Article

Improvement in Productivity and Quality of Soilless Saffron Crops by Implementing Fertigation

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Abstract: Saffron cultivation is important in global agriculture and is mainly flourishing in Mediterranean climates. Although it originated in Asia Minor, it is widely grown in regions such as Iran, India, Spain, Morocco, Greece, and Italy. Labour-intensive harvesting, mainly by hand, characterises its production and offers substantial employment opportunities in cultivating areas. However, traditional saffron-producing countries such as Spain, Italy, and Greece have witnessed declining production due to labour demands and competition from low-wage countries. Mechanisation remains unfeasible due to the delicate nature of the plant. To revitalise saffron cultivation, efforts have been focused on reducing labour costs, improving productivity, and improving quality through innovative techniques, such as soilless crops. In this study, the productivity and quality of saffron was evaluated in a soilless culture and three fertigation doses were evaluated: a control, consisting of Sonneveld and Voogt’s standard nutrient solution, and two treatments with two supplemented solutions, 30% K and 30% Ca. The results indicated that the solution with 30% K obtained higher corm productivity, as well as better quality saffron, as all the products of this treatment were included in Category I according to the ISO 3632 standard, while the quality of saffron grown with the control solution was lower.

Keywords: fertirrigation; substrate; nutrient solution; Crocus sativus; safranal; crocin; picrocrocin

1. Introduction

The cultivation of saffron (Crocus sativus, L.), beyond its botanical, historical, therapeutic, and culinary dimensions, plays an important role in the global agricultural landscape due to its crimson-coloured stigmas [1]. Saffron is a perennial geophyte that belongs to the order Asparagales, in the botanical family Iridaceae. C. sativus, in particular, is native to a mountainous and arid region in Greece but has been cultivated since ancient times in various Mediterranean countries. Specifically, several cytogenetic studies have confirmed that the saffron plant is a sterile autotriploid (2n = 3x = 24) [2,3] that annually produces replacement corms, which constitute its only form of vegetative propagation [4]. Saffron can be grown for several years; in Spain, it is usually grown for 2 to 4 years, while in Greece, it can be grown for up to 6 years. However, an annual crop cycle with rotations is recommended to preserve soil fertility and avoid the proliferation of soil-borne diseases. The saffron flower is purple with six petals, three stamens, and a style with three red stigmas. During harvest time, the flowers are meticulously handpicked one by one, and the stigmas are extracted and roasted the same day. This roasted stigma has an intense scent and constitutes the well-known spice [5]. Saffron production is mainly based in Iran, where more than 90% of the world’s saffron is grown. Following Iran, significant cultivation occurs in India, Spain, Morocco, Greece, and Italy [6]. Saffron harvesting is labour-intensive and provides significant employment, improving the socioeconomic conditions in disadvantaged...
regions. Moreover, its high market value encourages intensive cultivation, responsible land management, sustainable agricultural practices, and environmental conservation. Furthermore, saffron has a prominent place in traditional medicine systems as a result of its therapeutic properties, which lie in the anti-inflammatory and free radical-scavenging effects of saffron’s main constituents [5]. However, despite the renowned reputation of the Mediterranean region for producing high-quality saffron, certain traditional producing countries, such as Spain, Italy, and Greece, have experienced a decline in production in recent decades. In particular, in Spain, the reduction has been so important that this country has gone from contributing very significantly to the world saffron market to having a production of around 2.5 tonnes and around 190 hectares dedicated to the cultivation of this spice, 90% of which are concentrated in the region of La Mancha [7]. There are several causes for this decline, but the main one is that saffron cultivation requires very skilled labour for a short period of time, just a few weeks a year. This, along with wage costs and competition from emerging countries with low wage costs, has led to the gradual abandonment of this crop [8].

Due to the characteristics of saffron, crop mechanization is practically impossible. The plant is small and fragile, with the flower located just a few centimetres above the ground. And, as noted by Salas et al. in 2020 [9], mechanization is not sustainable due to the significant investment required, so all tasks related to this crop are performed by hand [10], involving more than a thousand hours of work per hectare, mainly for flower harvesting and stigma separation.

