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Computer based production of Saffron (Crocus sativus L.): From mechanical design to electronic control

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ABSTRACT

The article describes the design and implementation of a computer based industrial system for production of saffron. The proposal is based on an automated greenhouse with temperature, light and irrigation control together with harvesting and stigma separation devices. The harvesting device has been specifically developed using scalability properties and computer vision. The greenhouse is designed to increase the crop density if required generating a more sustainable and continuous production. The main advantages of the proposed method are as follows: the harvesting of the saffron flower and the procedure to get the stigmas are carried out in the same process; the greenhouse allows to significantly extend the flowering time of the saffron plant; and higher productivity per worker and per planting area is achieved. In order to show the feasibility and applicability of the proposed approach, real experimentation has been carried out for the extension of the flowering time and for the harvesting and stigma separation devices and successful results have been obtained.

1. Introduction

1.1. Basic concepts about saffron

Saffron is an ancient spice that comes from the dried stigmas of this plant. Saffron is one of the world's most expensive spices for decades and its cultivation is one of the oldest agricultural activities. It has a very high price per kilogram (Skinner et al., 2017), not so much for its cultivation difficulties but because flower pickup and stigma separation is usually carried out manually which is laborious and low in efficiency.

The conventional cultivation method is based on plating saffron corms (Sampathu et al., 2009). Saffron plant grows between 10 cm and 25 cm height and has a spherical corm with a diameter of 2.5 cm to 3.0 cm. Usually one to five flowers bloom for each corm. Each flower has six violet petals and three Pantone red stigmas. The dried stigmas, i.e., the saffron, have an intense aroma.

The saffron crop experiences four periods:

- *Vegetative period*: The corm developing starts at the end of autumn and continues during the whole winter. This period will mainly determine the final size, quality and number of flowers per plant.
- *Reproductive period*: This period occurs in the first month of the spring season and is the most critical phase for the saffron plant development.
- *Dormant period*: This period typically starts in the second month of the spring season when the temperature is high.
- *Flowering period*: This period starts at the end of the summer and ends with the emergence of the saffron flower, which requires days with short photo-period of less than 11.5 h to blossom and a low temperature, typically between 10 °C and 15 °C.

The corm planting is typically carried out in the second part of the spring season. Then, the saffron production undergoes a four-year cycle (Rubio Terrado, 2007). After these four years, the cycle begins again planting new corms and it is also convenient to consider soil fertility restoration (Lal, 2015). The corms multiply every year to such an extent that around five new corms are obtained from each planted corm (Mollafilabi et al., 2012). Lifting and separation of corms allows replanting them (Hill, 2004).

The degree of human intervention regarding the corm managing is quite automated and can be partly performed with farm vehicles (tractors), mechanization methods and specialized tools (Mohammadh, 2006). However, both the saffron flower harvesting and the stigma separation from the rest of the flower is still performed manually. In

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Abbreviations: FIFO, first-in first-out; AF, artificial flower; CRF, closed real flower; SRF, semi-closed real flower; ORF, open real flower; CBS, conveyor belt speed; FA, flower angle; DI, default illumination; AI, adjusted illumination; fpmr, flowers per minute and row; AVG, average value; STD, standard deviation

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this sense, the latter is the most delicate part of the process (Souret and Weathers, 2008) since the flower must be cut in the right position to get the desired quality, i.e., the lower part of the stigmas must not be included to have the highest saffron quality.

Nowadays, the human work required to produce saffron with the traditional method is approximately 1.200 hours in average per hectare and per year (Rubio Terrado, 2007), where 865 h (72%) are required for the flower harvesting and the stigma separation process. The average production of dried or roasted saffron is between 10 and 15 kg per hectare (Agrifood Statistics Yearbook, 2019), which means between 1.0 and 1.5 million flowers per hectare that are harvested in a period between 30 and 35 days.

1.2. Automation of saffron production

Although the use of pots and other containers for saffron production is not new for agronomic trials (irrigation, fertilization, etc.) and small farms, its use is not common for large-scale saffron farming. For instance, the Spanish company “Azafranes Machuela SL” has recently proposed the use of bins for saffron production, see https://www.youtube.com/watch?v=8iRM9a92sq8. These bins consist in prismatic containers made with wooden boards of around half a meter in height and an area of 0.6 m^2. The main advantages of this approach are as follows: ergonomic improvement for saffron flower harvesting; reduction of the cropping; better management of plant diseases, weeds and pests; and the possibility of water-control (irrigation and drainage).

The automation of saffron production could benefit from the results presented by Molina et al. (2004a,b) and Molina et al. (2005) about the role of temperature, humidity and illumination in the development of the saffron plant and flowers. In particular, Molina et al. (2004a) concluded that: temperature is the main environmental factor for the saffron flowering; sprouting could be accelerated by a short curing at 30 °C; shoot growth occurs at any temperature between 1 and 30 °C although the optimal temperature for shoot growth is 23–25 °C, which is also optimal for flower initiation; and the optimal temperature for flower emergence is 17 °C, which is markedly lower than for organogenesis.

Several devices have been independently proposed in the literature to automate and improve specific tasks of saffron production (harvesting, pruning, etc.), although none of them is focused on solving the global problem of industrial saffron production. For instance, Garvi (1987) presented a Spanish patent proposing a device to automatically produce the saffron, although the description is vague, imprecise and incomplete. Bertetto et al. (2010) and Bertetto and Ricciu (2012) proposed a manual device for harvesting and separating the stigmas as a tool to enhance deprived regions of the Mediterranean Sea, but the device is far from being an industrial solution. Finally, Melidis and Vatterott (1984) proposed an apparatus for harvesting the bloom parts of crocus flowers, although the flowers must be manually placed on a particularly adapted conveyor belt.

1.3. Proposed method

The method proposed in this work tackles the global problem of saffron production, providing a fully automated system with scalability properties. The proposal is based on an industrial farming area that includes: a greenhouse with temperature, light and irrigation control; conveyor lines to move the trays of saffron plants inside the planting area; an automatic harvesting device based on parallelization principles and computer vision; an automatic stigma separation system; etc. This work also proposes to extend the flowering time of the saffron plant from 5–6 weeks for the traditional method (Skinner et al., 2017) to 12 weeks using the information provided by Molina et al. (2004a),Molina et al. (2004b) and Molina et al. (2005), which helps to increase productivity and to amortize of the machinery and facilities of the proposed approach.

