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Posted Date: 6 November 2023

doi: 10.20944/preprints202311.0280.v1

Keywords: Saffron; single administration dose; Fertilization; Crocin doi:10.20944/preprints202311.0280.v1

Article

Optimizing Saffron (*Crocus sativus*) Yield and Quality through Nutrient Inputs and Timing: Insight from a Study in Lebanon

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Abstract: This study investigated the influence of nutrient inputs and their timing on saffron yield and quality. The study was conducted from 2016 to 2020 and involved the application of eight different fertilization treatments at various stages of saffron growth. These treatments included single doses in Autumn (A), Winter (W), and Spring (S); double doses in Winter-Spring (AW), Autumn-Spring (AS), and Winter-Spring (WS); and a triple dose in Autumn-Winter-Spring (AWS). A control group (C) received no fertilizer. A compound fertilizer with a 15-15-15 composition was applied across all treatments, with nitrogen (N) rates of 67.5 kg/ha for single doses (A, W, S), 135 kg/ha for double doses (AWF, ASF, WSF), and 202.5 kg/ha for the triple dose (AWSF). Similar rates were applied for phosphorus (P) and potassium (K). The findings demonstrated that fertilization generally enhanced saffron attributes. The triple dose treatment yielded the most effective results. The timing of fertilization also played a crucial role, as split applications during different growth stages led to higher production especially winter fertilization. However, spring fertilization had limited impact due to decreased plant activity and reduced nutrient absorption during that period. Although the yield increased, the qualitative aspects of saffron, including color (crocin), taste (picrocrocin), and aroma (safranal), were not significantly influenced by the fertilization treatments. Nevertheless, these attributes remained within the natural limits defined by ISO-3632, indicating that fertilization practices did not compromise saffron quality. Our study highlights the significance of nutrient inputs and their timing in optimizing saffron yield. It provides valuable insights for developing efficient fertilization programs to enhance saffron production while preserving its quality characteristics.

Keywords: saffron; single administration dose; fertilization; crocin

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1. Introduction

Crocus sativus belongs to the Iris family and is considered one of the precious species [1]. Although saffron thrives in a range of geographic zones and tolerates a variety of soil types, climate and environment have a significant impact on the quantitative and qualitative properties of saffron [2–4].

Due to its many benefits and the high price, Saffron was introduced to Lebanon two decades ago to improve the living conditions of farmers especially in marginal areas, and enrich the biodiversity in Lebanon [5].

The saffron spice production per hectare differs from country to country, with a range of 10 to 20 kg/ha [6]. In New Zealand, the estimated saffron spice production was projected to reach 24 kg/ha [7]. The variation in saffron yield can be attributed to various factors, including weather conditions, geographical factors, irrigation and soil quality, fertilizer usage, and pest management [6,8–10]. Multiple studies have indicated the importance of fertilization in enhancing saffron production, whether it is measured in terms of dry stigmas or bulb yield. [11] found that both the application of fertilizers and the specific type of fertilization positively affected saffron yield. A combination of cow manure and mineral fertilizers was found to improve soil fertility and consequently increase saffron production [12]. Ref. [13] reported that the integrated use of mycorrhizal fungus, organic fertilizers, and chemical fertilizers significantly influenced saffron production overall. The productivity of saffron is also linked to soil characteristics [5,14]. However, there are instances where mineral NPK (nitrogen, phosphorus, and potassium) fertilizers showed limited impact on saffron yield [15]. The primary determinant of saffron production is the development of new corms from the mother corm. As the plant's nutrient requirements may vary at different stages of growth, understanding the plant's growth stages (biological cycle) becomes crucial for designing an effective fertilization program.

The available information and studies regarding the optimal timing of mineral nutrient application for saffron are scarce. Furthermore, saffron cultivation in Lebanon is relatively new and confined to a few dispersed farms across various geographical regions. Hence, it becomes crucial to formulate fertilization programs that are tailored to local conditions. This is particularly important to incentivize farmers to engage in saffron cultivation, especially in marginal areas, owing to its promising economic benefits. The objective of the present study is to identify the optimal timing for fertilization and evaluate its impact on saffron yield.

