https://doi.org/10.17221/48/2018-RAE

Laser diffraction analysis of purified *Descurainia Sophia* seeds by a tribo-aero-electrostatic system

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Citation: Afsharipour M., Jafari-Naeimi K., Samimi-Akhijahani H. (2019): Laser diffraction analysis of purified *Descurainia Sophia* seeds by a tribo-aero-electrostatic system. Res. Agr. Eng., 65: 123–130.

Abstract: In order to separate the impurities in vegetable seeds, a tribo-aero-electrostatic separator was designed and manufactured. The data analysis of the pure *Descurainia Sophia* seed shows that the interaction of the voltage, distance and angle was significant on the weight of the *D. Sophia* at the level of 1%. To determine and compare the size of the separated seeds, a laser diffraction device with the possibility of analysing the size distribution of the particles was used. The results showed that the best purity (99.5%) with the highest percentage of the relative frequency of the *D. Sophia* seeds size was obtained for box 1 (the first box) with a seed size of 680 μm. By moving from box 1 towards box 4, the amount of the impurities due to the variation of the electrical properties of the materials increases, although the value of the impurities for the samples is acceptable.

Keywords: Cumulative curves; grain seed sorter; high voltage system; purification

One of the ways to separate solid particles, which are different in terms of the specific gravity and appearance, is electrostatic separation. In this method, the charged particles pass through an electric field under the influence of gravitational and centrifugal forces (McDonald, Copeland 1997). The electrostatic separation method is used to separate and purify various mineral materials, expensive stones, agricultural beans, legumes and conductors from the insulation parts of electronic boards (Li et al. 1999; Jiang et al. 2009). It works based on the absorption and diffusion of charged particles in an electrical field with a high voltage. This action is called high tensile separation (Cunha et al. 2012; Winkel et al. 2015; Patel et al. 2017). During the charging process via the electrostatic method, some factors have an effect on the amount of the produced charge on the particles such as the interface, the rubbing speed, the relative humidity of the environment and the type of the materials (Leonov 1984). Several studies have been carried out to develop electrostatic systems for separating different agricultural and mineral materials. In the research, the effective parameters, including the rotational speed, the applied voltage, the particle charging time, the sample mass and the percentage of the sample in the composition, were investigated for separating the polymer materials from the waste materials (Tilmatine, Bendimerad 2009). The results of the tribo-aero-electrostatic separation of the charcoal minerals indicated that in the tribo-aero-electrostatic separation process, the charcoal is positively charged and quartz, kaolin and pyrite are negatively charged (Xin-xi et al. 2009). Jafarri et al. (2019) developed

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an electrostatic system to separate straw from cereal grains. Due to the higher density, the seeds were more affected by the weight and the straw particles in the electrostatic field. The study on the separation of quartz, kaolin and pyrite showed that these materials can be effectively removed from the charcoal through a tribo-aero-electrostatic separation method (Dwari, Rao 2009). The effect of the microwaves on the separation mechanism of charcoal showed that by using a microwave method, the amount of the separation of the waste materials from the coal increased up to 49% with the power of 900 watts for 10 minutes (Turcaniova et al. 2004). In a study, the separation process of waste particles from wheat bran using a tribo-aero-electrostatic method was investigated (Chen et al. 2014).

Laser diffraction is a powerful and accessible method for determining the particle size and size distribution of materials with a wide range (Martin, Montero 2002). In this method, the laser beam passes through the particles and after collision with the particles they may pass through them or may return back during the process. This method has several advantages, such as it is easy to use, has high accuracy, it measures the particle size in a wide range of 0.20 to 3 mm and is a fast measuring process (maximum 400 microseconds for each experiment) (Healy 2013). The results of determining the particle size of a soil sample showed that the laser diffraction method is more accurate than the other methods which are used for this purpose (Pieri et al. 2006).

