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Effect of Varying Auxin Concentrations on Corm Weight Allocation, Reproductive Characteristics, and Stigma Yield of Saffron (*Crocus sativus* L.) under Aeroponic Culture

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Abstract

This study was conducted to evaluate the effects of priming saffron corms with different auxin concentrations (0, 1, 2.5, 5, 10, 25, 50, 100, 250, 500, and 1000 mg.kg^{-1}) on vegetative, reproductive, and propagation traits under aeroponic conditions. A completely randomized design with three replications was used during 2021–2022 at the research laboratory of the Faculty of Agriculture, Shahid Bahonar University of Kerman, Iran. The results revealed that saffron responses to NAA pre-treatment were predominantly dose-dependent and exhibited a biphasic pattern. At the propagative level, the greatest stimulation of lateral bud emergence occurred at lower concentrations. Specifically, 5 and 10 mg.kg^{-1} significantly increased the mean number of lateral buds by approximately 75% and 66%, respectively, compared with the control. Conversely, intermediate concentrations, particularly 50 and 100 mg.kg^{-1}, partially inhibited bud formation. The lowest value (1.4 buds) was observed at 250 mg.kg^{-1}. Reproductive traits followed a quadratic, dose-responsive trend. The maximum values for flower number, flower yield, and stigma dry weight were observed at 250 mg.kg^{-1}. Leaf length (14.4 cm) and leaf dry weight (2.68 g per plant) also peaked at this concentration. With respect to corm multiplication, the highest number of reproductive corms per 100 mother corms was recorded at 10 mg.kg^{-1} (525 corms). The lowest value (258 corms) was observed at 250 mg.kg^{-1}. However, the mean reproductive corm weight was maximized at 250 mg.kg^{-1}(11.06 g). The distribution of corm weight was strongly influenced by auxin concentration. Lower doses (5–10 mg.kg^{-1}) produced a higher proportion of small corms (<5 g; ≈73% at 5 mg.kg^{-1} and ≈63% at 10 mg.kg^{-1}), whereas 250 mg.kg^{-1}increased the proportion of large corms (>10 g) to about 45%. Overall, the findings indicate that lower auxin concentrations (5–10 mg.kg^{-1}) are more suitable for mass propagation. Intermediate concentrations particularly 250 mg.kg^{-1} are recommended to enhance flower yield and produce larger corms, which are desirable for economic and production purposes.

Keywords: Auxin, Corm; Lateral bud; Stigma; Naphthalene acetic acid (NAA)

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Introduction

Saffron (*Crocus sativus* L.) is among the most valuable medicinal and spice crops worldwide. Its value comes from distinctive qualitative and economic attributes (Srivastava et al., 2010). Bioactive constituents in saffron, including crocin, picrocrocin, and safranal, impart the characteristic color, flavor, and aroma. These compounds also enable a wide range of applications in the pharmaceutical, food, and cosmetic industries. Iran is the leading global producer and exporter of saffron, accounting for more than 80% of global production. This crop plays a central role in Iran's agricultural economy and foreign exchange earnings (Karbasi & Zandi Dareh Gharibi, 2022).

A major challenge in saffron cultivation in Iran is the considerable gap between actual farm yields and attainable potential yields (Feyzi & Moradi, 2020). Despite its global dominance in production, the average dry stigma yield in Iran in 2023 (2.27 $kg.ha^{-1}$) remains below the global mean of 5.1 $kg.ha^{-1}$ (Moradi et al., 2025). Notably, much higher yields have been documented domestically, underscoring the existing potential for improvement. For instance, peak dry stigma yields have reached 41 $kg.ha^{-1}$ in Ferdows, 38 $kg.ha^{-1}$ in Bakhazar, and 25–30 $kg.ha^{-1}$ in Torbat Heydarieh (Feyzi & Moradi, 2020). Bridging this yield gap through optimized agronomic practices is therefore essential. Such practices can help mitigate production constraints.

Because saffron growth and development largely occur underground, with corm formation taking place below the soil surface, monitoring growth indices with an emphasis on underground organ development provides a more accurate understanding of seasonal growth dynamics (Feizi et al., 2025). In this context, aeroponic cultivation, which has received increasing attention in recent years, offers a promising tool. Conventional breeding strategies have made limited progress due to saffron's triploid nature, underscoring the need for agronomic interventions to produce larger, high-quality corms. Multiple factors affect saffron yield and quality, including climatic conditions, nutrition, irrigation, pests, planting date, corm density, and planting depth. Among these, nutrient management is particularly influential in corm multiplication and in determining floral and stigma yield (Naderi Darbaghshahi et al., 2008).

In the saffron aeroponic cultivation system, two major phases are distinguished. During the first phase (flowering stage), saffron corms are kept without soil and without a nutrient solution. They are held solely in an environment with precisely controlled humidity, temperature, and light. At this stage, root activity is minimal. The corm depends entirely on its stored reserves for initiating floral buds and lateral sprouts. Thus, maintaining appropriate humidity, temperature, and light conditions is sufficient. Upon completion of the flowering period, the system transitions to the second phase (vegetative growth and replacement-corm production stage). During this stage, the corms require an external nutrient supply to support leaf growth and the formation of new daughter corms. Therefore, the corms are transferred to pots and cultivated in a nutrient-enriched hydroponic or soil-based system. This enables proper leaf development and corm renewal by providing a complete nutrient solution (Moradi et al., 2024).

Auxins represent a pivotal group of plant hormones in this context (Gomes & Scortecci, 2021). They are synthesized in actively growing tissues, such as shoot apices and young leaves. Auxins, whether naturally occurring or synthetic, are transported directionally via carrier proteins to establish spatial and temporal gradients (Tanaka et al., 2006). These gradients regulate key developmental processes, including organ initiation (phyllotaxis), vascular differentiation, and apical dominance. Plant tissue responses to auxin are often dose-dependent and can show threshold or biphasic patterns. Low concentrations promote growth,

whereas higher concentrations may inhibit it (Teale et al., 2006). The effective application of growth regulators in agriculture, therefore, requires precise control over dosage and delivery methods.

In corm and bulb-forming plants such as saffron, auxins can enhance assimilate allocation, strengthen sink capacity, and promote corm enlargement (Ameri et al., 2019). Imbalances in auxin distribution or interactions with cytokinins may lead to excessive production of small corms or reduced flowering (Chen et al., 2025; Ahmed et al., 2025). Priming saffron corms with synthetic auxins, such as naphthaleneacetic acid (NAA), may therefore elicit diverse effects on bud sprouting, flowering, and replacement corm production. The outcome depends on dose and timing.