2. Materials and Methods

The current study was carried out by the Lebanese Agricultural Research Institute under field conditions of Baaklin province between 2016 and 2020. Corms of uniform size were acquired from local farmer. Prior to planting in August 2016, corms were soaked in a copper solution to prevent fungal diseases. The Complex fertilizer 15-15-15 was selected for the current study. Each experimental unit with an area of 2.25 m2 was planted with 82 corms at a space of 15x15 cm.

The following 8 fertilization treatments were chosen:

Autumn (A), fertilizer rate 45g m-2.

Winter (W), fertilizer rate 45g m-2.

Spring (S), fertilizer rate 45g m-2.

Combination Autumn + Winter (AW), fertilizer rate 90g m-2.

Combination Autumn + Spring (AS), fertilizer rate 90g m-2.

Combination Winter + Spring (WS), fertilizer rate 90g m-2.

Combination Autumn + Winter + Spring (AWS), fertilizer rate 135g m-2.

Control, no fertilizer added.

The elemental rate of N was 67.5 kg/ha for single administration dose (AF, WF, SF), 135kg/ha for double administration dose (AWF, ASF, WSF), 202.5kg/ha for triple administration dose (AWSF). The same rates were for P K respectively. The treatments were organized in randomized complete block design with three blocks. Flowers were collected early in the morning. The separated stigmas (red part of stigmas) were dried under ambient lab temperature. The following yield attributes were studied: flowers (NF) m-2, flowers/mother corm(FMC), Dry weight of stigmas m-2 (DWS), Dry weight of single stigma (DSS) (they were weighted on a precise digital balance up to 0.000 g accuracy),stigma length(SL),plant length(PL),foliar biomass(FM). The components of air-dried stigmas (Crocin, Picrocrocin and Safranal) were determined according to ISO 3632-2:2010 test method by using UV-vis spectrophotometer. The results for these three compounds were obtained by direct reading of the specific absorbance at three wavelengths (257 nm-picrocrocin, 330 nm-Safranal, 440 nm crocin). In summer 2019, corms were pulled out from half area of each plot. The corms than were divided into three categories according to their weight: first category: corms less than 4 g, second category: corms between 4-8 g, third category: corms more than 8g.

Simple and mixed analysis of variance were performed in SAS 9.2 for Windows (SAS Institute Inc., Cary, NC, USA) to evaluate the effect of treatments, year and their interaction on yield parameters. Tukey's multiple comparisons test of significance at $p = 0.05$ was used to evaluate differences between these groupings at individual year.

3. Results

3.1. Flower yield

The results showed that saffron fertilization led to a significant increase in the number of flowers per square meter ($P = 0.0167$, $\eta^2 = 0.19$) (Table 1). Plots fertilized with triple administration dose (autumn-winter-spring) yielded the most significant number of flowers per m2, followed by double administration dose (winter-spring (WS), and Autumn-Winter (AW)) and single administration dose in Autumn (A). In the first year of planting, all plots, including control plots produced relatively low number of flowers. In the second year the number of flowers increased but no significant results were observed between treatments and control. Starting from the third year (2018), treatment with triple administration dose (AWS) showed a steady significant increase in the number of flowers compared to the control plots. The mixed model was conducted using Restricted Maximum Likelihood (REML) solution to determine if there were differences in flower number between the eight treatments (A, AS, AW, AWS, S, W, WS, and control) over the five years. The results of mixed model showed significant results for treatments ($F(7,78) = 10.17$, $P < .0001$), year ($F(4,78) = 71.01$, $P < .0001$), and their interaction ($F(28,78) = 2.55$, $P = 0.0006$). The model explained a large portion of the variability in saffron yield, with a residual variance of 5969.36, SD= 77.26. A compound symmetry covariance structure was used based on the lowest AIC and BIC values. The AIC (Akaike Information Criterion) of 976.0 and BIC (Bayesian Information Criterion) of 974.2 indicate good model fit. The significant interaction indicates that treatments and control behaved differently over 5 years. Plots fertilized with double (AS, AW), and triple administration doses (AWS) of fertilizer consistently improved flower yield from year to year. Spring fertilization had the lower yield compared with other treatments and did not differ significantly from control. In the control plots, the flower yield was observed to decrease from 84.7 flowers in 2019 to 68.1in 2020.