Descurainia Sophia (Linnaeus) is a tiny grain seed light brown in colour with an elliptical shape which is grows in a humid climate (Haji Sharifi 2003). Due to the very small size of the *D. Sophia* seeds and the presence of large impurities during the harvesting process, using a separation method (traditional or industrial) to remove the impurities from the seeds is very important. The dimension of *D. Sophia* is about 1.15 ± 0.12 mm in length, 0.64 ± 0.08 in width and 0.43 ± 0.07 in thickness. Due to the similar shapes and physical damage, the mechanical separation of *D. Sophia* is very hard and, in some cases, it is impossible. Moreover, the capacity of the mechanical methods as the main factor for the traditional separating process is very low. In this regard, the use of electrostatic methods as a separating method can solve the processing and marketing problems of the *D. Sophia* samples. Limited research has been performed on the separation of fine-seeds of agricultural products using the tribo-aero-electrostatic method and considering the purification measurement by the laser diffraction method. Thus, in this study, the tribo-aero-electrostatic separating process of the *D. Sophia* seed and the distribution analysis of the seed size in a collecting box using a laser diffraction method were investigated. Using a tribo-aero-electrostatic separator, more pure *D. Sophia* seeds could be obtained in less time and at a cheaper price.

MATERIAL AND METHODS

Theoretical basis. The separation of the charged particles takes place using the physical relationships governing electric fields. For every electrostatic separator, the initial force of the separator is calculated using Eqs 1 and 2, which depends on the intensity of the electric field and the charge on the surface of the particle:

$$F = E \times q\,; \qquad E = \frac{V}{d} \tag{1}$$

where F – the force acting on the particle (N); E – the electric field intensity (N/C); q – the charge value of the particle (C); V – the voltage applied on the particles (V); d – the distance between the two electrodes inside the charging unit (cm) (Zeinizadeh, Heydari 2002)

The most important forces acting on the falling objects inside the charging unit are the electrical and gravitational forces. The electrical force (F_e) acts in the horizontal direction on the particle and the gravitational force (F_g) affects the vertical direction. These forces are defined using the following equations (Eqs 2a and 2b) (Zeinizadeh, Heydari 2002):

$$F_e = q \times E = 4\pi r^2 \sigma \times E\,;\; F_g = mg = \frac{4}{3}\pi r^3 \rho \times g \tag{2a}$$

$$\frac{F_e}{F_g} = \frac{3\sigma \times E}{r\rho g} \tag{2b}$$

where: q – the electric charge (C); E – the electric field intensity (N/C); r – the radius of the particle (cm); σ– the surface charge density ($C \cdot cm^{-2}$), ρ– the specific mass ($g \cdot cm^{-3}$); g – the gravitational acceleration ($m \cdot s^{-2}$)

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The amount of the electric field intensity depends on the physical properties of the particles, thus, the ratio in Eq. 2 is an important factor through the rubbing separation process (Trigwell et al. 2001).