Studies in bulbs such as garlic, onion, and hyacinth show auxin can spur bulblet growth, boost cell division in side meristems, and improve vegetative growth (Khan et al., 2017; Solano et al., 2023; Zahraei Basir, 2022). Low auxin doses tend to increase the number of replacement bulbs and their weight; high doses may slow growth or cause abnormalities (Khan & Nabi, 2023; Sosnowski et al., 2023).

In saffron, however, direct studies on auxin application remain limited. Some studies suggest that priming corms with growth regulators influences dormancy release (Amini & Ziaratnia, 2019), sprouting (Taherkhani et al., 2024), flowering (Singh et al., 2023), and replacement corm development (Mir et al., 2018). In addition, combining auxins with cytokinins or gibberellins has shown synergistic effects on cell division and corm multiplication (Javid et al., 2022). Nonetheless, these findings remain inconsistent and highly context-dependent. The optimal range of auxin concentrations in saffron has yet to be established. This knowledge gap underscores the importance of systematically investigating the effects of varying auxin concentrations, particularly NAA, on vegetative, reproductive, and propagation traits of saffron. Addressing this gap could provide a foundation for developing optimized protocols to enhance propagation efficiency and overall productivity.

Accordingly, the present study was designed to examine the effects of priming saffron corms with different concentrations of NAA under aeroponic cultivation conditions. The research aimed to evaluate the impact of hormonal treatments on a range of critical traits, including vegetative growth indices (e.g., leaf number and length), reproductive traits (flower number, floral yield, and stigma characteristics), and propagation traits (number and weight of replacement corms).

Materials and Methods

Experimental Site and Design

This study was conducted during 2021–2022 at the research laboratory of the Faculty of Agriculture, Shahid Bahonar University of Kerman, Iran, to evaluate the effects of different auxin concentrations on vegetative, reproductive, and propagation traits of saffron (*Crocus sativus* L.). The experiment was arranged in a completely randomized design (CRD) with three replications. The treatments included eleven auxin (NAA) concentrations: 0, 1, 2.5, 5, 10, 25, 50, 100, 250, 500, and 1000 $mg.kg^{-1}$.

Plant Material and Priming Treatments

Uniform saffron corms (Torbat Heydarieh ecotype) with an average weight of 15 g were selected. The outer dry tunics were carefully removed, leaving one or two protective layers intact. Before planting, corms were disinfected first with the miticide propargite and then with the fungicide carbendazim. For priming treatments, corms were soaked for six hours in NAA solutions of the designated concentrations (Ziaei et al., 2024). Control corms were soaked only in distilled water.

Following the priming period, the corms were not subjected to any drying process; instead, they were immediately transferred to wooden trays (50 × 50 cm) and arranged for aeroponic culture. The

trays were placed in the controlled phytotrons (Noor Sanat Azma company), with 40 cm vertical spacing between layers to ensure adequate air circulation and unobstructed shoot development. To minimize potential confounding effects from tray position or microenvironmental variation within the phytotron, the trays were rotated systematically every 10 days so that each treatment experienced comparable vertical and horizontal positions throughout the experiment.

In the aeroponic system, only humidity is supplied to support the development of the floral bud and other lateral buds, and no nutrient solution is provided to the roots. Upon completion of the saffron flowering period, the corms are transferred to pots to allow subsequent vegetative growth.

Growth Conditions

For each replication of every treatment, 100 corms were placed in a wooden tray. Corm planting was carried out on August 22. From planting until 20 days later, corms were kept in complete darkness at 20–23°C and 70–75% relative humidity. Around September 10-13, when the average floral tube length reached 2–2.5 cm, light intensity was gradually increased over 6–7 days to approximately 140 lux. During this period, temperature and humidity were maintained at 23°C and 70–75%, respectively, until October 22.

On October 23, when the average floral tube length reached 10 cm, a temperature shock was applied by reducing the temperature to 12–13°C, while increasing relative humidity to 80–85% and maintaining light intensity at 1400 lux. Flowers were harvested daily from the onset of flowering until the end of the flowering period. The flower number, fresh flower weight, stigma length, and dry stigma weight were recorded.

Post-Flowering and Vegetative Assessments

After flowering, the number of lateral buds on each corm was counted. The corms were then transplanted into 3-kg pots filled with a growth medium composed of 30% well-decomposed cow manure, 20% leaf mold, and 50% loamy soil (v/v). Vegetative traits, including leaf length and fresh weight, were measured on March 16, while propagation traits (number and weight of replacement corms) were recorded in mid-May.

Statistical Analysis

Data analysis was performed using SAS software (Version 9.4). Analysis of variance (ANOVA) was conducted to determine the effects of treatments on measured traits. Means were compared using Duncan's multiple-range test at the 5% significance level. Quadratic polynomial regression was used to fit the dose–response curves, and the significance of the quadratic term was confirmed ($p < 0.05$). Dose–response curves were plotted to examine the pattern of saffron response to increasing NAA concentrations. All figures and graphical outputs were prepared using SigmaPlot software (version 10).

Results and Discussion

Number of Lateral Buds

Analysis of variance revealed that corm priming with different concentrations of NAA had a significant effect ($p \leq 0.01$) on the number of lateral buds (Figure 1).

Mean comparison indicated that the corm response to NAA exhibited a biphasic, dose-dependent pattern (Figure 2). Low concentrations of NAA (5–10 $mg.kg^{-1}$) resulted in the greatest stimulation of lateral bud formation, whereas 25 to 250 $mg.kg^{-1}$concentrations showed a strong inhibitory effect. At the highest concentration range (500–1000 $mg.kg^{-1}$), a partial recovery in bud number was observed.

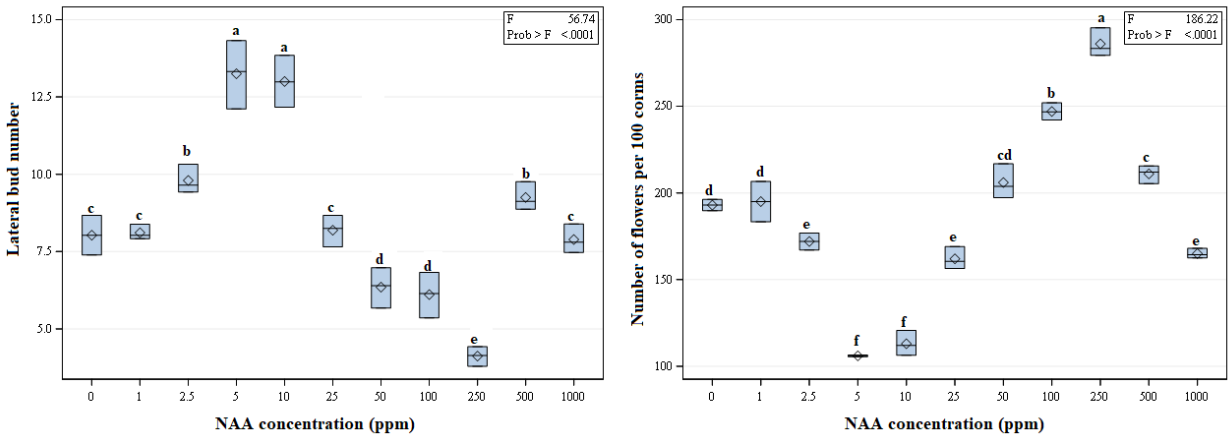

Figure 1. Effects of different concentrations of NAA on lateral bud number and number of flowers per 100 corms in saffron
Means with at least one common letter in each trait are not significantly different according to Duncan's multiple range test at the 5% probability level.