2. Material and methods

2.1. Overview of the industrial crop system

This work presents a method to industrially produce saffron. The process starts planting the corms extracted from a set of cold chambers in planting trays using previously prepared soil. Then, the trays are stored in a greenhouse where temperature, light and irrigation are controlled remaining there until the flowering time. When flowers of a planting tray have bloomed, they are cut and sent back to the storage area of the greenhouse waiting to a new group of flowers. The cut flowers are sent to the stigma separation device, where petals are removed. This is repeated until the last flower is cut, then corms are lifted from the planting trays and they are sent again to the cold chambers. If cycle of years is covered, corm division is performed before introducing them into the cold chambers. Finally, the process starts again.

Corms can be easily forced to stretch on saffron production up to 12 weeks by following the guidelines described by Molina et al. (2004a), Molina et al. (2004b) and Molina et al. (2005). Obviously, the production could be stepped along the whole year by controlling the four periods of saffron crop, e.g., an artificial winter could be generated in summer, although it would probably be too much expensive to make saffron production profitable.

2.2. Design of the industrial greenhouse

The industrial greenhouse proposed in this work is based on the design shown in Fig. 1. This figure represents the storage and growth area as the place where a set of planting trays are gathered. This storage and growth area is formed by a set of conveyors that have the same length and are arranged parallel one to another. The arrows indicate the forward movement direction of the trays that contains the corms. The trays are stored in this area while the corms produce saffron flowers. This area can be implemented in one or more storeys to increase the plant productivity. In case of multiple storeys, horizontal and vertical space between transport trays should be left in order to allow the natural light pass through and to allow flowers grow freely. The crop density in this case could be increased if needed (e.g. with two, three or four storeys).

Following the visual description of Fig. 1, the trays are extracted by a transfer mechanism from the storage and growth area to be sent to the cutting device through the feed conveyance line. Once the trays are processed (flowers are cut), they are sent back to the storage and growth area. The extraction and insertion movements of trays are obtained using a group of conveyance lines specially designed to create a closed circuit with a first-in first-out (FIFO) topology.

When trays of the greenhouse are not moving, corms are stored to favor flowers growth. When there is a tray with one or more flowers that must be cut, the tray is extracted transferring it from the storage and growth area to the feed conveyance line and then sent to the cutting area. In the cutting area, a set of cutting units automatically receive the trays in order to cut the flowers and a group of suction conducts bring them to a separation tank. The trays are provided with wheels in order to allow easy forward linear movements. Conveyance lines are equipped with a chain and an electrical actuator to move several trays at the same time. In this design, the tray extraction is performed by a transfer mechanism.

In the case that a tray in the middle of the storage and growth area has to be processed (cut), other containers can pass through the feed conveyance line avoiding being processed by the cutting unit. This allows a sequential access to any container when needed. To increase the performance of the system in long term, a selection of the most productive corms could be implemented so that the best of them could be used in the next season rejecting the less productive ones. To do so, each planting tray is marked with a barcode, a RFID label or an equivalent device. The cutting machine is continuously counting the

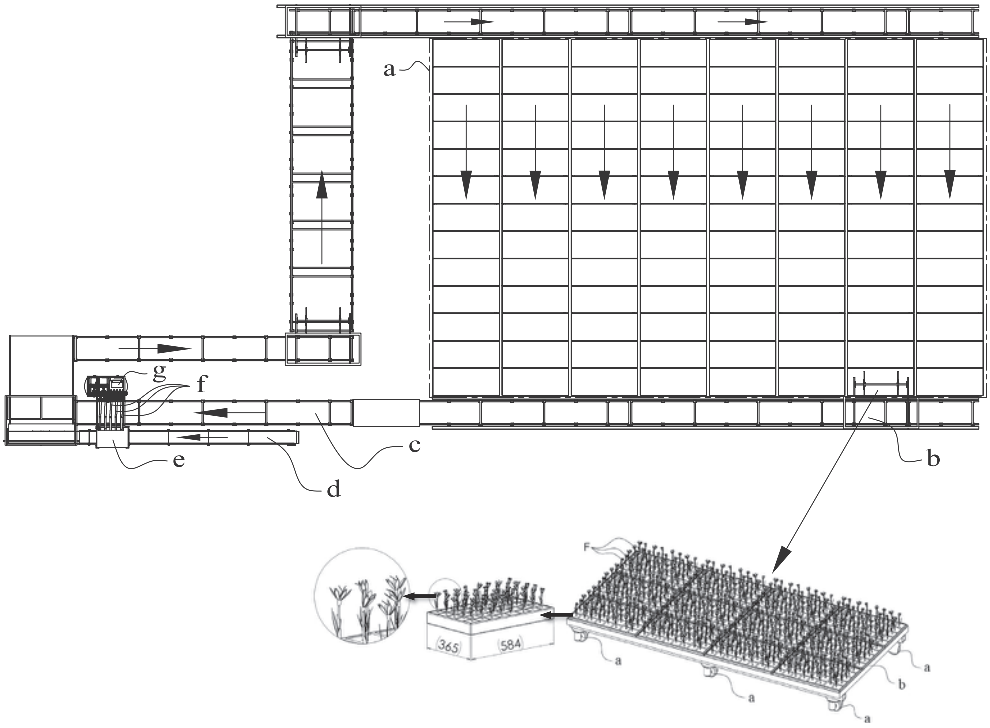


Fig. 1. Representation of the farming area as an industrial plant. This greenhouse allows growing flowers, harvesting them and separating stigmas as end product. A detailed description of how it works can be seen in https://www.youtube.com/watch?v. = 5qZA0CsAEAE.

number of flowers generated by each corm (in each planting tray) and, after the season, the most productive corms are selected.

The greenhouse is provided with an automated system to control irrigation, humidity, illumination and temperature in order to facilitate the saffron continuous production (Deng et al., 2018). The cutting devices need an absolute lack of leaves and the leaves can be eliminated by controlling the humidity and rain over the corms (Negbi et al., 1989).

2.3. Mechanical design of the parallel harvesting device

The purpose of this device is to detect the saffron flower directly from where it is planted and cut it at the right position. Modularity, parallelization and scalability properties have been the requirements for designing this element of the system.