Principal of the separating system. The impure *D. Sophia* samples were collected from one of the farms located in Mahan city of Kerman province. The tribo-aero-electrostatic separator system includes: a material feeding container, a material charger, a separator, a collecting unit, an air transfer channel and blower (Fig. 1). A polyethylene tube was located inside the charging unit to pass the samples through the separating unit. Underneath the charging unit, a chamber made from an iron sheet was located. Two aluminium electrodes were connected at the top of the iron chamber using hinges to make different angles for the separation process. All of the electrodes are connected to a high voltage DC adjustable supply with a range between 0–100 kV. A blower (Damandeh, Iran) with a polyethylene pipe was used to suspend the material inside the charging unit. A power supply (Damavand, Iran) was used for charging the raw materials including the *D. Sophia* seeds. The speed of the air blower was set at 1300 RPM. During the experiments, the relative air humidity and air temperature were about 21 ± 2% and 23 ± 1°, respectively. The composition of the materials for each use of the separating process for the *D. Sophia* samples included 240 g of impure materials and 760 g of pure materials. The material passes through the electrodes with the feeding rate of D = 3.1 g·s^{-1} and moves to the collecting box, which consists of a rectangular cube divided into ten small boxes according to Fig. 2. The purity of the materials in boxes A to D (Fig. 1), due to the difference in the colour of the *D. Sophia* seeds and the impurities, were analysed using the image processing program in MATLAB 6.5 (version 6.5). About 3 g of the separated samples were placed on a white colour paper and a picture of the sample was taken. The photos were analysed using the *k-means* function (Fig. 2). The mass of the separated material of four sections was measured using a balance (KIA, FRH, China) with an accuracy of 0.001 g. The experiments were carried out at three levels of voltages (applied to the electrodes) of 20, 30 and 40 kV, the distance between the electrodes of the turbocharger unit was set at 90, 150, and 210 mm, and the angle of the electrodes in the separating unit was set at three levels of 20, 30 and 40 degrees as was studied for the other sample by Kawamoto and Umezu (2008). Due to the high purity of the *D. Sophia* seeds in the box A, it is further and precisely discussed related to the other boxes. The data obtained from the experiments for box A analysed by SAS9.1.3 (version 9.1.3) and MSTATC (version 13.1). Duncan's multiple range tests was used at a 5% level of probability to compare the average weight of the materials in the box. Since the purity of the separated seeds in the first four boxes on the left side (Section A) is very high (Fig. 3), the materials inside these four boxes were selected to examine the seed size.

The sizes of the separated seeds were determined using the laser diffraction method, with a FRITSCH Laser Particle Size Analyzer (FRITSCH, Australia). The standard ASTM, E1617, 2009 was used to determine the particle size of the *D. Sophia* seeds. The laser beams collide with the *D. Sophia* seeds and the behaviour of the beams after the collision was analysed by

(a)

(b)

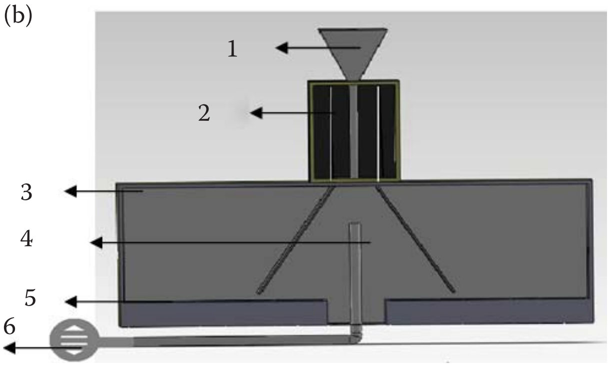

Fig. 1. (a) The tribo-aero-electrostatic system and (b) schematic of the components of the system

1 – the funnel and feeding tank; 2 – the charger unit (electrodes); 3 – the separating unit (slope plates); 4 – the air transmission channels (tube channels); 5 – the gathering unit (boxes); 6 – the blower

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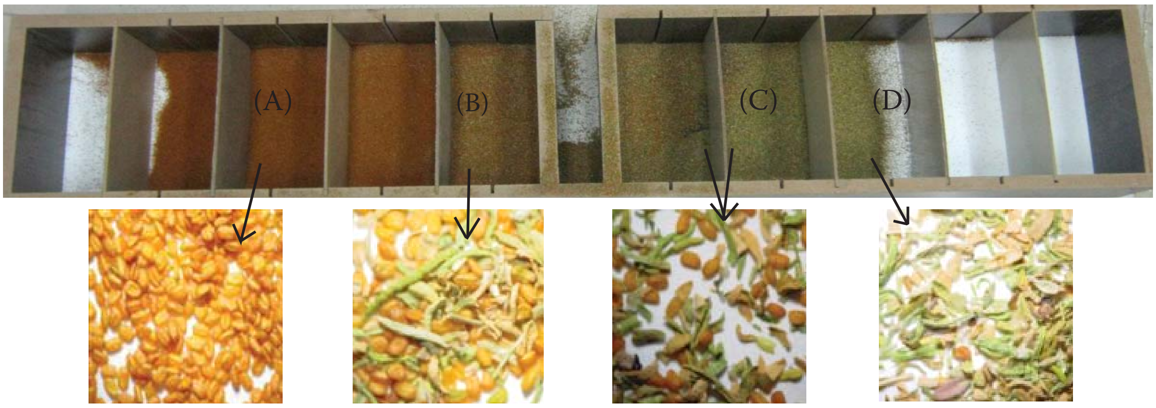