The highest mean number of lateral buds was recorded at 5 mg.kg^{-1} (13.9 buds) and 10 mg.kg^{-1}(13.2 buds), corresponding to approximately 75% and 66% increases, respectively, compared with the control (7.9 buds per corm). These two treatments differed significantly from all other NAA concentrations and demonstrated that low auxin doses can substantially enhance lateral bud initiation in saffron corms.

Also, treatments with 2.5 and 500 mg.kg^{-1} increased bud number by 28% and 18%, respectively, relative to the control. In contrast, priming with 1, 25, or 1000 mg.kg^{-1} did not differ significantly from the control, indicating a negligible effect on bud formation. Treatments at 50 mg.kg^{-1} (6.3 buds) and 100 mg.kg^{-1} (5.9 buds) significantly reduced lateral bud numbers by 20% and 25%, respectively, compared with the control. The lowest number of lateral buds (4.1 buds per corm) was observed at 250 mg.kg^{-1}, representing a 48% reduction relative to the control.

Number of Flowers

Analysis of variance showed that corm priming with different concentrations of NAA had a highly significant effect on the number of flowers per 100 corms ($p < 0.01$; Figure 1).

The maximum number of flowers was observed at 250 mg.kg^{-1} NAA, producing approximately 292 flowers per 100 corms, a 50.5% increase compared with the control (≈194 flowers). The minimum flower number was recorded at 5 mg.kg^{-1}, with only ≈106 flowers, corresponding to a 45.4% reduction relative to the control. Priming with 10 mg.kg^{-1} NAA also caused a significant decrease in flower production (≈40.2% lower than the control). In contrast, treatments with 100 and 500 mg.kg^{-1} NAA significantly increased flower number by 27.8% and 9.3%, respectively, compared with the control.

The overall response pattern to NAA followed a quadratic, dose-dependent (curvilinear) trend (Figure 2). As NAA concentration increased from 5 to 250 mg.kg^{-1}, flower number initially declined (at 5–10 mg.kg^{-1}), then progressively increased from 25 to 250 mg.kg^{-1}, reaching a peak at 250 mg.kg^{-1}. Further increases beyond this level led to a decline in flowering, with ≈166 flowers per 100 corms at 1000 mg.kg^{-1}, representing a 14.4% reduction compared with the control.

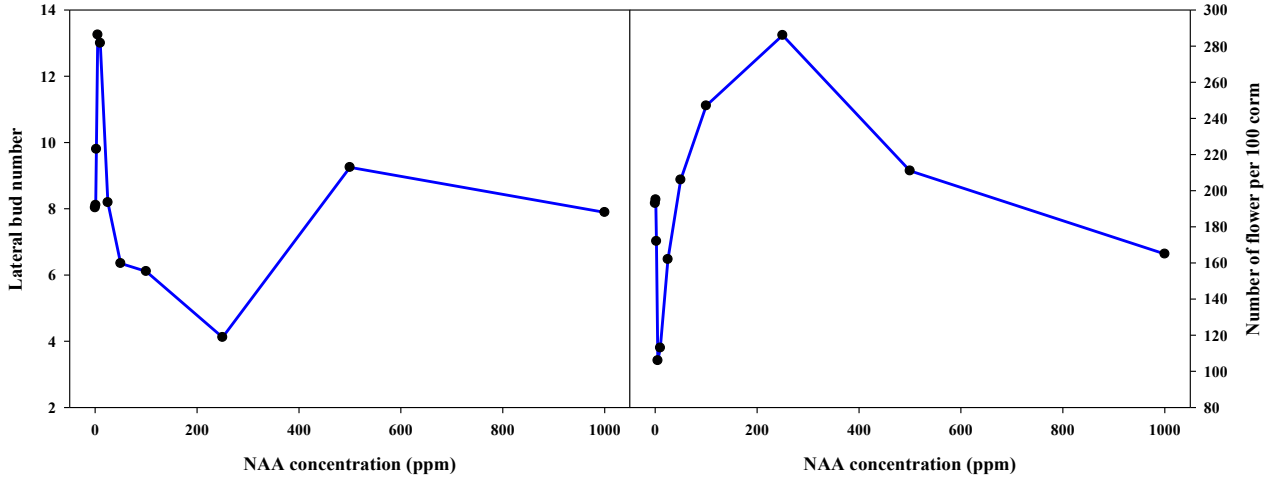

Figure 2. Dose–response of lateral bud number and number of flowers per 100 corms of saffron to different concentrations of NAA

Fresh Flower Weight

The fresh flower weight was significantly affected by NAA concentration at the 1% level of significance (Figure 3).

Mean comparison showed that corm priming with increasing concentrations of NAA (1-5 mg.kg^{-1}) led to a marked reduction in fresh flower weight compared with the control (Figure 3). The lowest mean fresh flower weight (≈37 g per 100 corms) was recorded at 5 mg.kg^{-1} NAA, representing a 54% decrease relative to the control (≈81 g per 100 corms) (Figure 3).

As the NAA concentration increased from 5 to 250 mg.kg^{-1}, the fresh flower weight increased sharply. Priming at 250 mg.kg^{-1} produced the highest flower yield (≈137 g per 100 corms), corresponding to a ≈70% increase over the control. However, a further increase in NAA concentration from 250 to 500 mg.kg^{-1} resulted in a 35% decline in this trait. At the highest concentration (1000 mg.kg^{-1}), fresh flower weight decreased significantly compared with 500 mg.kg^{-1}, resulting in about 15% less fresh flower weight than the control. These results indicate that the response of saffron corms to NAA in terms of flower biomass followed a clear dose-dependent and unimodal pattern, with the optimum concentration near 250 mg.kg^{-1}, beyond which flower production was substantially inhibited (Figure 3).

