backing rings by specific holes. The fourth class consists of fruits that are larger than 38 mm. In the case of adjusting the machine for sorting large-sized fruits, the clearances of the classes were 60, 74, and 88 mm, derived from 14, 13, and 12 rods, respectively. The rods are circumferentially distributed alternately on the backing rings by specific holes. The fourth class consists of fruits that are larger than 88 mm.

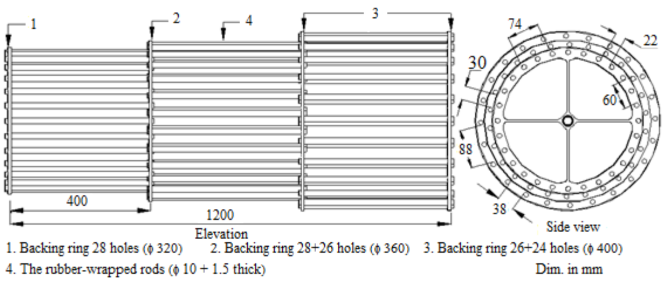

Figure 3. Elevation and side view of the sorting unit

5. The main drive shaft

The sorting unit was mounted on a horizontal shaft and based on the frame by a pair of bearings. Therefore, the torques which affected the main drive shaft were the torsion moment (T = 80 J) and the bending moment (M = 160 J). The forces and torques affecting the rotary shaft are shown in Figure 4. According to Ridwan et al. (2020), the shaft is solid and made of medium carbon steel (yield strength σ_y= 345 MPa).

Safety factor (K) was estimated by the following equation according to (Elkaoud, 2020).

$$k = k_{static} \times k_{repeated} \times k_{life} = 2 \times 1.2 \times 1.2 = 2.88$$

Shaft diameter was calculated by the following equation according to (Bhandari, 2010).

$$d^3 = \frac{16K}{\pi\ \sigma y \times 10^3}\sqrt{M^2 + T^2}$$

where:

d - design diameter of the main drive shaft, mm;

K - safety factor = 2.88;

σy - yield strength of medium carbon steel alloy 345 MPa;

M - bending moment; and,

T - torsion moment.

Thus, the diameter of the main shaft used in mounting and rotating the sorting unit is 20 mm and it has been verified that this diameter is safe.

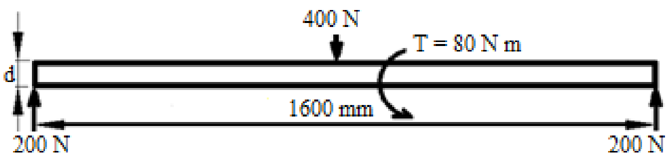

Figure 4. The affecting forces and torques on the main drive shaft

6. Adjusting the sorting unit slope

Two hinges were assembled at the legs of the frame to control the inclination angle of the sorting unit. The machine was tested for three slope angles of the sorting unit 20, 15, and 10° for oranges, apples, and plums, respectively.

The critical speed of the sorting unit can be calculated using the following equation (Hegzy & Mady, 2018).

$$n = \frac{30k}{\pi}\sqrt{\frac{g}{\mu r}}$$

where:

n - critical speed of the sorting unit, rpm;

k - factor that ranges from 0.33 to 0.40 according to Klenin et al. (1985);

g - gravity 9.81 m s^{-2};
μ - coefficient of friction = 0.4; and,
r - largest radius of the sorting unit = 0.2 m.

Thus, the machine was tested under three rotational speeds of the sorting unit 15, 20, and 25 rpm, in order to study its effect on machine performance under experimental conditions. The three rotational speeds chosen are less than the estimated critical speed of the designed sorting unit.