Fig. 2. The division of the image gathering sections at 20 times magnification

(A) the pure *D. Sophia* seed (B, C) a mixture of grains and impurities (D) impurities

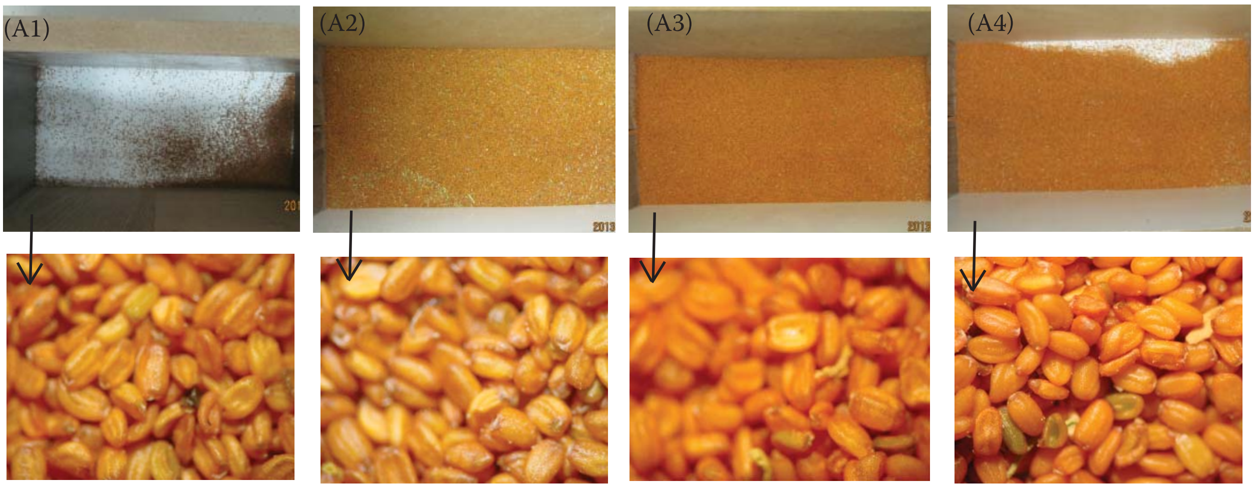

Fig. 3. Image of the materials in boxes 1 to 4 of section A with 20 times magnification using a camera with high resolution

A1, A2, A3, A4 – the pure *D.Sophia* seeds in the box A

the system. The results of the laser diffraction device are extracted graphically and the dispersion intensity distribution for each part is discussed using diagrams.

RESULTS AND DISCUSSION

The purity calculations of the separated *D. Sophia* seeds showed that the average purity of section A (in the first box) was higher than 98%, section B was 65 to 75%, section C was 30 to 50%, and it was less than 6% for section D. The results of the analysis of variance of the data for section A, as the most important section for producing the pure sample, is shown in Table 1. According to Table 1, all the simple and interaction effects of the parameters on the weight of the *D. Sophia* seed weight are significant at a level of 1%. The interaction of the factors on the weight of the separated materials was presented in a three-dimensional plot based on two variables and the

Table1. The analysis results of the variance factors affecting the weight of the materials of section A