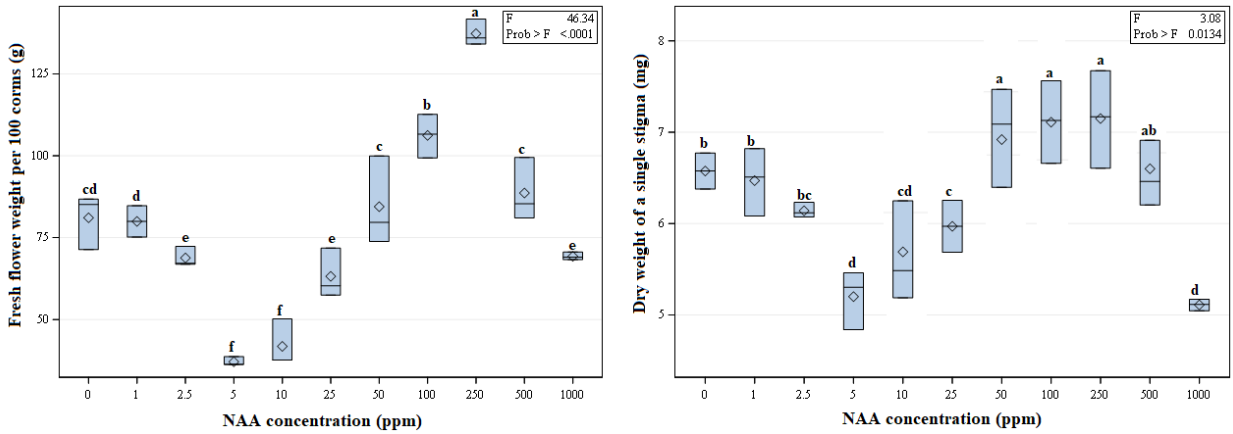

Figure 3. Effects of different concentrations of NAA on the number of flowers per 100 corms and the average dry weight of stigma in saffron

Means with at least one common letter in each trait are not significantly different according to Duncan's multiple range test at the 5% probability level.

Mean Stigma Dry Weight

Analysis of variance revealed that auxin concentration had a significant effect ($p < 0.05$) on stigma dry weight (Figure 3).

Increasing auxin concentration to 5 mg.kg^{-1} significantly decreased the mean stigma dry weight. Thereafter, a sharp increase was observed with the application of 10, 25, 50, and 100 mg.kg^{-1} auxin, reaching its maximum value (7.15 mg) at 250 mg.kg^{-1}. The use of 500 and 1000 mg.kg^{-1} auxin again caused a severe decline in this trait (Figure 3). Accordingly, pre-treatment of corms with 250 mg.kg^{-1} auxin resulted in the highest mean stigma dry weight, which, however, was not significantly different from those obtained at 100 and 50 mg.kg^{-1}. These three treatments increased stigma dry weight by approximately 9%, 8%, and 5%, respectively, compared to the unprimed control (Figure 4). No significant difference was detected between the control and the 1 or 500 mg.kg^{-1} auxin treatments. The lowest mean stigma dry weight (5.11 mg) was observed at 1000 mg.kg^{-1} auxin, corresponding to about a 22% reduction relative to the control.

Stigma Dry Yield

Auxin treatments had a significant effect ($p< 0.05$) on the dry stigma yield per 100 corms (Figure 5).

The stigma yield ranged from 0.55 to 2.04 g per 100 corms, corresponding to 5 and 250 mg.kg^{-1} auxin treatments, respectively (Figure 5). Results indicated that as auxin concentration increased from 1 to 5 mg.kg^{-1}, stigma dry yield sharply declined. However, priming corms with 10, 25, 50, 100, and 250 mg.kg^{-1} auxin resulted in a marked increase in this trait. Application of 500 and 1000 mg.kg^{-1} auxin significantly reduced stigma yield compared with 250 mg.kg^{-1}. Corm priming with 250 and 100 mg.kg^{-1} auxin increased stigma dry yield by approximately 61% and 38%, respectively, relative to the unprimed control (1.27 g per 100 corms). Conversely, priming with 5 and 10 mg.kg^{-1} auxin caused about 57% and 49% reductions in this parameter compared with the control.

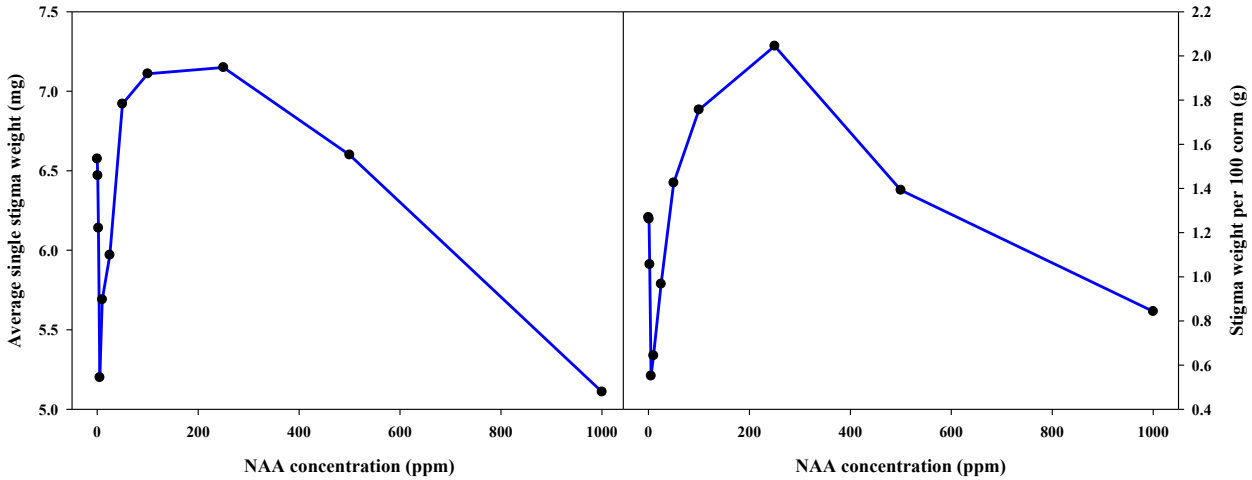

Figure 4. Dose–response of the average dry weight of stigma and stigma weight per 100 corms of saffron to different concentrations of NAA

