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Abstract. A separation device is described to obtain saffron spice after harvesting. To set the separation device, a vertical wind tunnel is developed which measures the terminal velocities of parts of saffron flower, with variations for different regions and years of production. The separation device is equipped with a vision system, which evaluates the separation and the percentage of purity of the saffron spice obtained after separation. In this paper, the design and the realization of the wind tunnel and of the separation device are described and the separation of the flower is performed and discussed, evaluating the separation efficiency.

Keywords: Saffron spice · Spice separation · Terminal velocity

1 Introduction

In recent years, the interest in the "organic" sector is growing up. In particular, in Europe and the USA, the importance of bio approach is increasing in order to emphasise the ecosystem management rather than external agricultural inputs, with the aim of maintaining the site fertility in the long term. Organic has become a way of working in many countries, mainly in EU and the USA. Consumers in general perceive these products of higher quality or healthier than those from conventional agriculture, while others prefer to believe to correspond to good practices towards the environment or the human workforce. Organic farming is a system that supports the health of ecosystems, people, processes, biodiversity and cycles by respecting local conditions. Organic agriculture focuses on innovating within tradition for environment preservation [1, 2]. Saffron is a commonly organic product. The production of saffron spice in the EU is about seven tons, four percent of world production, although ninety percent of the global commercialization of saffron, is led by European companies [3, 4]. The production of saffron has enormous labour and financial costs: one kilogram of dried spice comes from one hundred and fifty thousand flowers.

Saffron production has different phases that, nowadays, are carried out completely manually. Duration percentages of production phases are shown in (Fig. 1): duration is directly linked to the costs of the work necessary for executing each phase and to the cost of one hour of work, by dedicated personnel, in the region where this work is

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carried out [5, 6]. Harvesting and separating phases are the most time-consuming of the entire production cycle, and therefore the most cost affecting. The separation phase is the longest, while the harvesting phase is the most labour intensive [7]. Mechanisation of these phases would have a great impact in reducing these specific production costs.

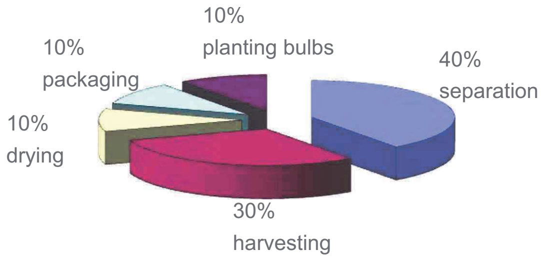

Fig. 1. The percentage of human work time to produce saffron spice.

Nowadays the most expensive and labour-intensive phases, flower harvesting and spice separation are carried out by hand, even if there are many proposals for mechanization and automation, some automatically controlled, of these production phases. A professional picker harvests about one thousand flowers per hour, considering also resting time, since harvesting is such a tiring activity. To separate the spice, one hundred minutes are on average necessary to process one thousand flowers. If an efficient robotic system had been proposed for the automation of the collection and separation phases, the production of saffron spice would have been competitive again in Europe where, today, it is marginal. Automated separation methods could bring future intensive saffron production. To this aim, many methods have been suggested to perform the separation of saffron spice. For a mechanized saffron spice separation, the most proposed method is based on the aerodynamics properties of flowers and part of it. To separate the saffron flower components, mainly the stigmas, air flows are generated to exploit the diversity of the aerodynamic characteristics of the components to be treated, in relation to their mass properties.

Researchers in [8, 9] describe and use a device where gravity and aerodynamic forces act on parts, allowing the separation in a vertical column where an air flow is generated. In [10], the authors illustrate mechanical devices to support human labour in harvesting and saffron spice separation. They describe a portable device to facilitate harvesting in the field and an air separator and also discuss the results of their method compared to the completely manual method and report the results in the field. In [11] the authors make a deep economic analysis of the saffron cultivation and the profit margin for farmers and for the brokers. In line with that analysis in [12] is shown the importance of a mechanical harvesting machine to improve the economy of a country, the efficiency and the profit margin for the farmers. In [13] a portable facilitating machine is shown and mathematically modelled, the harvesting device has a simple design capable of performing the cutting procedure using only one actuated degree of freedom. In the same paper separation of the stigmas was performed comparing three airflow systems for the separation by generating aerodynamic forces on the flower parts in the presence of gravity forces. The work reported in [14] is based on the different terminal velocities of saffron components: a separator is described to separate the stigma from the other parts of saffron flower. In [15] a new mechanised method to orientate the flowers to allow a successive separation of stigmas from saffron flowers is described. In addition, a model was validated by experimental tests, which defined the terminal velocity of the saffron flowers with given masses and geometries. The model was defined using the drag coefficient of wedges and cones vs. a half vertex angle measured and referred to in [16]. To have a more complete mechanised system to produce saffron spice, in [17] the research describes the design and characterization of a saffron flower harvesting and spice separation system. The main parts of the system are a harvesting portable device and a double flow, three-way controlled cyclone separator, where the weight, the mass centrifugal forces and the aerodynamic actions act on saffron parts for separation. The working principle is based on the difference of weight, terminal velocities and aerodynamic forces of different parts of the saffron flower. Many authors have offered systems to mechanise saffron spice production; authors also have proposed evaluating methods, using image analysis to optimise production strategies and to evaluate the efficiency of the proposed mechanised systems. In [18], using image analysis, a computer vision system is developed. The aim is to find the optimal cutting point of saffron flowers, in order to obtain stigmas. The identified cutting point is then sent to the cutting end effector. To recognize and locate saffron flowers in the field, an algorithm was developed in [19], based on image processing techniques, to enhance saffron quality by automated harvesting, with the idea of designing a saffron harvester robot for use in the fields.