Source of Variations	*df*	*MS*	*F* – value
Voltage	2	18,034.37	493.01**
Distance	2	36,931.56	1,009.61**
Angle	2	68,477.77	18,72.01**
Voltage × Distance	4	415.62	11.36**
Voltage × Angle	4	3,805.14	104.02**
Distance × Angle	4	664.09	182.17**
Voltage × Distance × Angle	8	30.08	8.24n.s
Error	54	36.58	

df – degrees of freedom; *MS* – Mean square; ** Significance at a level of 0.01; n.s – not significant

https://doi.org/10.17221/48/2018-RAE

third-order was weight of the pure *D. Sophia* seed gathered in section A. Increasing the applied voltage and decreasing the distance between the electrodes increase the electrical field inside the separating unit and, consequently, the weight of the pure material in section A increased (Fig. 4a). The interaction of the applied voltage and the angle of the plates showed that increasing the angle at higher voltages increases the weight of the material with a higher rate (Fig. 4b). Fig. 4c shows the interaction of the two factors (distance and angle) on the weight of the pure seed gathered in section A. By decreasing the distance between the electrodes and decreasing the angle of the electrodes, the purity of the *D. Sophia* seed increased. The highest amounts of purification of the *D. Sophia* seed (about 98.2%) was related to the experiment with an applied voltage of 40 kV, a distance of 90 mm and a 40° angle of the electrodes.

The mean values of Duncan's multiple range tests were set in the tables. A nonlinear multivariate regression equation was obtained for the parameters affecting the material weight of section A (Eq. 3). The correlation coefficient of the equation for the weight was about 90%. When moving the samples from the feeding tank through the charging unit, the seeds and the impurities charged. The amount of charging required for the samples directly depends on the distance between the electrodes (d) and the applied voltage (V). Eq. 3 also showed that increasing the distance between the electrodes has a positive effect and increasing the applied voltage has an adverse effect on the separation of the impure *D. Sophia* seed. After the charging process, the particles enter the separating unit, dispersed by the blower and move toward through the slope plates. The equation also indicated that decreasing the slope of the plates increased the impurities of the separated samples and reduced the purification efficiency of the separating system (Eq.3):

$$Y_1 = -289.73 + (31.89 \times b) - (0.05 \times V^2) + (0.0022 \times d^2) - \\ - (0.44 \times b^2) + (0.18 \times V \times b) - (0.043 \times b \times d) \quad (3)$$

where: Y_1 – the weight of pure *D. Sophia* seed; b –the angle of charging plates (°); d – the distance between the electrodes (mm); V – applied voltage (kV)

The weight of material in box A is expressed with a quadratic equation with three parameters. Considering the positive coefficients of b and Vb and the negative coefficient of bd in Eq. 3, it is confirmed that by increasing the applied voltage, increasing the angle of the electrodes and reducing the distance of the electrodes of the tribo-charge unit, the weight of the pure *D. Sophia* seed for section A increased up to 98%. Moreover, by increasing the applied voltage (for the tribo-charging and separating units), the raw material is placed inside the stronger electric field and more *D. Sophia* seeds are absorbed by the