The harvesting device is made up of a set of cutting units, see Fig. 2, that are fed by the saffron flowers hold in trays, where containers distributed in rows and columns hold the corms. The harvesting device is provided with a conveyor line for carrying trays, where they are configured and aligned in the direction Y-Y′ shown in Fig. 2, transverse to the forward movement direction X-X′ of the referred conveyor line. Each cutting unit is equipped with an image sensor (see camera [c] shown in Fig. 2) and a processing unit that computes the cutting height for each flower as they move. A background panel (see [g] in Fig. 2) is located opposite to the image sensor in order to prevent the camera to detect the rest of the flowers arranged in the viewing direction of said camera.

Each cutting unit is equipped with a cutting element (see [e] in Fig. 2) movable in height and configured for cutting the flower as it moves at the height computed by the processing unit of the image sensor. Once the flower is cut, a suction conduct (see [d] and [i] in Fig. 2) gets the flower (stigmas and petals) and sends it to the classification tank. A runner (see [b] in Fig. 2) is configured for tilting the stalk freshly cut by the cutting element so that it does not obstruct the view of the cameras of other shifted cutting units.

Fig. 3 shows a representation of the harvesting device with 8 cutting units using a parallelization scheme to increase productivity, i.e., each flower row is cut by a cutting unit, see the video https://www.youtube.com/watch?v = G6dw42XE4do for a visual description of a 5 cutting parallel units device. The cutting units are consecutively shifted according to the forward movement direction X-X′ such that each one progresively cuts the same row of flowers of the container. Note that the number of cutting units can be modified to adjust its features to the required production. Note also that the proposed parallelization allows to configure the device to get the desired productivity without changing the speed of the transport system.

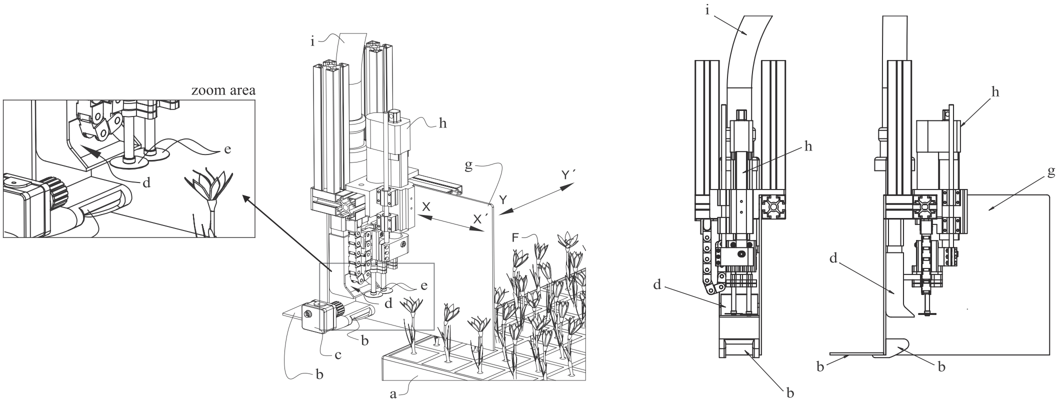
The implementation has been carried out using a linear actuator to modify the height of the cutting discs that will cut the flowers. The motors that move the cutting discs rotate at different speeds (speed of the cutting disc above must be lower than that of the disc below) so that the circular cutting blades perform a clean and precise cut.

In order to calculate the cutting position, a MiniPC is used to process the image acquired by a color camera, whereas a voltage regulator is used to control the luminance of a fluorescent lamp equipped with electronic ballast.

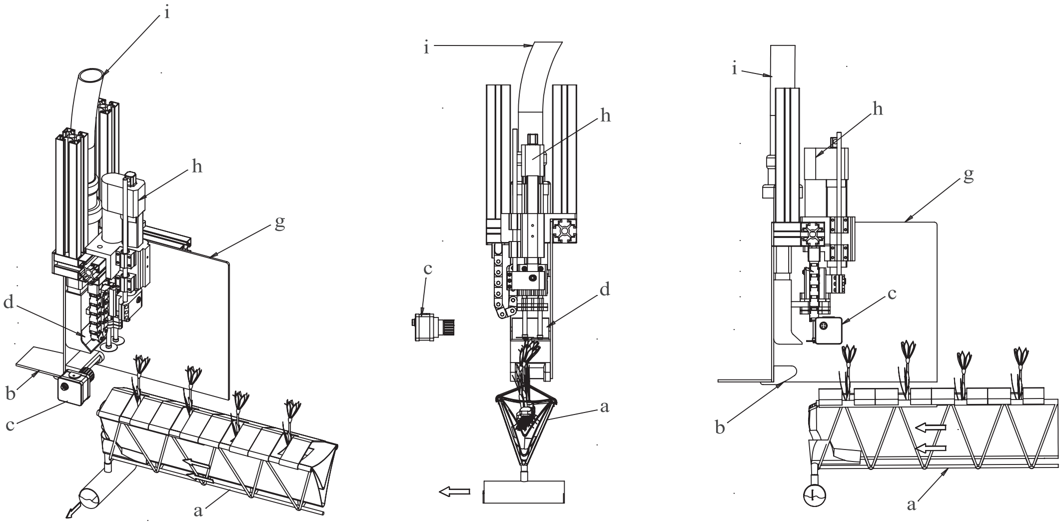
2.4. Image processing program

Computer vision has been recently used with success to improve the automation of many agricultural tasks, e.g., see Onwude et al. (2018), Patrício and Rieder (2018), Satorres-Martínez et al. (2018), and Wan et al. (2018), among others. In this sense, this work proposes a computer vision algorithm running in the processing unit (MiniPC) in order to compute the cutting height for each flower. It has been developed using the OpenCV library due to its popularity and versatility. A black background is used to make easier and faster the segmentation task. The Fisheye Camera Model module of OpenCV library (cv::fisheye) has been used to avoid barrel distortion in the acquired image. Moreover, the relationship between the image plane distance and the real distance has to be known and therefore, a calibration process has been performed.

Once the image is acquired, it is converted from the RGB color



(a) Cutting unit and flowers emerging from the container with corms. The container moves along the direction X-X’ towards the cutting unit. Depicted elements are: [a] corm container; [b] runner; [c] image sensor; [d] suction conduct inlet; [e] cutting elements; [F] flower/s; [g] panel to block the background view; [h] linear actuator and [i] suction conduct outlet.



(b) Cutting unit and flowers emerging from the container with corms. The container moves along the direction X-X’ towards the cutting unit. Depicted elements are: [a] corm container; [b] runner; [c] image sensor; [d] suction conduct inlet; [e] cutting elements; [F] flower/s; [g] panel to block the background view; [h] linear actuator and [i] suction conduct outlet.