Salas et al. [9] suggested that significant changes in cultivation methods are needed to make saffron profitable by reducing labour costs and increasing productivity and quality. They proposed managing diseases and pests, using irrigation and fertilization efficiently, and adopting soilless cultivation techniques. For almost 20 years, various studies have been conducted on the quality and production of saffron grown hydroponically or on different substrates. Maggio et al. [11] achieved yields of over 2 g/m² using substrates like perlite and peat mix in greenhouses, doubling the typical open-field yields in Italy [11]. Other trials on quartz sand produced lower yields but higher quality spice with more polyphenols and antioxidants [12]. Improvement in spice quality has also been observed in hydroponic and aeroponic trials, so it seems clear that these techniques can enhance quality [11,13]. For these reasons, it is necessary to adopt new techniques to increase production while improving the quality of the corms harvested. This is where intensive production systems offer advantages in crop development, being able to control light, temperature, humidity, substrate, pests, diseases, weeds, and plant nutrition, factors that are difficult to control in extensive field cultivation conditions. The use of good quality corms as the base material ensures the success of the crop. In this sense, the influence of corm size on the production of flowers and, therefore, fresh stigmas have been demonstrated [14,15]. For the crocus plant to flower, the diameter of the corm must be at least 2 cm in equatorial diameter and have accumulated the hours of cold necessary for the induction and formation of the flower bud. The number of flowers per corm increases as the size of the corm increases during planting [16]. In several countries in the Mediterranean Basin, plantation operations are carried out with well-developed corms that are 20–25 mm in height and 35–40 mm in diameter, which guarantees a high production of flowers, quality strands, and good-sized seed corms for subsequent sowing [17].

The quality of saffron is based on the colour and aroma of the stigma, especially when it is dry. These quality characteristics depend on the concentration of three main metabolisms: crocin, safranal, and picrocrocin. The dye substance, collectively called crocins (monoglycosyl or diglycosyl polyene esters), is easily dissolved in water, and a red-orange solution is produced. Therefore, it is used as a food dye. Safranal is the essential oil of terpene aldehyde, and is responsible for the fragrance of saffron; it is the most abundant volatile component of the stigma of saffron and found in concentrations of more than 60%. Picrocrocin is considered the main bitter principle of saffron. It is a precursor to the safranal monoterpane glycoside [18]. Furthermore, the quality parameters of saffron also depend
on crop management. Aspects such as seed corm size, treatments to break seed dormancy, cold treatments, sowing time, irrigation, and fertilization directly influence the quality of the harvested stigmas [19–21].

The intense cultivation of saffron allows for an increase in planting density, the use of substrates, fertigation, management of nutrient solutions, and incorporation of techniques such as in vitro cultivation that would guarantee the production of healthy corms, resulting in a higher flower yield. In essence, the process consists of controlling the environmental factors that affect the development cycle of the plant, in particular, shortening or accelerating the “dormancy” stage. With the appropriate management of substrates and nutrient solutions and in intensive production, it will be possible to obtain cleaner and healthier planting materials, which are essential for the success of this type of crop. Therefore, in this study, the quality and productivity of a hydroponic saffron crop were evaluated in which the fertigation solution was supplemented with K and Ca.

2. Materials and Methods

The experiment was carried out in the experimental greenhouse of the University of Almeria (36.49° N (latitude) and 2.24° E (longitude) and approximately 7 m asl), and in the laboratories of the Department of Agronomy of the Higher School of Engineering at the University of Almeria.

Saffron corms (Crocus sativus L.) with a diameter of 30 mm were used as the plant materials. To prevent diseases, they were immersed for 20 min in a propamocarb solution (0.2%), following the usual disinfection protocol for this plant material [9]. After sprouting, they were transplanted into containers with coconut fibre measuring 0.48 × 0.68 m, at a planting density of 18.5 corms m⁻² (Figure 1) Three fertigation treatments were then established. Sonneveld and Voogt’s standard nutrient solution was used as a control treatment [22]. This solution was supplemented with 30% K and constituted the treatment called 30-K. Finally, the nutrient solution of Sonneveld and Voogt was supplemented with 30% Ca, which formed the treatment called 30-Ca. Table 1 shows the ion concentrations of the different fertigation treatments applied. The pH and electrical conductivity (EC) of the nutrient solutions were measured and adjusted daily to maintain a pH between 5.5 and 6.0 and an EC of 3 dS m⁻¹ using a Crison MM 40 combined pH and EC meter (Crison Instruments S.A., Barcelona, Spain), and a fixed irrigation rate of 1 L per tray per day was applied to each treatment.