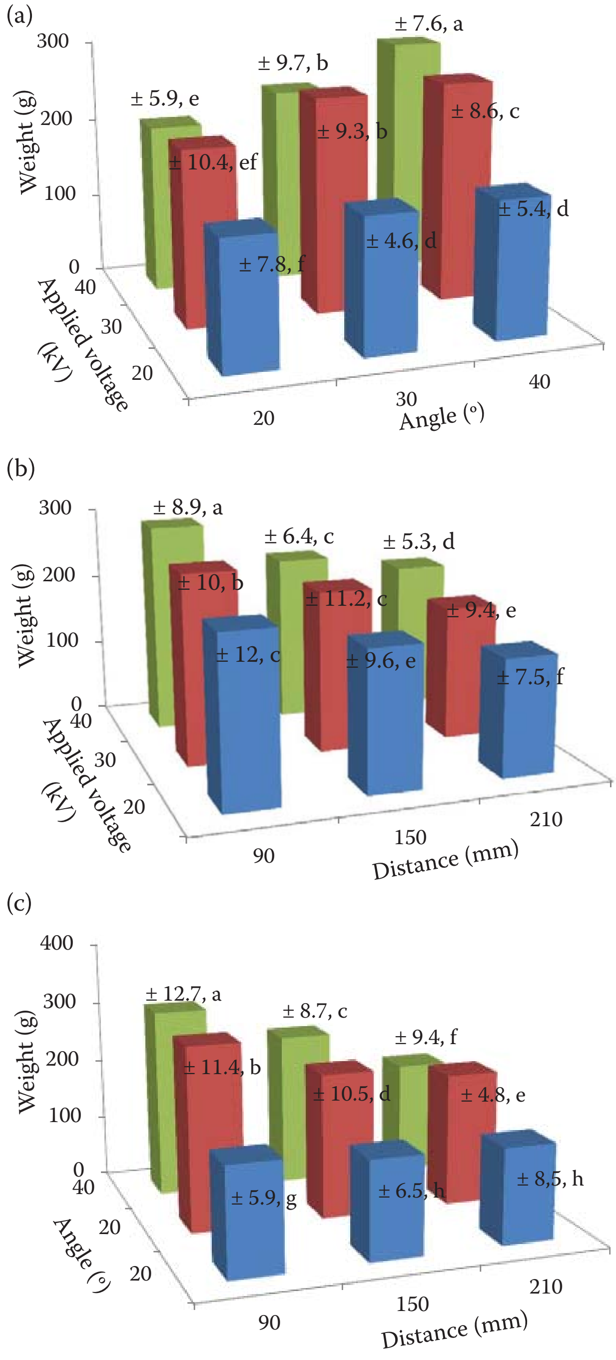

Fig. 4. Weight of section "A" of the separating box in terms of (a) the applied voltage and the angle (b) the applied voltage and the distance and (c) the angle and the distance letters indicates the significance of values

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negative electrode. The results are in good agreement with the results of other researchers such as: Dodbiba et al. (2003) for the separation of ABS and ABS-PC and Tilmathin and Bandimrud (2009) in the field of the tribo-electrostatic recycling of plastics, and Aksa et al. (2013) in the recycling of plastic particles. Since the force exerted by the object in the falling condition correlates with the distance between the electrodes of the tribo-charging unit, reducing the distance between the electrodes, increases the purity of the *D. Sophia* seeds in section A linearly. As the angle between the electrodes in the separator unit increases, during the falling process, the *D. Sophia* seeds with a negative charge move towards the positive electrode and the separated *D. Sophia* seeds fall further away from the centre of the gathering box. The findings about the effect of the location of the electrodes (Aman et al. 2004) are in agreement with result of this research. The polarisation of the materials varies depending on their position in the tribo-electrical unit. In this research, it was determined that the seeds which are negatively charged moved towards the positive electrode and then fall in the collecting box under the gravitational force. The result of calculating the purity of the material at each box under the various conditions of the applied voltage, the angle of the electrodes and the distance between the electrodes showed that the average amount of purity for boxes 1, 2, 3 and 4 of section A, is 99.5, 98.5, 97 and 95%, respectively. However, the purity percentage of *D. Sophia* in the market which are traditionally cleaned was less than 90%.

The laser diffraction analysis was performed to determine the dimensions of the *D. Sophia* seeds for the first four collecting boxes, which had a higher purity (Section A). According to the results on the relative frequency charts, the particle size obtained from the four collecting boxes was considered in three ranges of 0–210, 210–610 and 610–980. Three peaks can be observed in all the plotted graphs (Fig. 5.) as the first