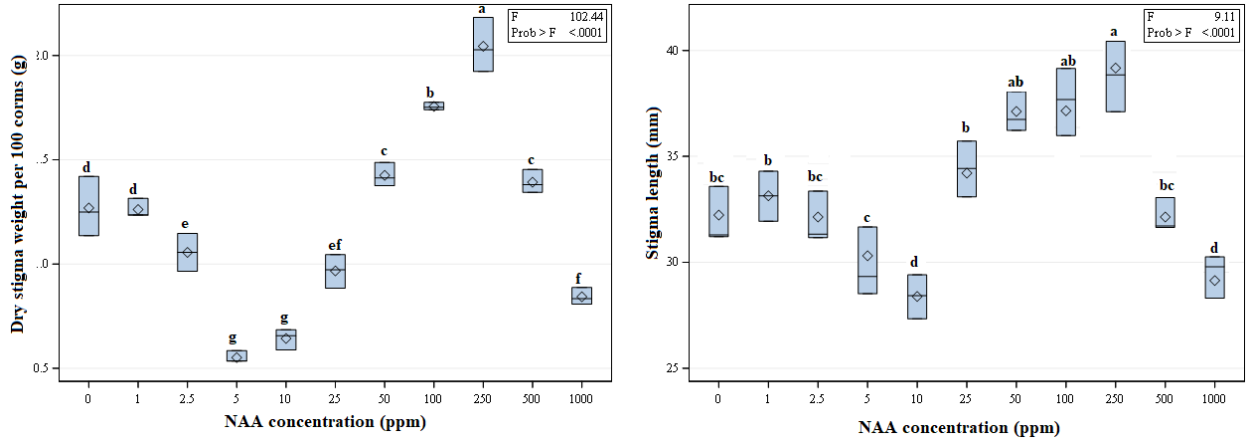

Figure 5. Effects of different concentrations of NAA on stigma length and weight of saffron
Means with at least one common letter in each trait are not significantly different according to Duncan's multiple range test at the 5% probability level.

Stigma Length

Stigma length was significantly affected by auxin concentration at the 1% probability level ($p < 0.01$; Figure 5).

No significant differences were observed among the control, 1, 2.5, and 5 mg.kg^{-1} auxin treatments (Figures 5 and 6). However, corm priming with 10 mg.kg^{-1} auxin reduced stigma length by approximately 12% compared with the unprimed control, resulting in the shortest stigmas (28.39 mm) among all treatments. As auxin concentration increased beyond this level, stigma length significantly increased, reaching a maximum (39.17 mm) at 250 mg.kg^{-1} auxin, representing about a 22% increase relative to the control. Further increases in auxin concentration (500 and 1000 mg.kg^{-1}) again caused a significant reduction in stigma length compared with the 250 mg.kg^{-1} treatment. The 500 mg.kg^{-1} treatment did not differ significantly from the control, whereas 1000 mg.kg^{-1} auxin produced significantly shorter stigmas than the unprimed treatment (Figure 5).

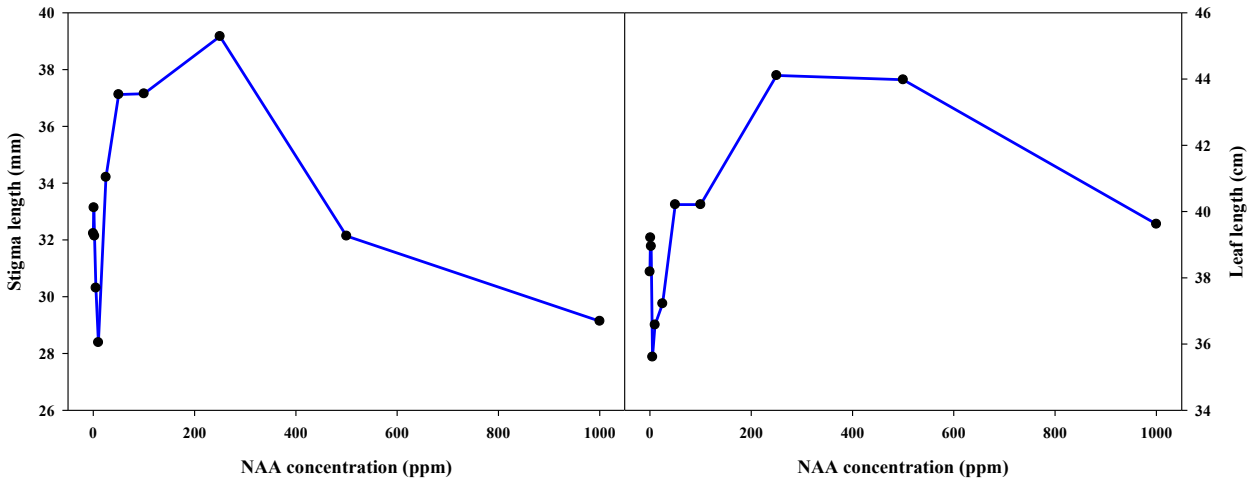

Figure 6. Dose–response of saffron stigma and leaf length to different concentrations of NAA
Means with at least one common letter in each trait are not significantly different according to Duncan's multiple range test at the 5% probability level.

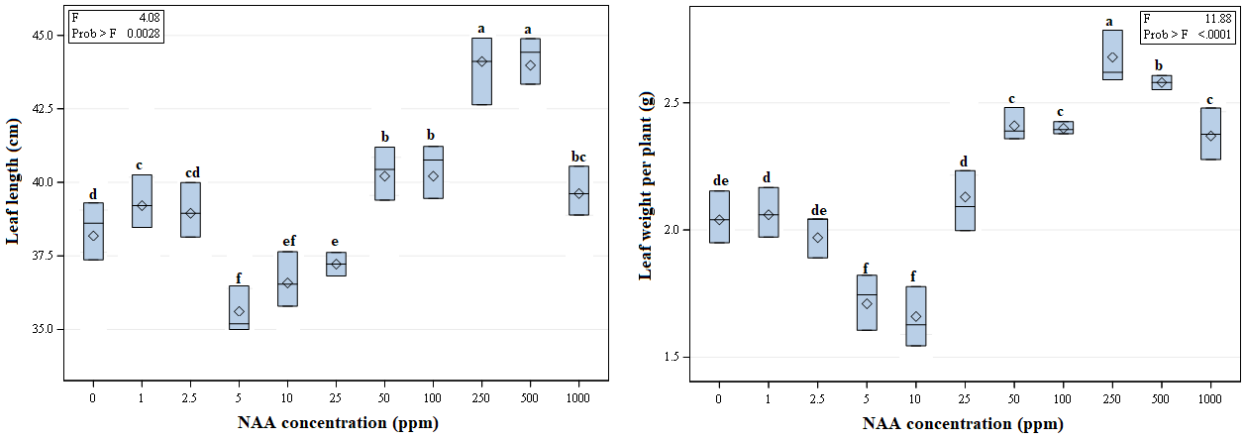

Figure 7. Effects of different concentrations of NAA on saffron leaf length and weight
Means with at least one common letter in each trait are not significantly different according to Duncan's multiple range test at the 5% probability level.

Leaf Length

Auxin concentration had a highly significant effect ($p < 0.01$) on leaf length (Figure 7).