Figure 1. Images of the containers used in the experimental set-up (left), flower showing the style with red stigmas (centre), and corms obtained at harvest (right).
Table 1. Ion concentrations in the applied nutrient solution treatments (mmol·L⁻¹).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Na⁺</th>
<th>K⁺</th>
<th>Ca²⁺</th>
<th>Mg²⁺</th>
<th>Cl⁻</th>
<th>NO₃⁻</th>
<th>PO₄⁻</th>
<th>SO₄²⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>4.71</td>
<td>5.93</td>
<td>5.95</td>
<td>3.63</td>
<td>4.42</td>
<td>13.91</td>
<td>1.24</td>
<td>2.77</td>
</tr>
<tr>
<td>30-K</td>
<td>4.70</td>
<td>7.61</td>
<td>5.94</td>
<td>3.62</td>
<td>6.69</td>
<td>12.47</td>
<td>1.09</td>
<td>2.98</td>
</tr>
<tr>
<td>30-Ca</td>
<td>4.96</td>
<td>5.28</td>
<td>7.53</td>
<td>3.62</td>
<td>7.64</td>
<td>12.12</td>
<td>1.32</td>
<td>2.56</td>
</tr>
</tbody>
</table>

The experimental design was a completely randomised design with 3 treatments and 4 repetitions, with 8 corms each. The following harvest parameters were assessed in each treatment and repetition: the number of corms, classified into three diameter groups (<25; 25–30; >30 mm); total and average corm weight; and fresh and dry mass of the stigmas from each planted corm. The dry matter weight was determined after drying at 70 °C in a JP Selecta Digitronic oven model (JP Selecta, Barcelona, Spain) for 48 h and quantified using an analytical balance with a precision of <0.01 g.

Throughout the crop cycle, the drainage volume, EC, and pH were measured weekly, and a sample of the drainage was stored in a refrigerator for later analysis. The concentrations of ions (Na⁺, Ca²⁺, Mg²⁺, K⁺, and Cl⁻) were determined using a Metrohm chromatograph, model 883 (Metrohm AG, Herisau, Switzerland), equipped with an autosampler with an anion separation column Metrosep A Supp 4 (250 mm/4.0 mm and particle size of 9 µm) with a guard column (Metrosep A Supp 4 Guard 4.0) and cation separation column Metrosep C4–100 (100 mm/4.0 mm and particle size of 5 µm) with a guard column (Metrosep C 4 Guard/4.0). The samples were measured after a 1:10 dilution with distilled water [9].

The analysis of safranal, crocin, and picrocrocin was carried out on aqueous saffron extracts prepared according to ISO 3632 part 2 [23]. Briefly, 250 mg of saffron powder, previously sieved, was added to a 500 mL flask. The solution was kept in the dark and stirred with a magnetic stir bar at 1000 rpm for 1 h, and then the solution was filtered and, in after the appropriate dilution, the absorbance of the extracts was determined at wavelengths of 330, 440, and 257 nm for safranal, crocin, and picrocrocin, respectively, using a Shimadzu UV–visible UV-1601 spectrophotometer (Shimadzu Corporation, Tokyo, Japan). The data were analysed and subjected to analysis of variance (ANOVA) using Statgraphics Centurion (XV) and Statistix 8 software; mean differences between treatments were compared by LSD (least significant difference) at a p ≤ 0.05.