Fig. 2. Mechanical design of the cutting unit.

channel to the HSV color channel using the cvtColor function (included in OpenCV). Then, a segmentation based on color is performed to discard the background and some parts of the cutting module. The resulting image is thresholded using the inRange function, obtaining a binarized image. On this image, dilating and erosion filters are applied to eliminate noise. After that, the entire matrix image is searched to find groups of pixels. The group that meets the size requirements will be identified as a flower. On this group of pixels a circle and a line are drawn at the height specified by the machine operator (this parameter is called Offset). The line represents the height where the flower will be cut. This operation is shown in Fig. 4, where a rightly offset value is chosen in Fig. 4(a), whereas a too high offset value is chosen in Fig. 4(b). The program implemented in this work has 12 configurable parameters. The most important of them are the following:

- Offset - This parameter is responsible for varying the height at which the flower will be cut. The higher this value, the lower the flower will be cut and less quality saffron will be obtained. A graphical example for this parameter is shown in Fig. 4(a) and (b).
- Binarize - This parameter varies between 0 and 255. It sets the threshold for which a certain gray level is considered to be white or black (this operation is performed after the segmentation based on color). The higher this value, the better the flower will be discriminated but, on the other hand, dark flowers will be detected worse. Fig. 4(c) and (d) show the effect of this parameter on the image.
- Width - The image is continuously processed and all flowers inside the image frame are located and marked, but the cutting signal is sent to the actuator only when a flower is inside a certain region or band. The greater the Width variable, the faster the flowers can move.
- Sliding - The sliding parameter modifies the horizontal position of the detection band (Width parameter previously described) to the right, so that the position is sent to the actuator when the flower reaches a certain position.

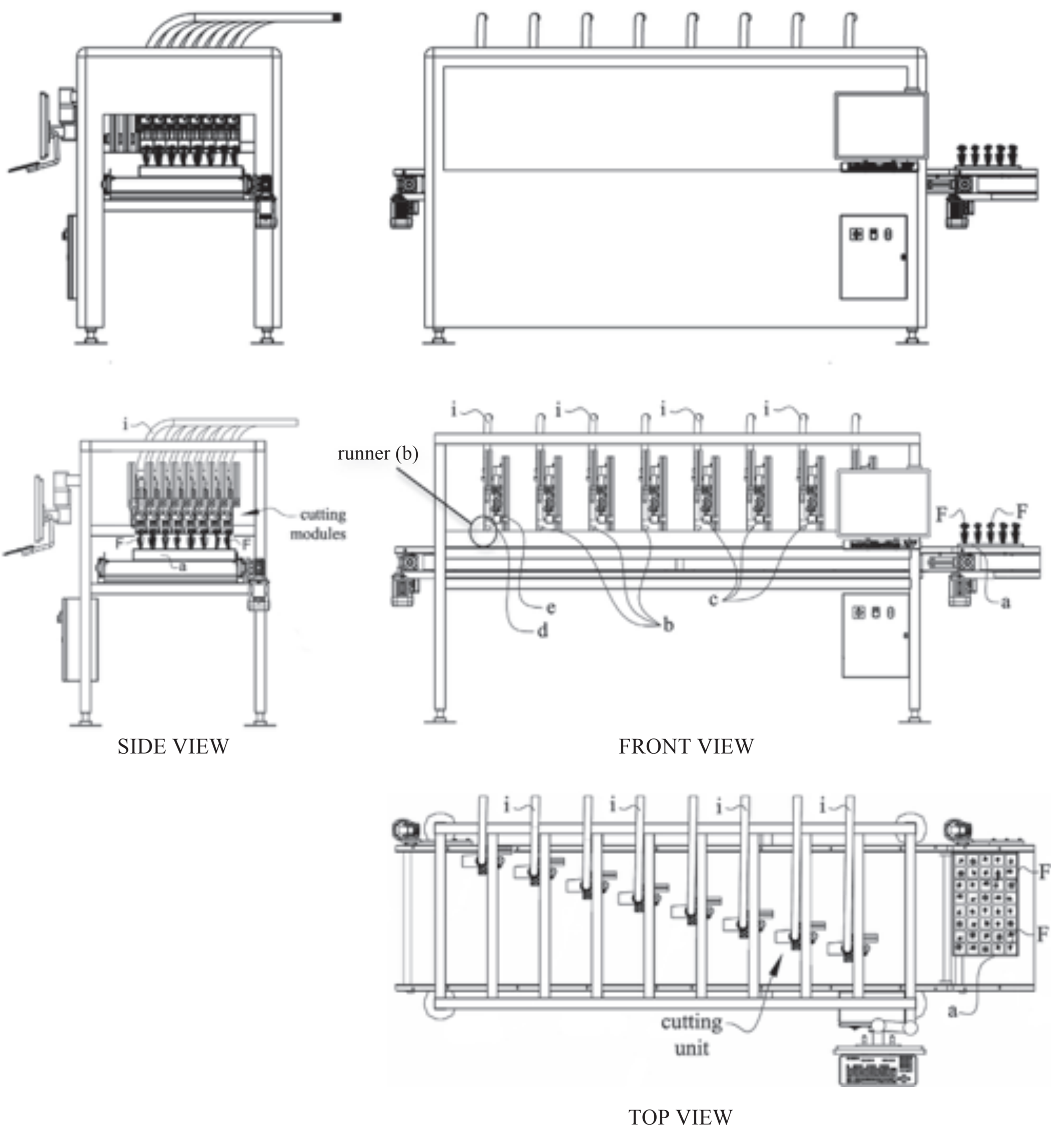


Fig. 3. Parallel harvesting device with the key elements: a conveyor belt leads the corm container or tray [a] through the device; a runner [b] is configured for tilting the stalk freshly cut by the cutting elements [e] so that it does not obstruct the view of the rest of the image sensors [c]; additional depicted elements are: [d] suction conduct, [F] saffron flowers and [i] suction conducts.