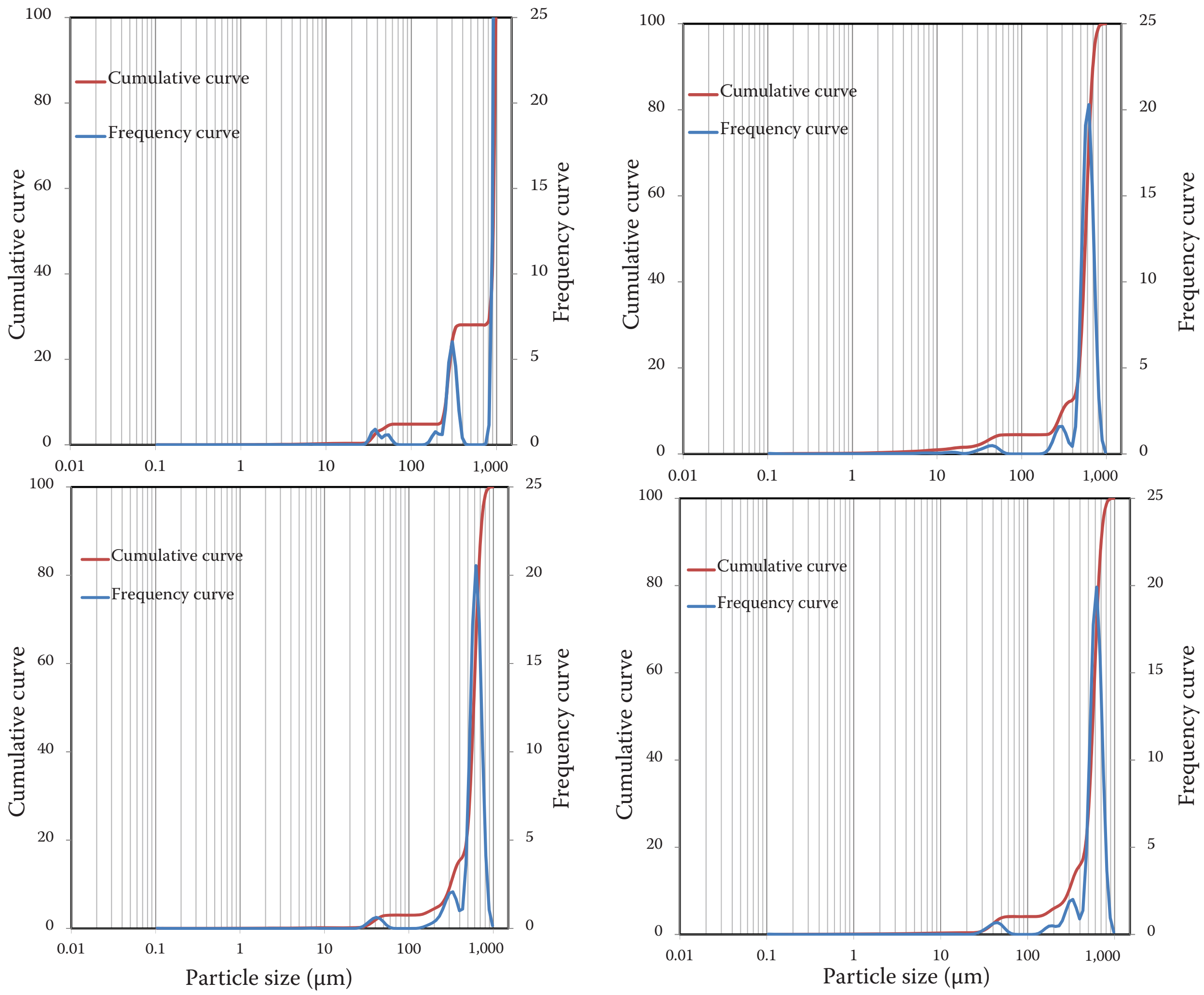

Fig. 5. The distribution of the particle size of box (a) 1, (b) 2, (c) 3, and (d) 4 versus the frequency and the cumulative curves obtained from the laser diffraction analyser