The highest leaf length values were recorded in corms primed with 250 mg.kg^{-1} (44.11 cm) and 500 mg.kg^{-1} (43.98 cm) auxin, both of which were significantly greater than all other treatments (Figure 7). Corm priming with 50 mg.kg^{-1} and 100 mg.kg^{-1} auxin produced leaves averaging 40.21 cm in length, representing about a 5% increase compared with the unprimed control. The shortest leaves (35.61 cm) were obtained at 5 mg.kg^{-1} auxin, which did not differ significantly from 10 mg.kg-1 (36.58 cm). Overall, auxin concentrations of 1 and 2.5 mg.kg^{-1} slightly increased leaf length, whereas 5 mg.kg^{-1} reduced leaf length by about 7% relative to the control. With further increases in auxin concentration to 250 mg.kg^{-1}, leaf length increased steadily, followed by a decrease at 1000 mg.kg^{-1}, resulting in about a 10% reduction compared with 250 mg.kg^{-1} (Figure 7).

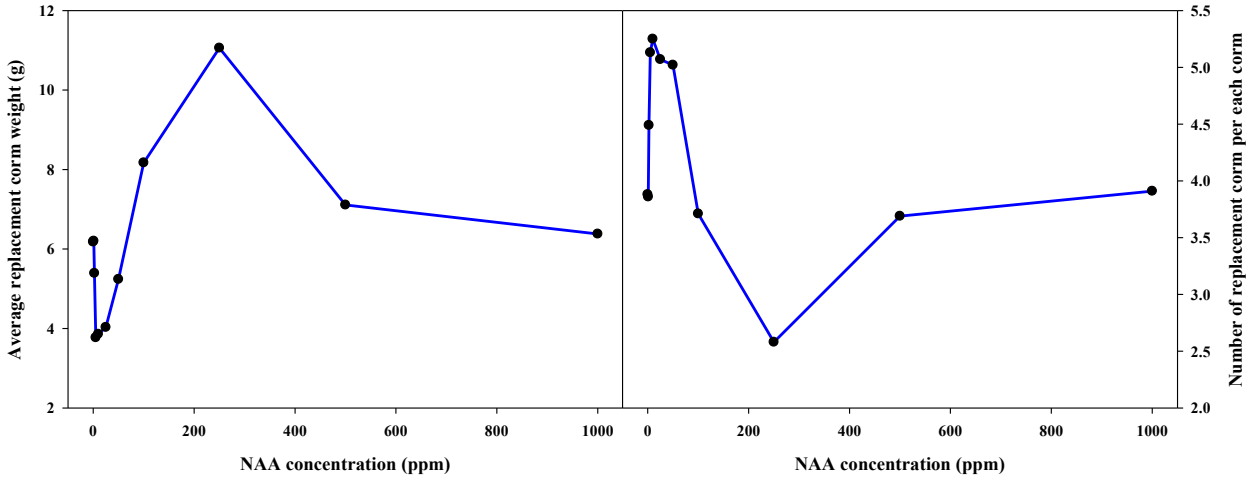

Figure 8. Dose–response of saffron replacement corm weight and number to different concentrations of NAA
Means with at least one common letter in each trait are not significantly different according to Duncan's multiple range test at the 5% probability level.

Leaf Dry Weight

Analysis of variance revealed that leaf dry weight was significantly affected by auxin concentration ($p < 0.01$; Figure 7). No significant differences were observed among the 0, 1, and 2.5 mg.kg^{-1} treatments (Figure 7). However, priming corms with 5 and 10 mg.kg^{-1} auxin significantly reduced this trait compared with the control, with the lowest leaf dry weight (1.66 g plant^{-1}) recorded at 10 mg.kg^{-1}. As auxin concentration increased further, leaf dry weight increased sharply, reaching its maximum value (2.68 g plant^{-1}) at 250 mg.kg^{-1}. Application of 500 and 1000 mg.kg^{-1} auxin significantly decreased leaf dry weight relative to 250 mg.kg^{-1}, although both concentrations still produced approximately 26% and 16% greater biomass than the unprimed control, respectively (Figure 7).

Number of Replacement Corms per Mother Corm

Auxin treatment significantly affected the number of replacement corms per mother corm ($p < 0.01$; Table 1).

The results revealed that increasing auxin concentration initially enhanced replacement corm formation, reaching the highest mean value (5.25 corms.corm^{-1}) at 10 mg.kg^{-1} (Figure 8, Table 1). No significant differences were detected among 10, 25 (5.07 corms.corm^{-1}), and 50 mg.kg^{-1} (5.02 corms.corm^{-1}) treatments. Beyond this point, a sharp decline was observed, with the lowest number (2.58 corms.corm^{-1}) recorded at 250 mg.kg^{-1}, approximately 34% lower than the control (3.88 corms.corm^{-1}). Further increases in auxin concentration led to a partial recovery, and the 500 (3.69 corms.corm^{-1}) and 1000 mg.kg^{-1} (3.91 corms.corm^{-1}) treatments were not significantly different from the control (Table 1).

Table 1. Response of saffron corm characteristics to different concentrations of NAA

NAA (mg.kg^{-1})	Number of replacement corms per mother corm	Mean corm weight	Number of corms per 100 mother corms	Number of corms < 5 g	Number of corms between 5–10 g	Number of corms > 10 g
0	3.88cd	6.18d	388.00c	75.12g	249.56a	63.32f
1	3.86d	6.20d	386.00c	162.12e	152.86de	71.02de
2.5	4.49bc	5.39e	449.00b	198.46d	186.34b	64.21ef
5	5.13a	3.77f	513.00a	375.72a	101.98g	35.29g
10	5.25a	3.86f	525.00a	331.49b	132.25ef	61.27f
25	5.07ab	4.03f	507.00a	252.59c	183.94b	70.47de
50	5.02ab	5.24e	502.00a	257.28c	155.87cd	88.85b
100	3.71d	8.17b	371.00c	161.53e	129.33f	80.14c
250	2.58e	11.06a	258.00d	47.00h	95.00bc	116.00a
500	3.69d	7.11c	369.00c	97.42f	177.86g	93.73b
1000	3.91cd	6.38cd	391.00c	160.19e	155.77d	75.03cd
F value	15.10**	64.81**	22.81	274**	33.37**	76.01**

Means with at least one common letter in each trait are not significantly different according to Duncan's multiple range test at the 5% probability level.

Mean Weight of Replacement Corms

Analysis of variance indicated that auxin concentration had a significant effect ($p < 0.01$) on the mean weight of replacement corms (Table 1).