2.5. Design of the device to get the stigmas

Once the flower is cut, a suction conduct (shown in Fig. 2[d]) absorbs the flowers due to the depression generated by the suction pump, see [c] in Fig. 5(a) and (b). The suction conducts converge into a single hopper in which there is arranged a blowing pump injecting air into a distributor ring (see [b] in Fig. 5(b)) configured in a toroidal shape, surrounding the single conduct, and with an outlet in the form of an opening or tangent groove (see [d] in Fig. 5(b)) according to a section of the toroid, towards the inside of the single tube which is oriented according to the forward movement direction of the air conveying the flowers. The flowers reach a tank (see [a] in Fig. 5(a) and (b)) inside which there are walls (see [g] in 5(b)) forcing a zig-zag flow. The tank is extended horizontally and the baffle walls are interposed in the flow. These walls are placed vertically, up and down in an alternating manner, to force this zig-zag flow and they cause low aerodynamic drag parts to fall to the bottom and become incapable of overcoming the baffle walls located downstream. The high aerodynamic drag parts are indeed capable of overcoming the baffle walls until they move in a slower flow causing the decantation. This configuration leads to a selective classification of the stigmas (i.e., the spice or end product to be marketed) from the rest of the flower in one of the cavities of the tank.

2.6. Sample preparation

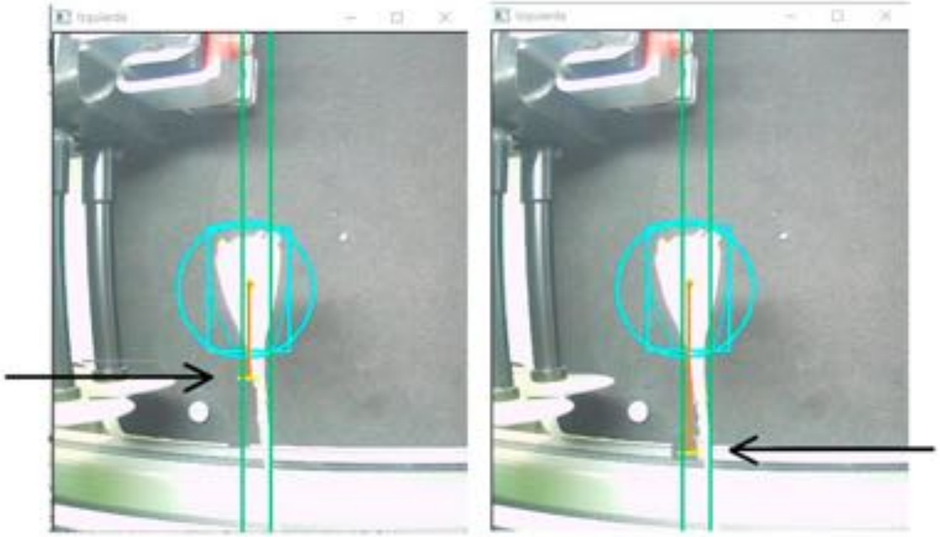
The flower must grow with very few or no leaf so that they do not occlude the flower or the corolla tube. In particular, in this work all tested corms had flowers growing normally but leaves were completely eliminated.

3. Results

3.1. Experimentation and implementation of the industrial greenhouse

Using the information presented by Molina et al. (2004b) and Molina et al. (2005), the blooming of the saffron flower can be extended by both controlling the temperature simulating the arrival of the autumn and controlling the illumination intensity. These actions are known as corm forcing.

Corm forcing techniques are well known in the state of the art. For instance, Dole (2003) presented the cold requirements for forcing and flowering of geophytes, whereas Cun-xiang (2006) focused his research



(a) Rightly configured Offset value (b) Too high value of the Offset parameter

(c) Poorly configured binarization threshold (d) Well configured binarization threshold

Fig. 4. Adjustment of the Offset value: this value is decreased to obtain a better saffron quality but with a detriment of the produced quantity. Binarization of the flower with different threshold values: the image has to be clearly defined and the outline of the flower has to be distinguished from the background.

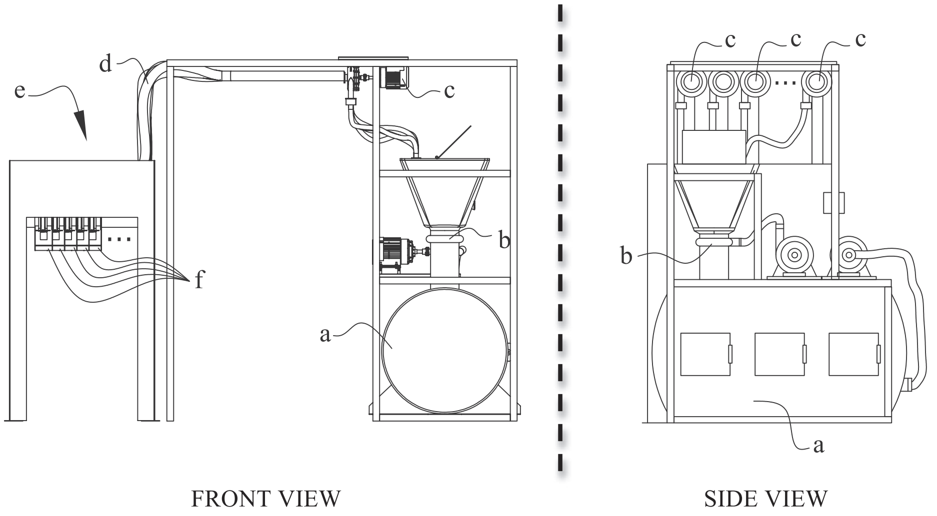
in forcing of Paeonia suffuticosa via low temperature.

In this work, corm forcing is performed by following the indications of Molina et al. (2004b) and Molina et al. (2005) so that the flowers in the greenhouse blossom step by step, from one side of the industrial facility to the other. Thus, the trays of one end of the greenhouse will be the first to bloom and those of the opposite the last ones, easily reaching a difference between one and another of 12 weeks.