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peak is related to the very fine particles (dust and fine impurities), the second and third peaks represent the size of the elliptical *D. Sophia* seeds. Fig. 5a indicated that for box 1, there is no particle with the size less than 0.446 µm. Also, the figure implied that 4.89% of the particles in the box have a mean size of 0 to 210 µm, 23.18% of them ranged between 210 to 680 µm and 71.93% were between 680 to 980 µm. Fig. 5b shows the variation of the relative frequency versus the particle size for box 2. The diagram also illustrated that 5.25% of the particles ranged between 0 to 210 µm, 29.14% were between 210 to 680 µm and 65.61% were between 680 to 980 µm. The curve of the particle size versus the relative frequency for box 3 states that 7.13% of the material is between 0 to 210 µm, 37.68% is between 210 to 680 µm and 55.19% is between 680 to 980 µm (Fig. 5c). Finally, Fig. 5d shows the relative frequency versus the particle size for box 4. It indicates 9.6% of the material is between 0 to 210 µm, 45. 27% is between 210 to 680 µm, and 45.13% is between 680 to 980 µm. As shown in the results by moving from box 1 toward box 4, the amount of seed with a larger size decreased and the purity decreased as well.

Fig. 6 shows the total comparison of the percentages of the frequency of the seeds for the different sizes of the separated materials in the box. According to Fig. 6, it can be seen that in the range of 0 to 210 µm, the percentage of the frequency in four boxes is almost the same. However, a slight increase appears in box 4, which indicates that there are a greater amount of impurities in this box. From the investigation, the separated sample which gathered from boxes 1 to 4, the amount of impurities increased as well as its effect on the percentage frequency of the seed, although the value of the impurities for the samples is acceptable. In the seed size with a range of 210 to 680 µm, the relative frequency of box B1 is significantly lower than the three boxes of B2, B3 and B4. However, in the range of 680 to 980 µm, the inverse of the result observed and a high percentage of the relative frequency was obtained for box B1. This result is in agreement with the results of other studies on the wheat bran (Chen et al. 2014), the separation of non-standard objects from pharmaceutical materials (Naik et al. 2016), the separation of metal powdered materials (Trigwell 2003) and the separation of industrial powder materials (Cross et al. 1981). Thus, it can be argued that using this machine for the separation process, the high purity of *D. Sophia* (up to 99.5%) and a lower cost can be achieved.

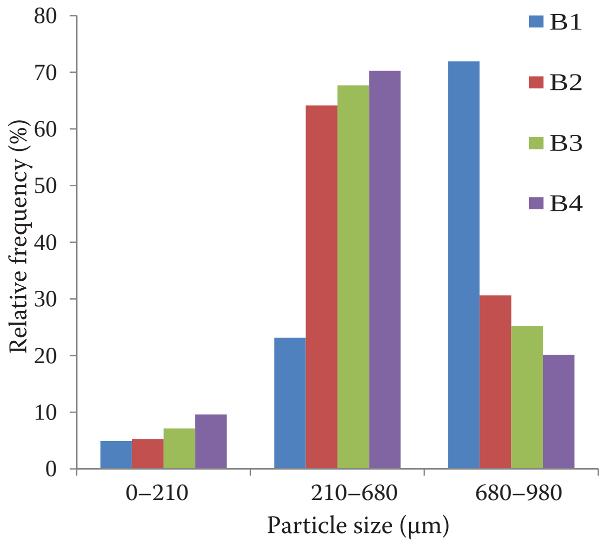

Fig. 6. The comparison of variations of the percentage of the relative frequency of the particle size in the four collecting boxes

B1, B2, B3, B4 – the divided sections of the box A

CONCLUSION

Using a laser diffraction device, a dimensional analysis was carried out on high purity *D. Sophia* seeds separated by a tribo-aero-electrostatic system. The average purity for the first section of the pure samples (A) was higher than 98% and was less than 6% for the last section of pure samples (D). The interaction of the applied voltage and the angle of the plates, the interaction of the applied voltage and the distance between the electrodes and the interaction of the distance between the electrodes and the angle of the plates on the weight of the seed gathered in the first section of the pure samples (A) were significant. According to the precision of the separation of the *D. Sophia* seeds, it can be stated that a tribo-aero-electrostatic device made with minor variations can be used to separate and purify fine products such as alfalfa and clover.

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Received for publication May 18, 2018
Accepted after corrections September 29, 2019