Table 1. Number of flowers m^{-2} as affected by treatments across five years.

Treatments	Picking year					Means
	2016	**2017**	**2018**	**2019**	**2020**	
A	1.3	73.8	154.8^{ab}	334.5^{ab}	341b^{c}	**181.1^{ab}**
AS	1.8	80.6	134.5^{abc}	185.8^{bc}	301.0^{c}	**140.7^{bc}**
AW	1.3	71.1	99.6^{bc}	292.1^{abc}	426.1^{b}	**178.0^{ab}**
AWS	1.5	73.0	205.0^{a}	471.1^{a}	547.6^{a}	**259.6^{a}**
c	1.8	32.0	52.1^{c}	84.7^{c}	68.1^{e}	**47.9^{c}**
S	2.1	80.4	105.3^{bc}	115.3^{bc}	186.4^{d}	**97.9^{bc}**
W	1.6	47.9	102.2^{bc}	224.9^{bc}	303.7^{c}	**136.1^{bc}**
WS	1.9	56.3	126.2^{abc}	346.1^{ab}	393.2^{bc}	**187.7^{ab}**
Means	**1.7**	**64.4**	**122.5**	**256.8**	**320.9**	**153.3**
SD	**0.83**	**37.7**	**72.1**	**189.1**	**150.9**	**63.6**
			Simple anova			
P	*0.97*	*0.5*	*0.05*	*0.02*	<.0001	0.0167
η^2	*0.18*	*0.59*	*0.74*	*0.75*	*0.89*	0.19

Means with similar superscripts (a, b, c, d, e) indicate a non-significant differences ($p > 0.05$) among treatments within each picking column based Tukey's HSD test.

3.2. The yield of dried stigmas

The mean values of dried stigmas/m2 over five years were recorded to be significantly higher in treatments (A, AW, AWS, WS) compared to control (Table 2). The yield of dried stigmas was observed to differ significantly between treatments and control staring from the third year (2018). During these years, the plots treated with triple administration dose produced a steady significant yield of dried stigmas (Table 2). In 2020, the difference in stigmas yield between control and spring fertilization was not significant. The significant differences between treatments and control and their performance over 5 years was confirmed by the mixed model analysis. The results of mixed model showed significant results for treatments (F (7,78) = 8.72, P 0.0003), year (F (4,78) = 55.81, P<.0001), and their interaction (F(28,78) = 2.14, P = 0.0078). The model explained a large portion of the variability in saffron yield, with a residual variance of 0.153, SD= 0.391. The AIC (Akaike Information Criterion) of 130.3 and BIC (Bayesian Information Criterion) of 128.5 indicate good model fit. The stigma yield was increased from 0.363 in 2017 to 2.441g in 2020 in the AWS treatment while in the control plots the yield was increased from 0.144g to 0.290 g for the same period. The other treatments increased the yield from less half gram per/m2 in 2017 to more than 1.3 g /m2 in 2020 except for spring treatment (S) which yielded less one gram.

Table 2. Yield of dried stigmas m^{-2} as affected by treatments and year.

Treatments	Picking year					
	2016	**2017**	**2018**	**2019**	**2020**	**Means**
A	0.005	0.336	0.737[ab]	1.603[ab]	1.381[bc]	**0.812[ab]**
AS	0.006	0.370	0.648[abc]	0.891[bc]	1.301[cd]	**0.643[bc]**
AW	0.004	0.330	0.474[bc]	1.350[abc]	1.846[b]	**0.801[ab]**
AWS	0.005	0.363	1.005[a]	2.293[a]	2.441[a]	**1.222[a]**
c	0.007	0.144	0.253[c]	0.404[c]	0.290[e]	**0.220[c]**
S	0.008	0.358	0.523[bc]	0.566[c]	0.809[de]	**0.453[bc]**
W	0.005	0.216	0.456[bc]	1.056[bc]	1.369[bc]	**0.621[bc]**
WS	0.007	0.259	0.616[abc]	1.742[ab]	1.683[bc]	**0.861[ab]**
Means	**0.006**	**0.297**	**0.589**	**1.238**	**1.390**	**0.812**
SD	**0.001**	**0.082**	**0.223**	**0.634**	**0.650**	**0.704**
			Simple anova			
P	*0.96*	*0.60*	*0.04*	*0.02*	*<.0001*	0.014
η^2	*.22*	*.53*	*.75*	*.77*	*.88*	0.20