Measurements

I. Some physical and mechanical properties of the fruits

- Axial dimensions and arithmetic mean diameter

A digital Vernier-caliper with an accuracy of 0.01 mm was used to measure the three axial dimensions of 100 randomly selected oranges, apples, and plums. Arithmetic mean diameter (Da) was calculated by the following equation (Mohsenin, 1986).

$$D_a = \frac{L + W + T}{3}$$

where:
D_a - arithmetic mean diameter, mm;
L - length, mm;
W - width, mm; and,
T - thickness, mm.

- Sphericity ratio

The sphericity percentage (Ø) of the fruits was calculated using the following equation (Mohsenin, 1986).

$$\varnothing = \frac{(LWT)^{1/3}}{L} 100$$

where:
Ø - sphericity ratio, %;
L - length, mm;
W - width, mm; and,
T - thickness, mm.

- Volume

The liquid displacement method was used to measure the true volume (V_t) of the individual fruit (Mohsenin, 1986). Toluene (C_7H_8) was used instead of water. The volume of displaced liquid was found by immersing the fruit in a graduated cylinder (0.1 cm^3 accuracy) with a known volume of toluene.

- Projected area

The projected area of the fruits was obtained from images captured using a 24 megapixels mobile phone camera. The fruit images were analyzed with AutoCAD 2012 software to calculate the projected area (A_p) of the fruit.

- Coefficient of static friction

The coefficient of static friction of the fruits was measured against two structural materials, rubber and galvanized iron sheets. The coefficient of static friction was calculated using the following equation (Mohsenin, 1986).

$$\mu = \tan \alpha$$

where:
μ -coefficient of static friction; and,
α -friction angle, in degree.

II. Performance of the sequential designed sorting machine

- Overall sorting efficiency

The overall sorting efficiency of the machine (E) was calculated using the following equation (Mangaraj et al., 2009).

$$E = \frac{N_t + N_{tm}}{N_t} 100$$

where:
E - overall sorting efficiency of the machine, %;
N_t - total number of fruits in the sample; and,
N_{tm} - total number of misclassified fruits in all categories

- Machine capacity

The machine capacity (MC) can be estimated by the following equation (Mangaraj et al., 2009).

$$MC\left(kg\ h^{-1}\right) = \frac{\text{The total weight of the sorted fruits (kg)}}{\text{Sorting time (h)}}$$

Results and Discussion

Table 1 shows the measured physical and mechanical properties of the fruits.

From Table 1, the average values of length (L), width (W), and thickness (T) were 71.9, 67.9, and 66 mm, 74.5, 62.1, and 58.9 mm, and 30.9, 30.2, and 29.9 mm for oranges, apples, and plums, respectively. The arithmetic mean diameters (Da) of the fruits were 68.6, 65.2, and 30.3 mm for oranges, apples, and plums, respectively.

From Table 1, the average values of sphericity (Ø) were 95.4 ± 5.1%, 87.3 ± 7.4%, and 98 ± 5.1% for oranges, apples, and plums, respectively. Buyanov & Voronyuk(1985) reported that if sphericity is less than 0.9, the fruit belongs to the oblate group; if sphericity is greater than 1.1, it belongs to the oblong group. The remaining fruits with intermediate index values were considered as round. Figure 5 indicates that the random samples of plum fruits selected were round, 97% of oranges were also round (sphericity 90 - 99.1%). A total of 74% of apples in the sample belonged to the oblate group (less than 90%).

From Table 1, the average values of the mass of fruits were 192.3, 107.5, and 17.6 g for oranges, apples, and plums, respectively. The average values of the true volume (V_t) of the individual fruits were 196.9, 165.9, and 16.5 cm^3 for oranges, apples, and plums, respectively. The average values of the projected area (A_p) of the fruits were 52.2, 55.3, and 8.5 cm^2 for oranges, apples, and plums, respectively.