3. Results

The main production parameters are listed in Table 2. The results show the yield per corm planted; although there were no differences in terms of the number of corms harvested after cultivation, there was a difference if the size of the corms was taken into account. In this sense, the treatments supplemented with 30% K or Ca showed a higher number of corms than the control in the short ones with a diameter between 25 and 30 mm. No differences were found between the fertigation treatments applied for either the total weight or the mean weight of the corms obtained. No differences were found between the fertigation treatments applied for either the total weight or the mean weight of the corms obtained. The applied fertigation treatments showed a positive effect on the total number of flowers per planted chromium. When fertigation was implemented with 30% more Ca or K, the number of flowers increased considerably; however, the best results appeared when fertigation with K was implemented, with almost double the number of flowers compared to the control treatment. The increase in the number of flowers was obviously reflected in a higher number of stigmas and therefore a higher weight. Thus, in the 30-K treatment, a higher productivity was achieved for the spice.
Table 2. Yield per planted corm according to the fertigation treatment applied.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Size (mm)</th>
<th>Corms</th>
<th>Flowers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;30</td>
<td>25–30</td>
<td>&lt;25</td>
</tr>
<tr>
<td>Control</td>
<td>1.00 ± 0.12 a</td>
<td>0.13 ± 0.07 b</td>
<td>3.83 ± 0.48 a</td>
</tr>
<tr>
<td>30-K</td>
<td>1.00 ± 0.12 a</td>
<td>0.29 ± 0.11 a</td>
<td>3.75 ± 0.41 a</td>
</tr>
<tr>
<td>30-Ca</td>
<td>1.13 ± 0.14 a</td>
<td>0.33 ± 0.12 a</td>
<td>3.67 ± 0.44 a</td>
</tr>
</tbody>
</table>

Means followed by SE (n = 48). Different lowercase letters (a, b, c) indicate significant differences within each treatment according to the LSD test, with \( p < 0.05 \).
Figure 2 shows the temporal evolution of the concentration of ions during cultivation. It was observed that the drainage Ca concentration increased during cultivation, especially at 105 days after transplanting, with hardly any differences between the treatments applied. However, analysing the K ion content in the drainage found that the 30-K treatment was the one that contributed the highest K\(^+\) concentration to the drainage at 135 days. However, the Mg ion in the drainage remained more or less constant throughout the crop cultivation and without appreciable differences between the different treatments. In relation to the anions, the evolution of these in the drainage during the cultivation was different depending on the anion, so for chloride ions, differences were found between the treatments, with the chloride concentration being lower in the control treatment than in the rest of the treatments, especially in the last days of the cultivation cycle.

![Figure 2. Average drainage ionic concentration (mg·L\(^{-1}\)) throughout the growing season. The vertical bars show the standard error (SE) (n = 4). The asterisks indicate significant differences within each day between treatments according to the LSD test, with \(p < 0.05\). The lack of a symbol indicates that there were no differences.](image)

Figure 3 shows the temporal evolution of EC in the drainage during the growing period. No significant differences were found in the drainage of the different treatments, but an increase in conductivity was observed on the 105th day after transplanting, which was maintained until the end of the cultivation cycle. On day 135 after transplanting, significant differences appeared between the 30-K treatment and the rest of the treatments, possibly due to the higher concentration of chlorides, potassium, and sodium in the drainage.

![Figure 3. Average drainage EC concentration (mg·L\(^{-1}\)) throughout the growing season. The vertical bars show the standard error (SE) (n = 4). The asterisks indicate significant differences within each day between treatments according to the LSD test, with \(p < 0.05\). The lack of a symbol indicates that there were no differences.](image)
where it was always above the international quality standards. Therefore, the products from the control treatment would be included in category III, while the products from the 30-K treatment would be included in category I. The results of the 30-Ca treatment suggest that its products would be included in category II: although the colour and odour levels were above the maximum standard, the bitter levels would place them in category II.

Figure 4 shows the quality of the saffron. Colouring, odour, and bittering strength are the parameters used to establish the quality of saffron and appear in the figure as horizontal lines. However, when the fertigation was supplemented with K and Ca (treatments 30-K and 30-Ca), the quality of the saffron improved considerably, especially in treatment 30-K, where it was always above the international quality standards. Therefore, the products from the control treatment would be included in category III, while the products from the 30-K treatment would be included in category I. The results of the 30-Ca treatment suggest that its products would be included in category II: although the colour and odour levels were above the maximum standard, the bitter levels would place them in category II.