Means with similar superscripts (a, b, c, d, e) indicate a non-significant differences (p > 0.05) among treatments within each picking column based Tukey's HSD test.

3.3. Weight of single stigma

The weight of single stigma was assessed during 5 years of the experiment. The data were exposed to linear mixed analysis. The results showed a significant difference for year (F (4,78) = 34.68, P<0.0001) (Table 3). However, treatment and treatment*year interaction were respectively not significant (F (7,78) = 0.66, P=7056), (F(28,78) = 0.40, P = 0.9946). The AIC (Akaike Information Criterion) of -959.5 and BIC (Bayesian Information Criterion) of -961.3 indicate good model fit.

Table 3. Effect of treatments on the weight of single stigma over five years.

Treatments	Picking year					
	2016	**2017**	**2018**	**2019**	**2020**	**Means**
A	0.0037	0.0045	0.0046	0.0047	0.0040	**0.0043**
AS	0.0035	0.0046	0.0048	0.0048	0.0043	**0.0044**
AW	0.0031	0.0044	0.0047	0.0045	0.0043	**0.0042**
AWS	0.0034	0.0049	0.0049	0.0048	0.0045	**0.0045**
c	0.0037	0.0043	0.0048	0.0044	0.0045	**0.0044**
S	0.0034	0.0044	0.0049	0.0047	0.0043	**0.0044**
W	0.0033	0.0045	0.0044	0.0047	0.0045	**0.0043**
WS	0.0035	0.0046	0.0048	0.0048	0.0043	**0.0044**
Means	**0.0034**	**0.0045**	**0.0048**	**0.0047**	**0.0043**	**0.0044**
SD	**0.0006**	**0.0004**	**0.0003**	**0.634**	**0.0003**	**0.0006**
			Simple anova			
P	*0.96*	*0.72*	*0.64*	*0.97*	*0.54*	0.95

η^2	0.10	0.21	0.24	0.9	0.28	0.02

3.4. Yield of flowers per mother corm

The overall yield of flowers per mother corm varied significantly between treatments and control (Table 4). The AWS treatment resulted in the highest number of flowers per mother corm, followed by AW, WS, and A treatments, all of which exhibited significant differences compared to the control. Initially, during the first two years of planting, no significant differences in the number of flowers per mother corm were observed among the treatments. However, in the subsequent years, there was a substantial increase in the number of flowers per mother corm for all treatments, except for the control group, which showed a slight decrease from 2.9 in 2019 to 2.5 in 2020. In the fifth year (2020), all treatments except control and S produced more than 10 flowers/mother corm. In addition to the simple ANOVA, a mixed ANOVA was performed to analyze the effects of treatment, year, and the interaction between treatment and year. The mixed models showed significant results for treatments ($F(7,14) = 7.40$, $P=0.0008$), year ($F(4,8) = 59.84$, $P<.0001$), and their interaction ($F(28, 56) = 1.92$, $P=0.019$). The AIC (Akaike Information Criterion) of 454.9 and BIC (Bayesian Information Criterion) of 453.1 indicate good model fit.

Table 4. Number of flower per mother corm as affected by treatments across five years.