From Table 1, the average values of the coefficient of static friction were 0.3 and 0.4, 0.2 and 0.28, and 0.15 and 0.17 on

Table 1. Some physical and mechanical properties of various fruits

The fruits	Properties	Min.	Max.	Mean	SD	CV%
	L, mm	59	89.2	71.9	8.3	11.6
	W, mm	56.5	85.6	67.9	7.6	11.2
	T, mm	52.1	83.9	66	7.2	10.9
	Da, mm	56	85.9	68.6	7.6	11.2
	Ø, %	86.8	99.1	95.4	5.1	5.3
Oranges	M, g	126	220	192.3	20.4	10.6
	V_t, cm^3	92.3	311.7	196.9	31.1	15.3
	A_p, cm^2	38.9	71.5	52.2	9.6	17.3
	µ for galvanized iron	0.2	0.33	0.3	0.05	10.1
	µ for Rubber	0.3	0.37	0.4	0.08	13.8
	L, mm	51.6	93.7	74.5	12.3	12.1
	W, mm	45.7	77.5	62.1	9.4	12.9
	T, mm	44	76	58.9	7.2	12.2
	Da, mm	48.9	81.3	65.2	9.9	13.2
	Ø, %	86.8	98.5	87.3	7.4	5.8
Apples	M, g	55	135	107.5	19.5	10.8
	V_t, cm^3	78.6	288.5	165.9	36.2	18.9
	A_p, cm^2	39.6	73.8	55.3	10.8	15.5
	µ for galvanized iron	0.2	0.26	0.2	0.04	9.1
	µ for Rubber	0.21	0.3	0.28	0.06	11.8
	L, mm	21.6	39.5	30.9	6.4	20.8
	W, mm	21	39.1	30.2	6.3	21.1
	T, mm	21	38.2	29.9	7.2	24.1
	Da, mm	21.3	38.9	30.3	6.4	21
	Ø, %	86.8	99.8	98	5.1	5.2
Plums	M, g	14.8	29	17.6	2.9	16.3
	V_t, cm^3	5.4	30.7	16.5	9.24	25
	A_p, cm^2	3.5	13.42	8.5	3.52	21
	µ for galvanized iron	0.14	0.16	0.15	0.04	9.1
	µ for Rubber	0.16	0.18	0.17	0.04	9.2

L - Length; W - Width; T - Thickness; Da - Arithmetic mean diameter; Ø - Sphericity ratio; M - Mass; V_t - True volume; A_p - Projected area; µ - Coefficient of static friction; SD - Standard deviation; CV - Coefficient of variation

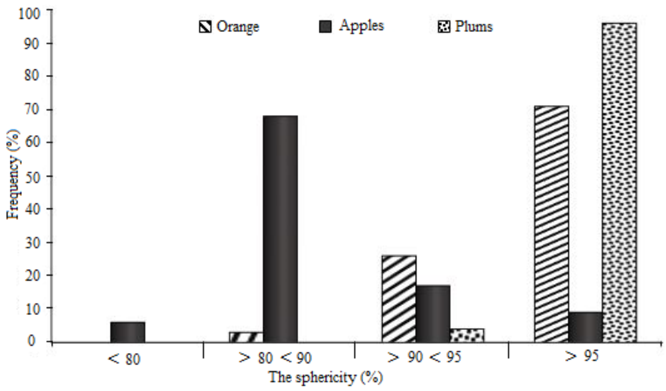

Figure 5. Classification of fruit samples according to sphericity

a galvanized iron sheet and rubber for oranges, apples, and plums, respectively.

When the fruits are mechanically sorted by the sequential machine, there are three possibilities for the fruits to fall: 1) lengthwise, 2) widthwise, and 3) by thickness. Accordingly, the fruits were manually classified according to the sorting classes of the machine to study the different cases of fruit fall, which in turn will greatly affect the efficiency of the sorting process. Figure 6 shows the manual classification of the fruit samples into the four classes produced by the machine.