With increasing auxin up to 5 and 10 mg.kg^{-1}, mean corm weight declined sharply (Figure 8). Thereafter, a pronounced increase occurred with further increases in auxin concentration, peaking at 250 mg.kg^{-1} (11.06 g.corm^{-1}), which was approximately 1.79 times higher than the control. Treatments with 500 and 1000 mg.kg^{-1} auxin again resulted in a significant decline, reducing mean corm weight by 56% and 73%, respectively, relative to 250 mg.kg^{-1} (Table 1).

Replacement Corm Yield (per 100 Mother Corms)

Auxin concentration had a highly significant effect ($p < 0.01$) on the number of replacement

corms produced per 100 mother corms (Table 1).

The number of replacement corms ranged from 258 to 525, corresponding to the 250 and 10 mg.kg^{-1} auxin treatments, respectively. As auxin concentration increased from 0 to 50 mg.kg^{-1}, replacement corm yield increased significantly (Table 1). Treatments with 5, 10, 25, and 50 mg.kg-1 produced the highest yields, showing no significant differences among them. A further increase in auxin concentration to 100 and 250 mg.kg^{-1} caused a steep decline, reaching the minimum value (258 replacement corms per 100 mother corms) at 250 mg.kg^{-1}. However, increasing auxin to 500 and 1000 mg.kg^{-1} significantly enhanced replacement corm production again compared with 250 mg.kg^{-1}. These results indicate that corm yield followed a biphasic, dose-dependent pattern in response to auxin priming (Table 1).

Weight Distribution of Replacement Corms

The effect of varying NAA concentrations on the weight distribution of saffron replacement corms showed a highly significant effect ($p < 0.01$), indicating that auxin modulates corm formation patterns in a dose-dependent manner (Figure 9). The plant's response to NAA was clearly nonlinear, with shifts in the proportional distribution of small, medium, and large corms depending on the concentration applied.

In the control treatment, the majority of corms (≈64% of ~250 corms) fell within the medium weight class (5–10 g), while small and large corms accounted for 19% and 16%, respectively, reflecting the typical distribution under natural, untreated conditions (Figure 9).

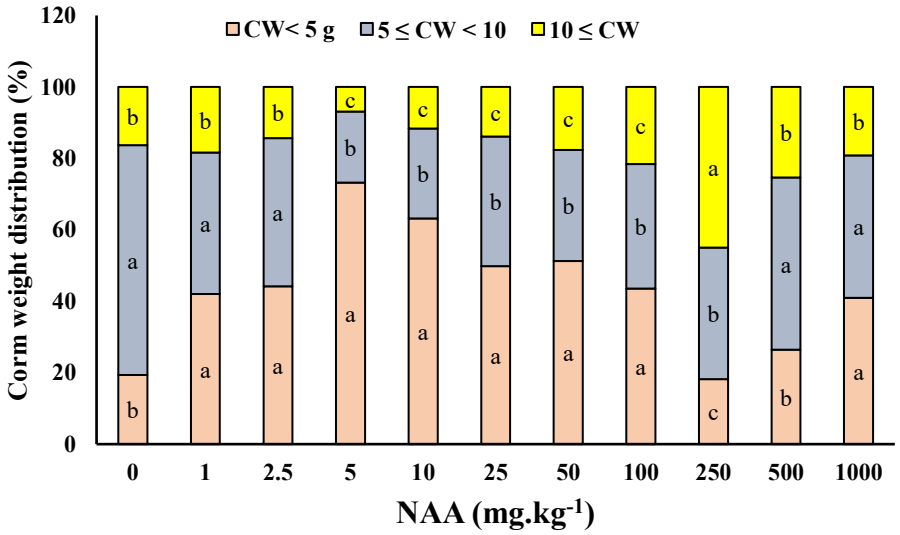

Figure 9. Effect of different NAA concentrations on the percentage distribution of saffron replacement corms across three weight classes

Means with at least one common letter are not significantly different according to Duncan's multiple range test at the 5% probability level.

Low to moderate NAA concentrations, particularly 5 and 10 mg.kg^{-1}, dramatically altered this pattern, favoring the production of small corms. At 5 mg.kg^{-1}, approximately 73% (~375 corms) were classified as small (<5 g), while at 10 mg.kg^{-1}, more than 63% (~331 corms) fell into this category. This pronounced increase in small corms highlights the stimulatory effect of low NAA concentrations on corm number, which, although advantageous for rapid propagation, results in a majority of corms below the optimal size for future agronomic performance (Figure 9).

At intermediate concentrations (25–100 mg.kg^{-1}), the distribution became more balanced. For example, at 50 mg.kg^{-1}, small, medium, and large corms accounted for 51%, 31%, and 17%, respectively, whereas at 100 mg.kg^{-1}, small corms represented 43% (~162 corms), medium 35% (~129 corms), and large 22% (~80 corms). These results suggest that intermediate NAA concentrations reduce the excessive formation of small corms while slightly enhancing the proportion of large corms, although the overall distribution still favors smaller sizes (Figure 9).

A marked shift occurred at 250 mg.kg^{-1}, where the proportion of large corms was maximized (Figure 9). In this treatment, large corms (>10 g) comprised 45% (~116 corms), while small and medium corms decreased to 18% (~47 corms) and 37% (~95 corms), respectively. This indicates that 250 mg.kg^{-1} represents a critical threshold favoring the production of heavier corms rather than increasing the total number of small ones. At higher concentrations (500 mg.kg^{-1}), medium and large corms accounted for 48% and 25%, respectively, with a relative decline in small corms. At 1000 mg.kg^{-1}, the distribution became approximately balanced across the three weight classes (41%, 40%, and 19% for small, medium, and large corms, respectively).

Overall, these findings indicate that low NAA concentrations (5–10 mg.kg^{-1}) preferentially enhance the production of small corms, suitable for rapid propagation. In contrast, higher concentrations, particularly 250 mg.kg^{-1}, favor the formation of larger, higher-quality corms. Hence, NAA-induced shifts in the distribution of replacement corm weight are dose-dependent and can serve as a practical management tool in saffron cultivation (Figure 9).