Treatments	**Picking year**					
	2016	**2017**	**2018**	**2019**	**2020**	**Means**
A	0.04	2.4	5.1^{ab}	10.5^{ab}	10.9^{cd}	**5.8^{ab}**
AS	0.06	2.7	4.8^{ab}	7.5a^{bc}	12.3^{bc}	**5.5a^{bc}**
AW	0.05	2.9	4.3^{bc}	11.8ab	17.3a	**7.3^{ab}**
AWS	0.06	2.4	6.9^{a}	15.1^{a}	16.6^{ab}	**8.2^{a}**
C	0.07	1.2	2.0^{c}	2.9^{c}	2.5^{e}	**1.7^{c}**
S	0.07	2.9	4.0^{bc}	4.3^{bc}	7.1^{d}	**3.7^{bc}**
W	0.07	1.8	3.7^{bc}	7.6^{abc}	10.2^{cd}	**4.7^{abc}**
WS	0.07	2.0	5.0^{ab}	12.5^{a}	13.8^{abc}	**6.7^{ab}**
Means	**0.1**	**2.3**	**4.5**	**9.0**	**11.3**	**5.4**
SD	**0.0**	**0.6**	**1.4**	**4.2**	**4.9**	**2.1**
			Simple anova			
P	0.97	0.6	0.04	0.05	<.0001	0.04
η^2	0.18	0.57	0.80	0.76	0.87	0.20

Means with similar superscripts (a, b, c, d, e) indicate a non-significant differences ($p > 0.05$) among treatments within each picking column based Tukey's HSD test.

3.5. Corm yield

In 2019, the corms were pulled from half area of each experimental plot. The corms were counted and categorized into three categories based on corm weight; category I included corms weighing equal or less than 4 g; category II includes corms weighing 4-8 g; category III included corms weighing more than 8 grams. AWS and AS were the only treatments that produced a significant number of corms/m2 and corms/ mother corm as compared to control (Table 5). The second and third categories accounted for approximately 46% of all pulled corms, while the first category comprised the remainder. The significant variation in corm number between treatments and control occurred only in the first and third categories. Control plots yielded the highest number of small corms (66.0%) and the fewest large corms (6%).

Table 5. Corm yield as affected by treatments.

	Total # of corms	**# corms /mother corm**	**Corm categories**		
			I	**II**	**III**
A	326.3abc	11.5ab	0.54abc	0.24	0.22ab

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AS	405.3a	13.3a	0.57abc	0.26	0.17abc
AW	263.7abc	11.3ab	0.50bc	0.26	0.24a
AWS	387.0ab	12.6a	0.45c	0.28	0.28a
c	146.7c	8.4b	0.66a	0.28	0.06c
S	255.3abc	10.1ab	0.63ab	0.24	0.12bc
W	193.0bc	8.4b	0.46c	0.31	0.24ab
WS	271.0abc	10.9ab	0.53abc	0.23	0.24a
Means	281.0	10.8	0.54	0.26	0.20
SD	4.7	2.6	2.3	0.67	3.6
P	0.0064	0.05	0.0867	0.69	0.0204
η^2	72	.57	.76	.49	.82

Means with similar superscripts (a, b, c, d, e) indicate a non-significant differences (p > 0.05) among treatments within each picking column based Tukey's HSD test.

3.6. Qualitative attributes

The qualitative standards of saffron, such as color (Crocin), taste (Picrocrocin), and aroma (Safranal), were not affected by the fertilization dose and their splitting time, as indicated by the statistical analysis shown in the table. The analysis also shows no significant interaction between treatments and year (Table 6). However, these characteristics varied significantly from year to year. The ISO/TS 3632 standard has established certain laboratory standards for color, taste, and aroma to determine the quality of saffron threads and saffron powder. The values of the main components of saffron, including crocin (color), picrocrocin (taste), and safranal (aroma), are determined by means of photo-spectroscopy. The qualitative specifications of saffron remained within the natural limits set by ISO-3632, indicating that the fertilization treatments and their timing did not have a significant negative impact on the quality of the saffron produced.

Table 6. Qualitative saffron parameters as affected by treatments and year.