The number of fruits sorted into the four classes were 5-25, 54-59, 16-35, and 0-6%; 13-59, 35-37, 4-30, and 0-22%;

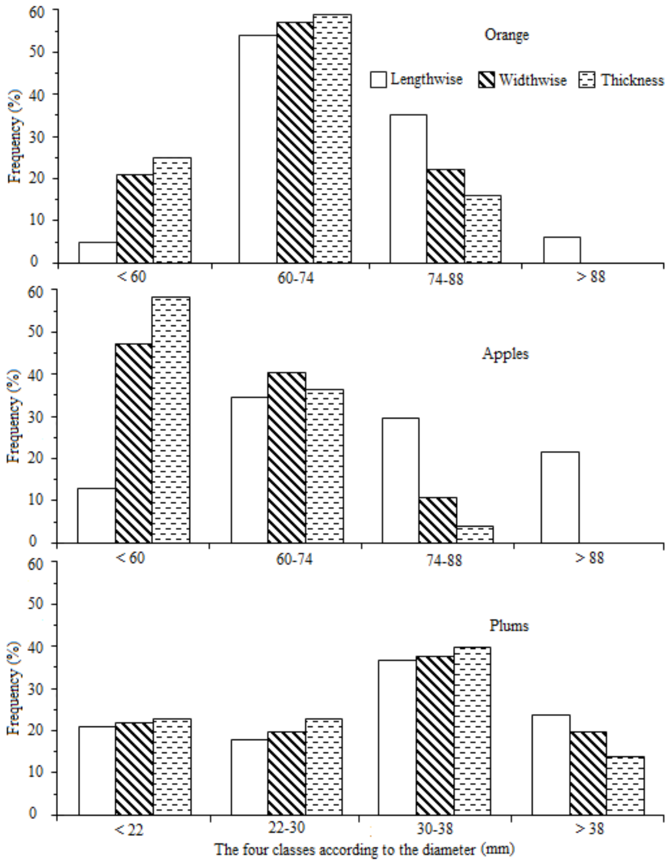

Figure 6. Manual classification of the fruit samples into four classes

and 21-23, 18-23, 37-40, and 14-24% for oranges, apples, and plums, respectively. For one class, this range depends on the direction of fall of the fruits. The largest range was from 13 to 59% in the first class of apple sorting, while the lowest range was from 21 to 23% in the first class of plums sorting. Apples recorded a large variation in length, width, and thickness, and this may be because the fruit belongs to the oblate group. Conversely, plums have little variation in length, width, and thickness, and this is because it is spherical in shape. Maybe the main factor that will determine the percentage of fruits for each class is the behavior of the fruit within the rotary sorting unit and the direction of its fall.

The sorting of fruits according to the true volume was used to estimate the overall sorting efficiency of the machine. Figure 7 shows the manual sorting of fruits according to the true volume of the four classes that the machine will be adjusted, to sort large-sized fruits (oranges and apples) and small-sized

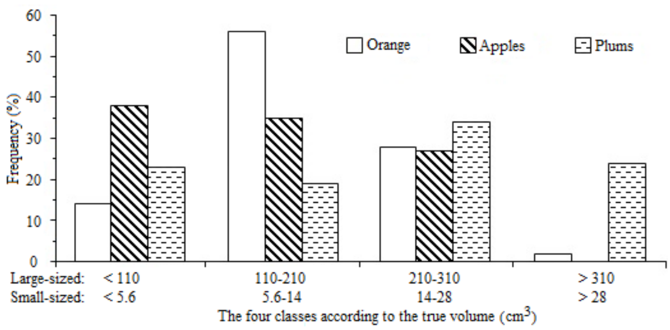

Figure 7. Manual sorting of fruits according to their true volume

fruits (plums). The sorting of fruits was 14, 56, 28, and 2%; 38, 35, 27, and 0%; and 23, 19, 34, and 24% for oranges, apples, and plums, respectively.