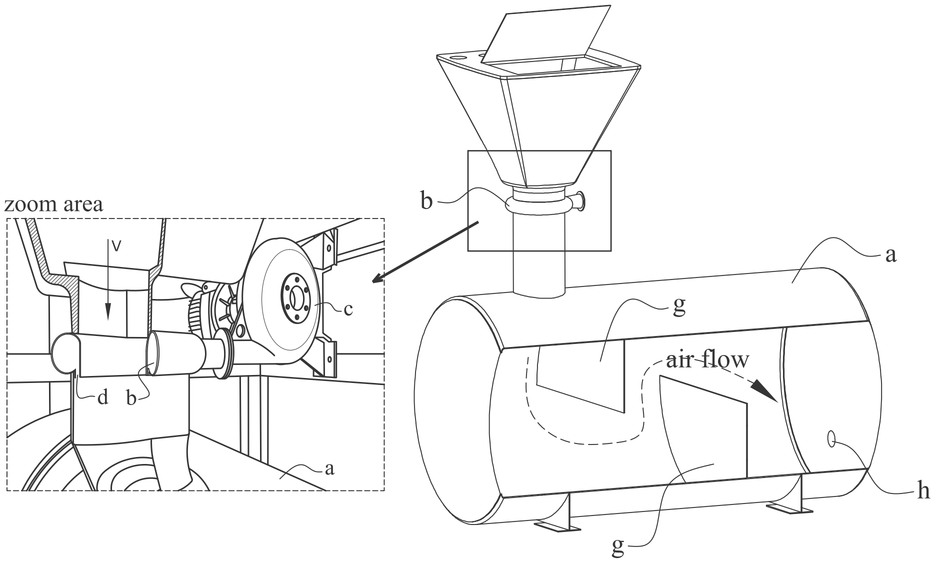
In the experimentation the corms were lifted after leaf withering and they were stored at 25 °C for a non-specific period of time until the flowering is forced using a temperature of 17°C. This allowed a flowering period from September to December. The earlier flowering was achieved lifting the corms before leaf withering (in May) and curing the corms at 30 °C for twenty days before using special chambers for incubation at 25 °C. Flowering was delayed storing the corms at a low temperature to simulate a longer winter.

The layout of the greenhouse is based on well known and widely tested commercial platforms. Companies like New Growing System (NGS, http://ngsystem.com/en) have developed automatic greenhouses to perform intensive agriculture in arid and semiarid regions optimizing the needed resources (especially water and manpower). In the case of NGS, the company has created a growing system aiming the optimization of space and automation and their system is suitable for the Crocus sativus production proposed in this work. The natural light can be controlled through the use of automatic blinds and curtains (Tripanagnostopoulos et al., 2005) and, in case of supplementary illumination needs, additional elements can be added to the facility (Wang et al., 2002).

The planting trays shown in Fig. 1 have been selected to maximize



(a) Front view and Side view of the stigma separation system: [a] tank; [b] air distributor ring; [c] suctioning/blowing pumps; [d] suction conducts; [e] cutting machine and; [f] cutting units.



(b) Detail view: [a] tank; [b] air distributor ring; [c] blowing pump; [d] output of the distributor ring designed to produce an air blade to generate a depression in the hopper; [g] walls to force zig-zag air flow; [h] air outlet.

Fig. 5. Representation of the device to get the stigmas. It includes the elements to get the stigmas from the rest of the flower and decantation tanks for classification.

the density of the industrial greenhouse making the system as much intensive as possible. In this sense, the distance between single flowerpot centers has been empirically set to 60 mm. This distance is the minimum required by the great majority of corms to fit in having the minimum amount of soil required to grow. The depth of the flowerpots is 10 cm and it contains the soil required by corms to grow and bloom.

The planting tray can be easily found from different manufacturers or sellers. The company Servovendi (https://www.servovendi.com/) supplies standard planting trays of 40 flowerpots (5 rows and 8 columns) with a size of 315 mm × 495 mm. That means an amount of soil of 0.015 m^2 and around 15 kg weight. This type of tray can be managed by a human operator in the harvesting device.

3.2. Experimentation of the image processing program

The computer vision algorithm that obtains the cutting height of the flower has been tested with four types of flowers: artificial flower (AF), closed real flower (CRF), semi-closed real flower (SRF) and open real flower (ORF). The results of this test are shown in Table 1 where five groups of 25 flowers of each type have been tested to get a success percentage of the computer vision algorithm. It can be seen that the average success percentage is 95, 2% and 89, 6% for CRFs and SRFs, respectively, and it drops down to 59, 2% when the flower is not on the best conditions, i.e., for ORFs. These data show how important is to cut the flower between the blossom day and no longer than 3 days after,

Table 1
Success percentage of the computer vision algorithm for each type of flower (25 flowers of each group have been evaluated). Abbreviations: AF, artificial flower; RF, real flower; CRF, closed real flower; SRF, semi-closed real flower; ORF, open real flower; AVG, average value; and STD, standard deviation.

Trial No.	AF	RF			AVG	STD
		CRF	SRF	ORF		
1	100	96	88	60	86	15,62
2	96	96	92	64	87	13,38
3	100	92	88	60	85	15,07
4	96	96	92	56	85	16,82
5	100	96	88	56	85	17,29
AVG	98,4	95,2	89,6	59,2		
STD	1,96	1,60	1,96	2,99		

when the flower is still open.

About the image processing time, the whole algorithm, including image acquisition and data transferring, takes around 50 ms, which allows to process each flower five times before sending the average cutting height to the actuator.

3.3. Experimentation of the parallel harvesting device

Two reduced versions of the cutting machine have been implemented, one for one row and another one for two rows trays. The reduced version for one row can be seen in https://www.youtube.com/watch?v=1bwGmkEvqCw and has been used to test the concept of the cutting unit. The two rows implementation can be seen in Fig. 6 and a 3D model showing the designed device can be seen in https://www.youtube.com/watch?v=q69VrRZzeGE. The real performance for the two rows implementation can be played at https://www.youtube.com/watch?v=VMtM_sXGwBM, which illustrates how simple is to add a new cutting unit to a cutting machine. Note how the runner is tilting the stalk freshly cut so that it does not obstruct the view of the rest of the image sensors. Table 2 indicates the cutting success obtained with the harvesting device depending on:

- The flower type: CRF and SRF.
- The conveyor belt speed (CBS), from 10 flowers per minute and row (fpmr) to 40 fpmr.
- The flower angle (FA) θ, considering two cases: $\theta < \theta_{th}$ and $\theta > \theta_{th}$, where $\theta_{th} = 15^\circ$ represents a reference angle used to establish if the FA is low or high.
- The illumination adjustment: default illumination (DI) and adjusted illumination (AI).

Note that, since the separation distance between flowers is 60 mm, $10, 20, \ldots, 50$ fpmr correspond to a conveyor belt speed of $0.01, 0.02, \ldots, 0.05$ m/s, respectively. It is interesting to note as well that the maximum CBS is related with mechanical issues rather than image processing issues. In particular, the linear actuator has a maximum speed of around 4 cm/s and, hence, needs a maximum of 1 s to get the desired height, since the maximum height difference between consecutive flowers is typically less than 4 cm. Thus, the cutting unit needs at least 1.25 seconds ($1 + 0.05 \cdot 5$) to cut a flower, yielding the limit of 48 flowers per minute (60/1.25). For this reason, a maximum CBS of 40 fpmr has been considered in Table 2.