	Picrocrocin				Crocin				Safranal			
	2017	2018	2019	**Mean**	2017	2018	2019	**Mean**	2017	2018	2019	**Mean**
A	86.8	87.8	99.5	**91.4**	199.0	227.2	263.9	**230.0**	26.3	32.5	29.5	**29.5**
AS	78.2	89.0	93.7	**87.0**	196.7	228.1	246.8	**223.9**	27.2	32.6	29.3	**29.7**
AW	90.0	90.7	92.9	**91.2**	214.2	234.3	238.6	**229.0**	29.9	32.8	30.3	**31.0**
AWS	89.0	98.6	90.2	**92.6**	209.3	231.9	235.7	**225.6**	28.0	37.2	29.1	**31.4**
C	91.4	90.7	99.1	**93.7**	218.3	239.6	260.6	**239.5**	28.4	32.1	31.4	**30.6**
S	86.4	89.3	92.4	**89.4**	194.1	231.9	252.5	**226.2**	27.4	31.5	27.0	**28.6**
W	84.3	89.5	104.5	**92.7**	193.9	224.1	274.8	**231.0**	26.1	33.3	31.2	**30.2**
WS	88.1	96.7	98.9	**94.6**	205.5	240.9	262.9	**236.5**	27.3	34.7	32.6	**31.5**
Means	86.8	91.5	96.4	**91.6**	203.9	232.3	254.5	**230.2**	27.6	33.3	30.0	30.3
SD	4.1	3.9	4.8	**2.5**	9.4	5.9	13.5	**5.4**	1.2	1.8	1.7	**1.0**
					Simple Anova							
P	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
η^2												

Means with similar superscripts (a, b, c, d, e) indicate a non-significant differences (p > 0.05) among treatments within each picking column based Tukey's HSD test.

4. Discussion

Our study demonstrated that nutrient inputs, as well as the timing of their splitting, play a key role in increasing saffron yield. Although saffron is known to thrive in various types of soil, including poor ones, previous studies indicated the feasibility of using fertilizers to increase saffron production. [14,16–18]. reported that the most change in saffron yield was induced by fertilizers and soil amendments inputs. Moreover, comprehending the physiological aspects and life cycle of saffron facilitates the design of an efficient fertilization program. Our study aimed to achieve this goal by implementing fertilization at various stages of saffron growth.

The nutrient requirements of saffron vary depending on the stage of growth. The period from autumn to mid-spring, which marks the physiological activity of saffron [19], is a crucial phase in terms of nutritional needs. While the newly sprouting buds receive energy from the mother corms, they also rely on soil nutrients to support their growth. As a result, it is important to ensure an adequate supply of nutrients during the active growth period, especially during flowering, vegetative growth, and the formation of daughter corms.

Our study showed that fertilization generally increased quantitative attributes of saffron regardless of the timing of fertilization. The results indicated that fertilization with triple administration doses was effective in increasing number of flower/m2, dried stigmas, and corm yield. Double and single administration doses were also effective in increasing saffron attributes. The presence of saffron in the soil for many years depletes the nutrients of the soil, which requires adding fertilizer to it to ensure a good production. The decline in saffron yield observed in control plots after 5 years, compared to fertilization treatments that exhibited increased saffron yield, suggests that fertilization prolongs and sustains saffron productivity.