An electric motor of 1/3 hp can be used to drive the machine. The possibility of controlling the number and distribution of the rubber-wrapped rods on the circumference of the backing rings gives the flexibility to change the clearance between the rods, therefore it can be adjusted to suit fruits of different sizes. The rotation speed of the sorting unit should be lower than 35 rpm which represents a critical speed.

Table 2 shows a summary of the machine efficiency under different experimental variables.

Experiments were repeated ten times and the averages were calculated. From Table 2, considering plums, the maximum sorting efficiency of the machine was 98% at 20 rpm of rotational speeds of the sorting unit. While using apple fruits, the minimum sorting efficiency of the machine was 76% at 25 rpm of the sorting unit. Figure 8 shows the effect of the rotational speed of the sorting unit on the sorting efficiency using various fruits.

The data indicated that ω_{gu} = 20 rpm of the sorting unit gives the greatest sorting efficiency of the machine with all fruits. This may be because this rotational speed gives a greater chance for the fruits to fall into the correct sorting class. Plums were sorted with high efficiency of up to 98%, followed by oranges with an efficiency of 88%, and finally apples with an efficiency of up to 80%, and this is an indication that the machine efficiency increases with increasing fruits sphericity.

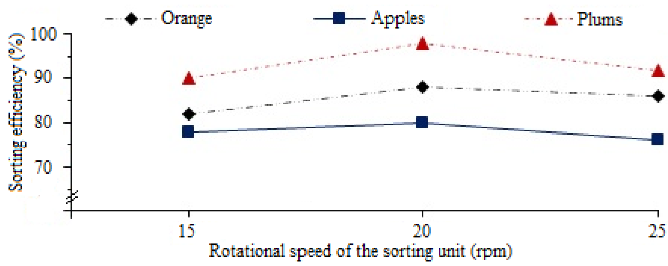

Figure 8. Effect of sorting unit speed on sorting efficiency

Figure 9 shows the machine capacity using various fruits. The results indicated that the rotational speeds of the sorting unit did not significantly affect the machine capacity. But the machine capacity was affected by the type of fruits sorted. The machine productivity was 280, 250, and 212 kg h^{-1} at (ω_{gu} = 20 rpm) for oranges, apples, and plums, respectively.