A separation device is here described to obtain saffron stigmas after harvesting. To set the separation device a vertical wind tunnel is developed for measuring the terminal velocities of the different saffron parts; terminal speed that varies with the different regions and years of production. The separation device is equipped by a vision system, to evaluate the separation phase production and the obtained percentage of purity of the saffron spice, after separation.

2 Materials and Methods

The system was designed to be used in two configurations: as a wind tunnel for measuring terminal velocity or as a separator to divide stigmas from the rest of the flower.

2.1 Vertical Wind Tunnel for Terminal Velocity Measurement

The vertical wind tunnel is created using a 110 mm diameter tube (COES blue power) of 1000 mm length. At half height a window is opened in order to insert the sample which needs to be measured. The opening is sealed with a straight coupling with a transparent window. The sleeve was created by machining the straight coupling from the same line of product. At the top of the tube is inserted an unequal double branch with main diameter of 110 mm and secondary diameters of 50 mm, jointed with an angle of 45°. At the top of the branch a cap is inserted, specially modified to house a light to enlighten the test chamber. The tube is supported in vertical position by a custom-made support in wood (Fig. 2). Inside the bottom part of the tube, a 3D-printed, honeycomb-shaped, flow addresser (Fig. 3) is placed to reduce as much as possible the turbulence. The flow addresser is designed to have the characteristic length ten time greater than the diameter of the opening. Also, the wind tunnel is designed to have the diameter greater than ten times the maximum diameter of the tested object. To help the flow inlet from the bottom without creating a vortex, a 3d-printed convergent is inserted. At the bottom of the test chamber's opening there is a tray to support the material which is being tested (Fig. 4). In the higher part of the wind tunnel (near the branch), a fine wire mesh is fitted in to prevent the tested part being aspirated by the aspirator motor. Two aspirators with 1000 W power each are connected to the branch. The two motors are controlled by an electronic board (Fig. 5) to change the supply voltage using a TRIAC. The two aspirators are controllable independently. With this configuration the wind tunnel can achieve fluid speed in the chamber from 1,0 m/s to 8.5 m/s. The fluid velocity is measured with a hot-wire anemometer (Testo 405i – Range from 0 to 30 m/s – Resolution 0.01 m/s – Precision ± (0,1 m/s + 5% of m.v.)) mounted slightly above the test chamber, using a 3d printed support, specifically designed to provide a tight and sealed fit.

Fig. 2. Wind tunnel configuration, at the centre the main tube, with the windows opened, at the sides the two aspirators, at the bottom the control panel, at half-height (in orange) the anemometer.

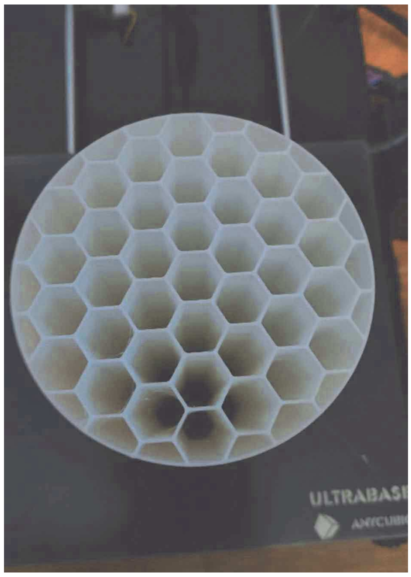

Fig. 3. Honeycomb-shaped flow addresser; its length is more than ten times greater than the characteristic size of the alveoli.

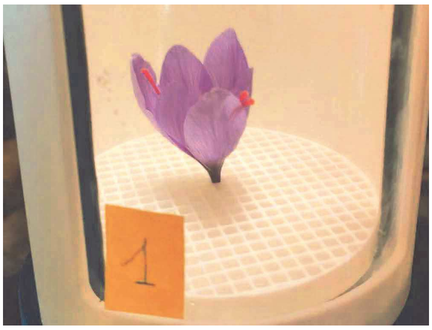

Fig. 4. Particular of the test chamber with a complete flower ready to be tested. In the figure can be seen the grid to support the flower and the reference to identify uniquely every flower.