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Figure 3. Temporal evolution of electrical conductivity in the drainage, according to the treatment applied. The vertical bars show the standard error (SE) (n = 4). The asterisks indicate significant differences within each day between treatments according to the LSD test, with \( p < 0.05 \). The lack of a symbol indicates that there were no differences.

Figure 4. Saffron colouring, odour, and bittering strength by fertigation treatments. The horizontal lines indicate the thresholds of the different commercial categories according to the ISO 3632 norm. Category I: green line; category II: red line; category III: black line. For odour, the ISO 3632 norm only sets a range for all categories (blue line). The vertical bars show the standard error (SE) (n = 6).
4. Discussion

In bulbous plants, the flowering capacity depends directly on the size of the bulb and the corm. In saffron, as a bulbous plant, its production of corms, flowers, and saffron will therefore depend on the size of the corm [24]. The flower yield per plant will depend on the number of corms produced in the annual cycle, but it also depends on the size of the corm, as more buds are formed in larger corms. In our experiment, the corms used were around 30 mm in size and our results showed that, per planted corm, the largest number of corms obtained was around 25 mm in size (Table 2). These results can be considered normal and appropriate for our experimental conditions: a soilless crop, where the corms received fertigation and where the substrate presented physicochemical characteristics that differed greatly from those of an arable soil. Although there is controversy about the production of corms depending on the size of the planted corm, in general, the larger the corm size, the greater the number of corms produced, and the larger the size. All studies carried out on this aspect were carried out in open-air crops and in agricultural soils, following the traditional saffron growing cycle. In this regard, de Juan et al. [25] indicated a very strong relationship between corm size and planting density, and that medium corms (around 22 mm) can produce a similar number of corms as a large corm if the planting density is slightly lower [25]. The effects of fertigation supplemented with K or Ca on the number of flowers were notable, although it only resulted in an increase in the dry weight of the stigma when fertilisation was supplemented with K. In general, K application has positive effects on improved flowering, particularly in small corms [26]. Furthermore, the application of K positively affects the saffron yield, as the dry weight of the stigma increases. In a study by Yatoo et al. [27], it was found that corms of around 22 mm in size were capable of producing almost 8% more dry saffron. Our results are in agreement with these investigations, so the combination of K-supplemented fertilisation and a medium corm size led to an increase in the stigma dry weight.

Fertigation solutions are usually formulated by adjusting with different salts to achieve the desired concentration of nutrients. This leads to some disorders that are usually reflected in the composition of the drainage. Generally, potassium chloride and calcium chloride are often used to increase the K and Ca concentrations in the management of fertigation [28]. Therefore, the addition of these chlorides implies that the chloride concentration will increase in the drainage solution. This situation, which was observed in our experiment, did not represent a problem for crop development and production. Avarseji et al. [28] indicated that saffron plants can significantly control the negative effects of Cl\(^-\) if they are fertilised with K\(^+\) input. In fact, the nutrient solutions that these authors used in their trials reached an EC as high as 9.4 and 12.4 dS m\(^{-1}\), far from the EC caused by our treatments. The observed increase in the K\(^+\) and Ca\(^{2+}\) concentrations in the drainage solution (Figure 2) may be due to increased water consumption, as the volume of water applied was kept constant throughout the crop cycle. Saffron is highly water efficient and drought tolerant, and plant water consumption usually decreases in the last stage of the growth cycle, so an increase in K\(^+\) and Ca\(^{2+}\) in the drainage solution after 105 days of cultivation is normal [29].