Table 2 shows that for low FAs ($\theta < \theta_{th}$), the CRFs are 96%

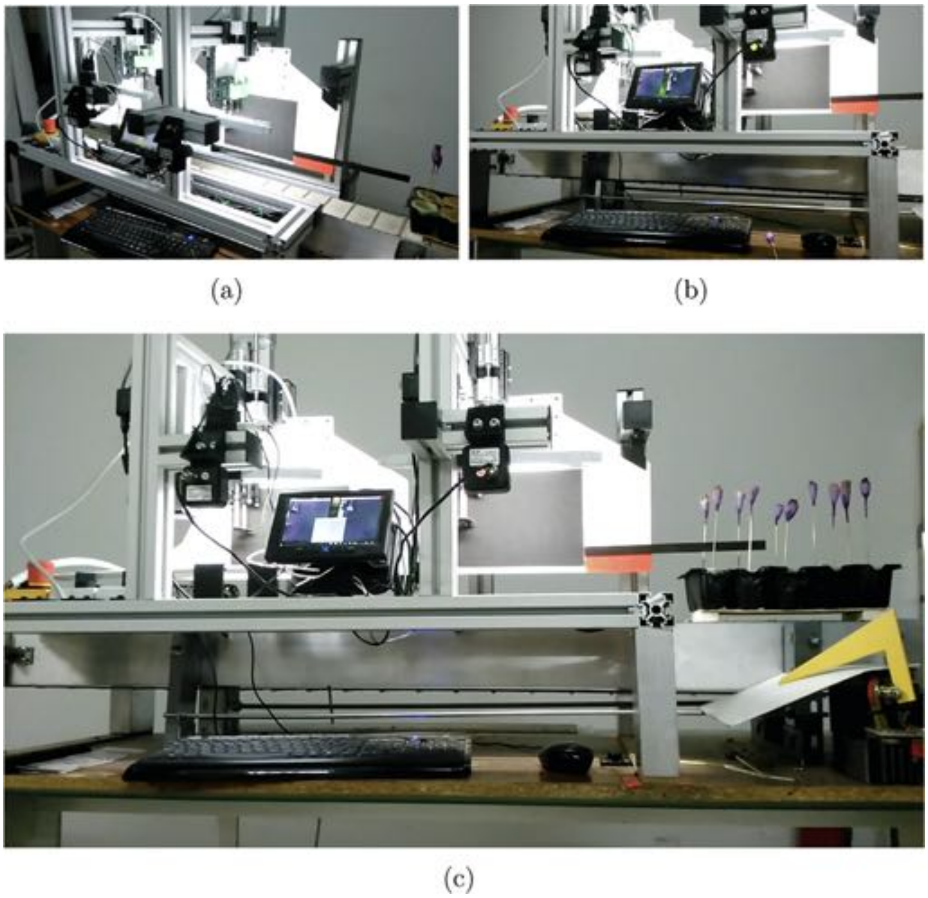


Fig. 6. Real implementation of a cutting machine with two cutting units (two rows machine). Elements shown are: image sensors, linear actuators with cutting elements, panels to block the background view, illumination systems and the conveyor belt that transports the bulb containers.

Table 2

Cutting success (%) of the parallel harvesting device depending on the flower type, speed of the conveyor belt, flower angle and illumination adjustment (25 flowers of each type were analyzed and the success rates were obtained with fully flowered plateaus). Abbreviations: CBS, conveyor belt speed; fpmr, flowers per minute and row; FA, flower angle; DI, default illumination; AI, adjusted illumination; CRF, closed real flower; SRF, semi-closed real flower; AVG, average value; and STD, standard deviation.

CBS (fpmr)	FA	DI			AI				
		CRF	SRF	AVG	CRF	SRF	AVG	Total AVG	STD
10	$\theta < \theta_{th}$	96	88	92	96	92	94	93	2,99
	$\theta > \theta_{th}$	88	76	82	96	84	90	86	6,65
20	$\theta < \theta_{th}$	88	84	86	92	92	92	89	3,20
	$\theta > \theta_{th}$	80	80	80	88	84	86	83	3,20
30	$\theta < \theta_{th}$	72	68	70	80	76	78	74	4,31
	$\theta > \theta_{th}$	64	64	64	72	68	70	67	3,20
40	$\theta < \theta_{th}$	68	64	66	76	72	74	70	4,31
	$\theta > \theta_{th}$	60	56	58	64	56	60	59	2,99
Total AVG		77	72,5		83	78			
STD		12,12	10,48		11,09	11,66			

successfully cut for low CBS (10 fpmr) independently of the adjustment of the illumination parameters. In case of using the AI, the CRFs and SRFs are successfully cut for both low ($\theta < \theta_{th}$) and high ($\theta > \theta_{th}$) FAs (the maximum FA used in the tests was around 30°).

The results presented in this work have been obtained using AFs and RFs. The harvesting device behavior is quite similar in both cases as it can be seen in Table 1. This similarity is also reported by Antonelli et al. (2011) and it allows to use AFs for image processing tests and adjustments when out of the flowering period.

Next, a design example for the parallel harvesting device is detailed based on the results of Table 2. A producer needs an average of 20 people per hectare for harvesting and separating the stigmas during the season. However, during the production peak (blossom days), up to 35 workers can be needed to perform the task. Moreover, a worker can produce at an average rate of 10 flowers per minute (see Section 4.1). Therefore, one hectare requires a maximum production capacity of 350 flowers/min, which can be obtained according to Table 2 using a nine-row harvesting device working at a speed of 40 fpmr. With this configuration the success ratio of the machine would be between 59% and 70%, too low for an industrial plant. Hence, speeds higher than 30 fpmr should be avoided. In particular, to get a success ratio between 84% and 92%, two nine-row harvesting devices would be needed in order to speed down the conveyor belt to 20 fpmr. Using this configuration, and taking into account that one corm requires around 40 cm^2, the harvesting of a greenhouse hectare would take $(10^4/0.004)/(2{\cdot}20{\cdot}9{\cdot}60{\cdot}24) = 4.82$ days. Note that real flowers should be processed when closed or semi-closed. Thus, the cutting machine has only two or three days to process a flower after the blooming day.

3.4. Experimentation of the device to get the stigmas

The pumps and blowers are implemented using a device with three phases and two poles motor that supplies an air flow of $1.82\,\mathrm{m}^3/\mathrm{min}$ with a tube diameter of 1.5 in.