Fig. 5. The control panel with the voltmeter of the mains voltage, two rotary switches to turn on/off the aspirators, the potentiometers to set the speed, and two voltmeters/ammeters indicating the voltage and current supplied to the aspirators.

2.2 Vertical Separator with Computer Vision to Evaluate Separation

For this purpose, the system uses parts of the wind tunnel. The flow addresser is removed. At the end of the main tube, an unequal single branch with main diameter of 110 mm and secondary diameter of 50 mm, is connected (main diameter and secondary diameter are positioned at 45°). At the end of the branch there is a tube of same diameter with a length of 500 mm. The bottom part of the tube is inserted in the base to hold all the assembly in vertical position. Under the base, where the separated stigmas will accumulate after the separation, a camera (Panasonic NV-GS15) is set up directly connected to a pc with the RoboRealm software (Fig. 6). In the software the image is processed with some filter to reduce flickering and to improve the contrast and brightness of the image. The image is then processed by some blobs filters in order to remove the background,

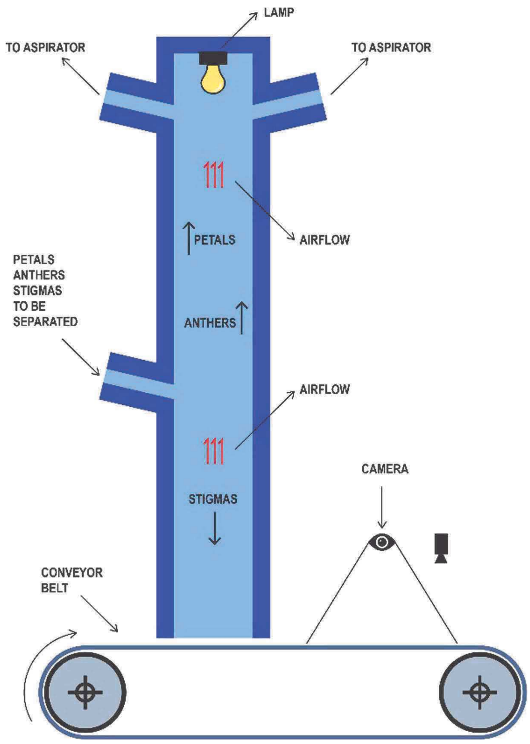

Fig. 6. Diagram showing the operating principle of the separator

then it is processed by some colour filter to identify anthers and stigmas from dimensions and colour. Then, after the software has correctly recognised stigmas and anthers, a custom-written script is used to identify uniquely each anther and stigma and to count them despite the movement of the conveyor belt (Fig. 7).

In this configuration, the concept is to aspire air from the bottom part of the tube and to move the fluid from down to up. In this case the fluid speed is set slightly above anther's maximum terminal velocity. In this system the airflow is aspirated from the top part, unlike the system discussed in [13], where the flow was generated from the bottom with a rotating fan. So, the system showed in [13] suffers from more turbulence in the air flow while the system illustrated in this paper has a steady and regular flow. Worth noting also that in this system stigmas are collected on a conveyor belt with computer vision, and the system is continuous, while the system showed in [13] is discontinuous because to collect the separated stigmas is necessary to stop the machine. If this concept is right, the stigmas should fall and drop on the conveyor belt which moves them under the camera to evaluate the correct separation. Anthers should, instead, be aspirated and caught by the net positioned above the upper window.

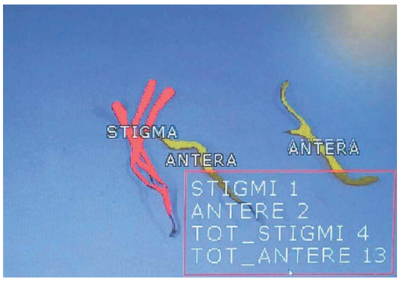

Fig. 7. Image of the PC screen with the computer vision output

3 Results

The research was done using four different batches of flower with ten flowers each: batch one and two came from the same farm and batch three and four were from different farms. Every batch had results that were congruent and collimating with the other batch.