In addition to the concentration of fertilizers, the timing of their application also played a crucial role in enhancing saffron production. Our results indicate that applying fertilizers at the appropriate times of the year can optimize nutrient management practices and contribute to increased saffron yield. Splitting the fertilizer application into three or two periods during the growth cycle of saffron resulted in higher production compared to applying fertilizer at a single time. The importance of strategic timing in fertilizer application to maximize saffron productivity is further emphasized by the findings of [20,21], who highlighted the significance of split foliar fertilization in improving saffron yield. Similarly, Ref. [22] reported that applying nitrogen fertilizer in three splits and delaying topdressing fertilization until the G40 stage of winter wheat resulted in increased total grain yields. These studies provide additional evidence of the benefits of timing and splitting fertilizer applications for optimizing crop yield in different agricultural systems. Among the treatments applied, spring fertilization did not show a significant difference compared to the control. This lack of significant effect could be attributed to several factors. Firstly, during the spring season, the physiological activity of the saffron plant decreases, resulting in a reduced ability to absorb nutrients from the soil. Secondly, the decrease in rainfall during spring further limits the plant's ability to take up nutrients from the soil. Lastly, the early cessation of rainfall in February and March can induce the saffron corms, which are not fully developed, to enter the dormant stage prematurely. These factors collectively contribute to the limited response of saffron to fertilization during the spring season. Nevertheless, when spring fertilization was combined with fertilization in the fall or winter, it resulted in enhanced saffron production. Specifically, plots that received a triple administration dose split into three periods (autumn, winter, and spring) throughout the duration of the experiment exhibited the enhance of most saffron attributes compared to the control group and plots that received a single administration dose applied only in autumn or spring. This finding highlights the effectiveness of a comprehensive fertilization strategy involving multiple applications at different stages of the saffron growth cycle. Ref. [23] demonstrated that the timing of fertilization significantly influenced saffron yield. Winter treatment, alone or in combination with others, was superior to fall application. The demand for nutrients is minimal at early stage (Fall). The winter application was even more efficient, especially when paired with spring or/and fall applications. As for many crop, the active uptake pattern of crocus is at vegetative stage which coincides with winter period. Crocus, like many other crops, actively absorbs nutrients during the vegetative stage, which corresponds to the winter season [23]. It is worth noting that splitting N fertilization into two or three portions did not lead to increased grain yield in corn crops, as indicated by [24]. This suggests that the timing of nutrient application may have different effects on various crops. Crop growth depends on environments (rain, temperature, solar radiation, etc.) and soil nutrient availability. Plant nutrient requirement during growth stages has different mode dynamics.

Furthermore, it is important to note that while higher concentrations of fertilizers resulted in higher yields, the use of double and single doses still produced saffron production that remained within reasonable and economically viable limits. The production of dried stigmas/m2 from 1.301g/m2 to 2.441g/m2 for all treatments ranged except for control and spring application. This suggests that growers have the flexibility to choose fertilizer concentrations that align with their specific needs and resources without sacrificing saffron quality or economic feasibility.

Although the treatments had an impact on most of the saffron characteristics, such as yield and other quantitative attributes, they did not significantly affect the average weight of a single stigma or the qualitative properties (Color, taste, and aroma) of the dried stigmas. However, it is worth noting that the values of these characteristics showed variation from year to year, indicating that their expression is influenced by genetic composition and climatic conditions rather than the applied treatments. These findings are remarkable as they demonstrate that the inclusion of mineral fertilizers at different concentrations did not adversely affect the qualitative attributes of saffron. The quality characteristics of saffron remained within the natural limits defined by ISO-3632, indicating that the fertilization practices did not compromise the inherent quality of the saffron produced.

5. Conclusion

Our study highlights the significance of nutrient inputs and their timing in enhancing saffron yield. Understanding the physiological aspects and life cycle of saffron allows for the development of an effective fertilization program. Fertilization with triple administration doses, split into autumn, winter, and spring applications, proved to be the most effective in increasing the quantitative attributes of saffron, including flower yield, dried stigmas, and corm yield. Single and double administration doses also showed positive effects on saffron attributes. The lack of significant effects on the average weight of a single stigma and the qualitative properties of dried stigmas suggests that the applied treatments did not negatively impact the qualitative attributes of saffron. These findings demonstrate that the inclusion of mineral fertilizers at various concentrations can enhance saffron yield without compromising its quality characteristics, which remained within the natural limits set by ISO-3632.

Author Contributions: Conceptualization, Abdel Kader El Haj.; methodology, Abdel Kader El Hajj.; software, Abdel Kader El Hajj.; validation, Abdel Kader El Hajj.; formal analysis, Abdel Kader El Hajj. and S.B.M.; data curation, Nadine Oueidat.; writing—original draft preparation, Abdel Kader El Hajj.; writing—review and editing, Abdel Kader El Hajj. and All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The Managing Board of the Lebanese Agricultural Research Institute (LARI)-Lebanon is gratefully acknowledged for financial support. Technical staff of Lebaa station (Vera Talj, Soha Oleik, Nour Taha, and Oxana Baghdadi) and Baklin station (Ashwak Bu Nassif, Hiba Sari Eldine, and Marcelle Hareb) are thankful for their help.

Conflicts of Interest: The authors declare no conflict of interest.

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