The device to get the stigmas shown in Fig. 5 has been tested for 100 cut flowers. The flowers have been thrown inside the hopper as the cutting machine would have done. The size of the tank is 800 mm of diameter and 1200 mm long. Moreover, the two walls have been placed at 400 mm and 800 mm as shown in the figure. With this features, the test has been performed getting the results shown in Table 3. Between 82,35% and 97,62% of the elements were properly separated. These results could be improved by optimizing the device or the position of the walls. Although these results are acceptable, the improvement of this subsystem remains as further work.

It is worth noting that the stigma filaments obtained in this results were not joined. However, the cutting height used in the image processing algorithm of the cutting phase can be modified to have the dried stigmas joined (three filaments) in order to meet the product quality specifications of some countries such as Italy.

4. Discussion

4.1. Comparison with traditional approach

For the traditional method, the saffron production distribution during the four-year cycle (Rubio Terrado, 2007) is: 0% in the first year; 12% in the second year; 48% in the third year; and 40% in the fourth year. After these four years, the cycle begins again. To comparatively analyze the traditional system and the proposed approach, the third year, i.e., the year with the highest production, is considered. In particular, the production in the third year is around 1.4 million flowers (i.e., 14 kg of dried saffron) per hectare (Agrifood Statistics Yearbook, 2019), which requires 1760 h of manual work: 640 h for collecting the flowers (i.e., harvesting) plus 1120 h for peeling the flowers (i.e., separating the stigmas). This means a productivity of $1,400,000/(1760 \times 60) = 13$ flowers per minute. Considering a time efficiency of 0.8 (defined as productive time divided by total time) gives a real productivity of around 10 flowers per minute. Note also that the flower harvesting and peeling for the traditional system is performed in a period slightly longer than one month (30–35 days).

For the proposed automated approach, the parallel harvesting device reaches a sustainable cutting frequency of 40 cuts per minute for each cutting line. However, since not all the flowers of the container blossom around the same time, there is an outcome of uncut flowers that must be processed again, giving rise to an estimated cut efficiency of 0.6. Therefore, to cope with the harvesting required for one hectare in the third year (highest production), during 30 days at a rate of 8 h per day, it would be necessary a harvesting device with four cutting lines to achieve the required productivity. That is, 4 lines × 40 cuts per line and minute × 60 min/h × 8 h/day × 30 days/campaign × 0.6 efficiency ≈1.4 million flower cuts per campaign. Thus, the performance of the harvesting machine is: 4 lines × 40 cuts per line and minute × 0.6 of efficiency ≈100 flowers per minute. Hence, the harvesting performance of the proposed machine is 10 times better than that of the traditional manual approach.

The total production of the traditional approach during the four-year cycle is 29 kg of dried saffron (Agrifood Statistics Yearbook, 2019), giving rise to an average of 7.3 kg per year. Nevertheless, the proposed continuous production system is able to work 12 months per year and, hence, its work capacity is equivalent to 12 hectares of cultivation, which means 14 kg per month × 12 months per year = 168 kg of dried saffron per year. Therefore, the outcome of the proposed continuous production system (greenhouse with the equivalent machine to the traditional production procedure) is 23 times higher than that of the

Table 3

Results of the device to get the stigmas for 100 flowers grouped in three batches: amount of elements found in each compartment of the tank (see [a] in the side view of Fig. 5(a)).

	Distance	1st compartment 0–400 mm	2nd compartment 400–800 mm	3rd compartment 800–1200 mm
Batch No. 1	Petals, %	2	11	87
	Stigmas, %	11	73	16
	Classification ratio, %	84,62	86,90	84,47
Batch No. 2	Petals, %	3	15	82
	Stigmas, %	14	84	2
	Classification ratio, %	82,35	84,85	97,62
Batch No. 3	Petals, %	3	12	85
	Stigmas, %	16	75	9
	Classification ratio, %	84,21	86,21	90,43
	Average value	83,73	85,99	90,84
	Standard deviation	0,99	0,85	5,38

traditional saffron production.

Finally, the economic comparison between both production systems is out of the scope of this work due to the fact that some relevant issues still remain unspecified, giving rise to great uncertainty. Some of them are: climate controlled chambers; corm optimization and management; containers transport system, energy consumption analysis, system to control the greenhouse conditions (temperature, light, humidity, irrigation, etc.), among others.

4.2. Advantages and drawbacks of the proposed method

The main advantages of the proposed method are as follows:

- The harvesting of the saffron flower and the procedure to get the stigmas are carried out in the same industrial process.
- The proposed industrial greenhouse with temperature, light and irrigation control allows to significantly extend the flowering time of the saffron plant (e.g., from 5–6 weeks to 12 weeks in preliminary experiments), which helps to increase productivity and to amortize of the machinery and facilities of the proposed approach.
- Labor conflict is mitigated since the low-skilled workers are replaced by high-skilled workers capable of using, maintaining, etc. the machinery and facilities of the proposed industrial farming area.
- The proposed industrial saffron production does not depend on the casual workforce.
- Ergonomic conditions for the workers are improved, not only for the flower harvesting but also for the corm planting, collecting and division.
- Higher labor productivity is achieved.
- The saffron production ratio with respect to the farming area is significantly improved. In particular, the proposed approach produces around five times more saffron per area than the traditional method, i.e., the traditional case requires around 200 cm^2 per corm (Rubio Terrado, 2007) while the proposed approach only requires 36 cm^2 per corm. This ratio can be further enhanced storing the plant trays in the industrial greenhouse at different levels, e.g., three storeys of plant trays can be used with a separation distance of one meter between them.

The main drawbacks of the proposed approach are given below:

- Maintenance and repair costs of the machinery and facilities.
- Energy costs for machinery, temperature control, etc.
- Costs of skilled workers and auxiliary elements.

5. Conclusions

A new industrial system for saffron production has been presented in this work. The method has been developed considering a greenhouse with temperature, light and irrigation control together with harvesting and stigma separation devices specifically designed for this purpose using scalability design and computer vision. The main advantages of the proposed are as follows: the harvesting of the saffron flower and the procedure to get the stigmas are carried out in the same industrial process; the industrial greenhouse allows to significantly extend the flowering time of the saffron plant; and higher productivity per worker and per farming area is achieved.

The feasibility and applicability of the proposed approach have been shown with successful experimental results for the extension of the flowering time and for the harvesting and stigma separation devices.

Declaration of Competing Interest

None.

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