The slight differences in the Mg\(^{2+}\) concentrations in the drainage between treatments show that the increase in the K\(^+\) and Ca\(^{2+}\) concentrations did not affect the consumption of this nutrient, as expected due to competition between cations (Figure 2) [9]. However, although the antagonistic effects of K\(^+\) on Mg\(^{2+}\) are generally well established, synergies have also been found depending on growing conditions and species, as well as a limitation of antagonism if plant nutrition is balanced [29]. This could be the reason for what is shown in Figure 1 in relation to the Mg\(^{2+}\) content in the drainage. Furthermore, the plant age determines the relationships between Mg and K, with antagonism observed when the crop is in the final stage of its cycle and the leaves and stems are older [29]. The highest concentration of cations in the drainage occurred in the 30-K treatment at the end of the 135 ddt cycle since the K needs are covered in the early and middle stages of the crop cycle. With senescence and the translocation of elements to storage organs, the demand for nutrients decreases and a higher concentration of ions is found in the drainage solution.
This higher concentration of ions in the drainage resulted in an increase in the EC of the drainage (Figure 3). The increase in K$^+$ in the drainage solution from 105 ddt onwards would indicate that the concentration of K$^+$ in the irrigation solution can be decreased in the final stages of the cycle.

The quality of saffron is determined by the ISO 3236 standard [23]. Compliance with this standard means that the contents of crocin, safranal, and picrocrocin reach certain threshold levels to classify the quality of saffron into three categories. In our experience, the results were clear: the quality of the saffron from the control treatment was lower than that of the rest of the treatments (Figure 4). The supplementation of fertigation with K$^+$ (30-K treatment) resulted in the saffron obtained being considered category I since all evaluated quality components were well above the minimum values. In other words, there was a positive influence of K on the quality of the saffron. The positive influence of K on the yield of saffron stigmas is well known. There are quite a number of studies that indicate higher yields, both in production and quality, after the application of K$^+$ [26,28,30]. Although these studies have been carried out in traditional open-field cultivation, other studies carried out in hydroponic saffron cultivation point in the same direction: the positive influence of potassium on the quality of saffron [9,31,32]. When considering the role of potassium in saffron flowering, it should be noted that K$^+$ can mitigate the consequences of stressful conditions and improve yield. Although our crops were not grown under stressful conditions, it should be noted that K$^+$ and Ca$^{2+}$ were supplemented through the addition of the corresponding chlorides, leading to an increase in chlorides in the nutrient solution (Figure 2), so that the supplementation of K$^+$ could neutralize the negative effects that the chloride ions could have. However, through comparing the quality and K$^+$ content results in the drainage solution (Figures 2 and 4), it can be recommended to maintain the K-supplemented fertigation solution until day 105, as it improves the quality of the saffron. After day 105, it is possible to return to the concentration applied in the control.

The implementation of the Ca-based fertigation solution resulted in a higher quality compared to the control fertigation solution. The ISO 3632 standard is clear in this respect. For a saffron to be classified as category I, II, or III, it must satisfy the requirements of three parameters (colouring, odour, and bittering strength) [23]. Under these conditions, the products from the 30-Ca treatment narrowly missed meeting these requirements, as the bittering strength results fell into category II. These results can confirm the importance of calcium in quality, and although there are hardly any studies on this aspect in saffron grown in soilless conditions, there are quite a few studies carried out in traditional crop cultivation indicating that a higher amount of Ca in the soil leads to better quality, as a positive correlation was found between the colour, aroma, and calcium carbonate present in the soil [33]. It should be noted that the aroma is one of the quality components of saffron that attracts the attention of consumers. Safranal, a terpenic aldehyde, contributes to the aroma and a positive correlation has been found between soil calcium and the volatile terpene composition [31]. Thus, the products from our 30-Ca treatment showed high safranal values that indicate that the odour strength values reached the minimum required by the standard.

5. Conclusions

Saffron is commercially grown for medicinal and culinary purposes due to its stigma and for the daughter corms as the sole propagation material. Growing saffron as a soilless crop, with suitable and adjusted fertigation, has proven to be a useful tool for improving productivity. In the fertigation technique, the composition of the nutrient solution and its balance are a critical point that determines the quality and productivity. Our results show that, for the growth of hydroponic saffron, the supplementation with potassium and, to a lesser extent, calcium is a practice that improves the quality and productivity. However, it is necessary to control the drainage to adjust or reduce the concentration of potassium in the final stages of cultivation when the plant’s demand for potassium decreases.
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Conflicts of Interest: The authors declare that they have no conflicts of interest.

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