Table 1. Results of the measurement done with the machine in the wind tunnel configuration

	Min velocity	Mean velocity	Max velocity
Petals	1.65 m/s	1.82 m/s	1.98 m/s
Anthers	1.6 m/s	2.07 m/s	2.43 m/s
Stigmas	2.7 m/s	3.13 m/s	3.5 m/s

To keep the data of every batch as much as consistent as possible, measurements were performed, when possible, immediately after the flower picking; otherwise the flower has been kept in controlled temperature and humidity conditions, the time necessary to carry out the tests. From the collected and elaborated amount of data (it must be remembered that for each saffron flower there is a stigma, three anthers and six petals), it clearly emerges that each part of the flower has a very specific range of speed, with stigmas with the highest speed followed by anthers and petals (Table 1). This trend agrees also with [8], although speeds in this research are uniformly higher for the bulbs of the high productive type and therefore producing larger flowers with higher speeds. Data show clearly that the lowest speed of stigmas is always higher than the highest speed of anthers; this allows a single-stage separation to separate stigmas from other parts of the flower, and, if separation is correctly implemented, the process should give a complete separation without the need to add more stages of separation in order to increase the purity of the separated material. It is also important the fact that, from the distribution of the terminal velocity (Fig. 8), there are not any anomalies in the trend of value, and terminal velocity almost follows a normal distribution.

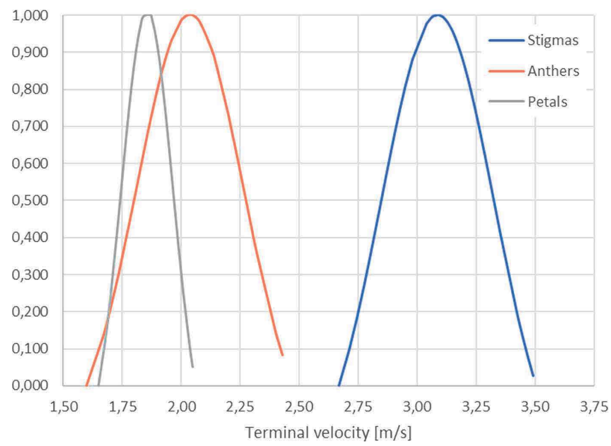

Fig. 8. Graph showing the distribution of the flower parts terminal velocity.

Comparing the flowers terminal velocity here measured, with those measured in [15] for flowers having the same half vertex angle, the values are in good agreement; the maximum error is about 15%. For a better understanding of result found in the separator configuration, it is necessary to explain in detail which objective is pursued and define some indexes to better evaluate the performance of the separator. For every flower inserted in the machine, only one stigma is expected to be dropped on the conveyor belt, and six petals and three anthers are expected to be aspirated and caught by the net. If the stigma is aspirated or anthers and petals are dropped on the conveyor belt, the separation is not correct.

The index P_{am} (Percentage of aspirated material) is calculated for each part of the flower and is defined by number of parts aspirated divided by number of flower parts inserted.

$$P_{am} = \frac{N_{P\_aspirated}}{N_{P\_inserted}} \tag{1}$$

The separation is done correctly if P_{am} index is equal to 0% for stigmas and to 100% for petals and anthers.

Table 2. Table showing the goal and the result obtained from the test for the P_{am} index.

P_{am}	Goal	Result
Petals	100%	100%
Anthers	100%	96.67%
Stigmas	0%	0%

The P_{am} index is helpful to understand whether the machine separates too much (eliminating valuable anthers) or too little (leaving anthers and petals between the anthers), but does not tell us anything about the quality of the separated product; to better understand this, a Purity index is created. The purity index is defined by the number of correctly separated stigmas, divided by the total of anthers, stigmas and petals introduced in the machine, multiplied by a coefficient due to the number of each component for every flower.

$$Purity = \frac{N_{Separated\_Stigmas}}{N_{Inserted\_Stigmas} + \frac{1}{3} * N_{Inserted\_Anthers} + \frac{1}{6} * N_{Inserted\_Petals}} \quad (2)$$

Table 3. Table showing the goal and the result obtained from the test for the Purity index.

	Goal	Result
Purity	100%	96.77%

Results referred in Tables 2 and 3 show that the separator can remove easily all petals and almost all anthers, without aspirating any stigmas. The most challenging task is to correctly remove anthers due to the closeness of the anther's maximum terminal velocity with the minimum terminal velocity of stigmas. The difference between these velocities is about 8% referred to the mean stigma's terminal velocity and the difference between maximum petals terminal velocity and minimum terminal velocity of stigmas, referred to the mean stigmas terminal velocity is about 25%. Due to the above consideration, the separation of anthers is very high but not complete.

4 Conclusion

The system here designed and realized yielded the expected results both for the dynamic and aerodynamic characterization of flower parts and for the separation process; authors consider the wind tunnel to be essential to set the correct separation threshold. In addition, results clearly show the effectiveness of this type of separation system: separated material has a high grade of purity and, above all, there is not any loss or damage to the stigmas which are the most important part due to their low quantity and high value. The vision system is effective to evaluate the efficiency of the realized separation system. Authors are confident to be able to further improve separation efficiency, mainly by improving the geometry of the tunnel and choosing other types of materials to build the separation machine. To improve production, the authors believe that a mechatronic controlled handling system for supplying the incoming material and one for the handling of the separate outgoing material may be effective.

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