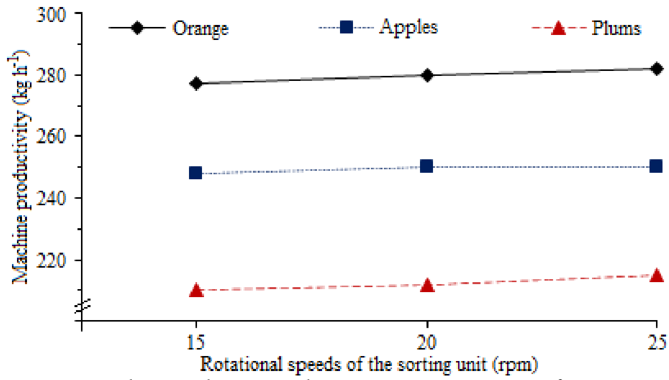

Figure 9. The machine productivity using various fruits

Table 2. The machine efficiency under variables of experiments

<table>
<tr><th rowspan="3">Fruits</th><th rowspan="3" colspan="2">Sorting process</th><th></th><th colspan="4">Four classes according to the true volume (cm^3)</th></tr>
<tr><td>Large-sized</td><td>< 110</td><td>110-210</td><td>210-310</td><td>> 310</td></tr>
<tr><td>Small-sized</td><td>< 5.6</td><td>5.6-14</td><td>14-28</td><td>> 28</td></tr>
<tr><td rowspan="10">Oranges</td><td colspan="2">Manually</td><td>N_t</td><td>14</td><td>56</td><td>28</td><td>2</td></tr>
<tr><td rowspan="9">Mechanically at three rotational speeds of the sorting unit (rpm)</td><td rowspan="3">15</td><td>N_t</td><td>12</td><td>49</td><td>33</td><td>6</td></tr>
<tr><td>N_{tm}</td><td colspan="4">18</td></tr>
<tr><td>E (%)</td><td colspan="4">82</td></tr>
<tr><td rowspan="3">20</td><td>N_t</td><td>18</td><td>51</td><td>30</td><td>1</td></tr>
<tr><td>N_{tm}</td><td colspan="4">12</td></tr>
<tr><td>E (%)</td><td colspan="4">88</td></tr>
<tr><td rowspan="3">25</td><td>N_t</td><td>20</td><td>58</td><td>22</td><td>0</td></tr>
<tr><td>N_{tm}</td><td colspan="4">14</td></tr>
<tr><td>E (%)</td><td colspan="4">86</td></tr>
<tr><td rowspan="10">Apples</td><td colspan="2">Manually</td><td>N_t</td><td>38</td><td>35</td><td>27</td><td>0</td></tr>
<tr><td rowspan="9">Mechanically at three rotational speeds of the sorting unit(rpm)</td><td rowspan="3">15</td><td>N_t</td><td>29</td><td>33</td><td>31</td><td>7</td></tr>
<tr><td>N_{tm}</td><td colspan="4">22</td></tr>
<tr><td>E (%)</td><td colspan="4">78</td></tr>
<tr><td rowspan="3">20</td><td>N_t</td><td>30</td><td>44</td><td>25</td><td>1</td></tr>
<tr><td>N_{tm}</td><td colspan="4">20</td></tr>
<tr><td>E, %</td><td colspan="4">80</td></tr>
<tr><td rowspan="3">25</td><td>N_t</td><td>44</td><td>41</td><td>15</td><td>0</td></tr>
<tr><td>N_{tm}</td><td colspan="4">24</td></tr>
<tr><td>E (%)</td><td colspan="4">76</td></tr>
<tr><td rowspan="10">Plums</td><td colspan="2">Manually</td><td>N_t</td><td>23</td><td>19</td><td>34</td><td>24</td></tr>
<tr><td rowspan="9">Mechanically at three rotational speeds of the sorting unit, (rpm)</td><td rowspan="3">15</td><td>N_t</td><td>20</td><td>17</td><td>35</td><td>28</td></tr>
<tr><td>N_{tm}</td><td colspan="4">10</td></tr>
<tr><td>E (%)</td><td colspan="4">90</td></tr>
<tr><td rowspan="3">20</td><td>N_t</td><td>22</td><td>19</td><td>35</td><td>24</td></tr>
<tr><td>N_{tm}</td><td colspan="4">2</td></tr>
<tr><td>E (%)</td><td colspan="4">98</td></tr>
<tr><td rowspan="3">25</td><td>N_t</td><td>24</td><td>19</td><td>37</td><td>20</td></tr>
<tr><td>N_{tm}</td><td colspan="4">8</td></tr>
<tr><td>E (%)</td><td colspan="4">92</td></tr>
</table>

N_t-Total number of fruits in the sample; N_{tm}- Total number of misclassified fruits in all categories; E- Overall sorting efficiency of the machine

Conclusions

1. The sequential fruit size sorting machine was designed and implemented according to some of the physical and mechanical properties of the sorted fruits. The machine is powered by a 1/3 horsepower motor. The rotation speed of the sorting unit should be less than 35 rpm.

2. The machine has a flexible design that allows the sorting of different sized varieties of fruits. The machine was tested to sort large-sized fruits such as oranges, and apples, and small-sized fruits such as plums.

3. The rotational speed of 20 rpm of the sorting unit produced the greatest sorting efficiency of the machine with all fruits. Plums were sorted with high efficiency of up to 98%, followed by oranges with an efficiency of 88%, and finally apples with an efficiency of up to 80%. The machine productivity was 280, 250, and 212 kg h^{-1} at 20 rpm for oranges, apples, and plums, respectively.

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