Discussion

Saffron growth and yield are strongly influenced by early-season hormonal regulation, making the study of auxin priming highly relevant for improving reproductive performance (Solano et al., 2023). Aeroponics provides a controlled root-zone environment with uniform nutrient delivery and high oxygen availability, allowing the direct effects of NAA to be evaluated without soil-related variability (Moradi et al., 2024). This controlled setting helps reveal clear dose–response patterns, such as the biphasic reactions observed in our study, and highlights the value of aeroponics for mechanistic research on saffron physiology. The present study demonstrated that lateral bud germination in saffron exhibits a distinct auxin-concentration-dependent response pattern. Low concentrations of NAA promoted lateral bud emergence, whereas intermediate concentrations, particularly around 250 mg.kg^{-1}, significantly suppressed this process. At high concentrations (500–1000 mg.kg^{-1}), partial recovery of lateral bud germination was observed, suggesting a dual role of auxin in regulating apical dominance and complex interactions with other hormones, notably cytokinins. Physiologically, auxin synthesized in the apical meristem is transported polar-wise to other plant regions (Yadav et al., 2023). Adequate auxin levels in the main axis inhibit lateral bud growth, a phenomenon known as apical dominance (Cao et al., 2023). At low auxin levels, the reduction of this inhibitory signal permits activation of lateral growth pathways (Fukaki et al., 2017). In contrast, intermediate auxin concentrations maintain sufficient apical dominance, markedly reducing lateral bud emergence (Balla et al., 2016). Interestingly, at very high concentrations (500–1000 mg.kg^{-1}), partial alleviation of auxin inhibition occurred, likely due to shifts in the auxin/cytokinin balance, as high auxin levels can enhance cytokinin synthesis or tissue sensitivity through negative feedback mechanisms (Shimizu-Sato et al., 2009), thereby stimulating lateral bud growth. Additionally, high auxin may activate noncanonical pathways, such as ethylene induction, which can further modulate lateral bud development.

The response of reproductive traits, including

flower and stigma formation, to NAA pretreatment also showed a clear, bell-shaped, nonlinear pattern. Very low concentrations (5–10 $mg.kg^{-1}$) significantly reduced flower number, fresh flower weight, and dry stigma yield (e.g., ≈106 flowers per 100 corms and ≈37 g fresh weight at 5 $mg.kg^{-1}$ vs. ≈194 flowers and 81 g in the control). Increasing the concentration to ~250 $mg.kg^{-1}$ maximized these indices (≈292 flowers per 100 corms and ≈137 g fresh flower weight), with peak dry stigma weight also observed at this concentration. Concentrations above 250 $mg.kg^{-1}$ (500–1000 $mg.kg^{-1}$) again led to declines. This "initial decline–increase to peak–subsequent decrease at very high concentrations" pattern reflects a multi-level, dose-dependent regulation of hormonal and metabolic pathways governing reproductive organ formation and growth.

The enhanced flower number and fresh weight at 250 $mg.kg^{-1}$ can be explained by auxin's pivotal role in organ initiation. Localized auxin maxima in specific tissues activate genes and networks that define meristem identity and boundary regions (Smetana et al., 2019). Polar auxin transport, mediated by PIN proteins, generates these maxima, initiating organogenesis (Křeček et al., 2009). Auxin response factors (ARFs) and floral identity genes (e.g., LFY and AP1) interact with these pathways, ultimately inducing flower development (Liu et al., 2015). At the optimal concentration (250 $mg.kg^{-1}$), NAA pretreatment likely optimizes local auxin distribution and magnitude, satisfying meristem induction thresholds and enhancing cell division and differentiation in reproductive tissues, resulting in increased flower number and fresh flower weight. Auxin's role in accelerating floral initiation and development, as well as enhancing carbohydrate and nutrient allocation to reproductive organs via source–sink modulation, has been corroborated in other studies (Ebrahimzadeh & Abrishamchi, 2001; Zhao et al., 2022; Wan et al., 2024).

The reduction in performance at very low (5–10 $mg.kg^{-1}$) and very high (≥500 $mg.kg^{-1}$) concentrations can be attributed to several mechanisms. Low concentrations may disrupt endogenous auxin distribution, altering meristematic maxima formation (Hayward et al., 2009), shift the hormonal balance toward vegetative growth at the expense of reproduction (Khan et al., 2023), or modify floral induction pathways (e.g., gibberellin or photothermal signalling), leading to initial reductions in flower production. High concentrations may cause tissue stress (Grossmann et al., 2001), negative feedback regulation of auxin signalling, activation of inhibitory pathways (e.g., ethylene or ROS), or perturbations in local auxin canalization, reducing reproductive performance. Such nonlinear, biphasic responses are consistent with hormesis phenomena in biology.

Importantly, the regulatory mechanisms for vegetative and reproductive traits differ. As observed, low auxin concentrations promoted lateral bud emergence while suppressing flower formation, indicating tissue-specific sensitivity or distinct pathways for vegetative versus reproductive allocation. Consequently, selecting the optimal dose for enhancing flower production requires consideration of these contrasting responses. Previous reports have shown that plant growth regulators (PGRs) in saffron can modulate flower morphology and yield, with effects dependent on hormone type, concentration, and application timing (Chen et al., 2025; Hoseinifard et al., 2018; Amini & Ziaratnia, 2019).

Similarly, the response of replacement corm production followed a concentration-dependent pattern. In the control, most corms fell within the medium weight class (5–10 g), with a few large corms (>10 g), reflecting the plant's natural propagation capacity. Low NAA concentrations (5–10 $mg.kg^{-1}$) increased total replacement corm number but skewed the distribution toward small corms (<5 g), indicating activation of rapid proliferation pathways without sufficient time for growth and resource accumulation. While

beneficial for initial propagation, these small corms have limited flowering potential and low first-year yield. Conversely, 250 mg.kg^{-1} NAA produced the most favorable shift in corm weight distribution, increasing the proportion of large corms to ~45% while reducing small corms. This effect likely results from enhanced cell division, elongation, and reserve accumulation (e.g., carbohydrates and proteins), increasing the sink strength of developing corms and promoting their enlargement (Jose-Santhi et al., 2024). At higher concentrations (500–1000 mg.kg^{-1}), although the large corm proportion remained higher than the control, it decreased relative to 250 mg.kg^{-1}, and the small corm proportion increased again, likely due to inhibitory effects of excessive auxin, including stress-induced responses and disrupted auxin distribution.

Despite the valuable findings of this study, the external validity of the results should be interpreted with caution. The experiment was conducted under controlled aeroponic conditions, which differ fundamentally from soil-based field environments in terms of root-zone aeration, moisture dynamics, nutrient distribution, and overall physiological stresses experienced by the plant. Therefore, although 250 mg.kg^{-1} NAA produced the highest reproductive outputs in this study, this concentration should be considered as the "optimal level under the specific conditions of the aeroponic system and the experimental season," rather than a universally optimal dose for saffron cultivation. To strengthen the generalizability of these results, further evaluations of NAA priming at similar concentrations under field and soil-based conditions are necessary to determine whether the same response patterns are reproduced in real-world production systems.

Conclusion

The results of this study demonstrated that saffron exhibits a distinct, dose-dependent, and often biphasic response to auxin priming. Low NAA concentrations (5–10 mg.kg^{-1}) promoted vegetative propagation by enhancing lateral bud formation and increasing replacement corm number, but simultaneously reduced flower number, fresh flower weight, and stigma yield. This pattern suggests that low auxin levels may shift resource allocation toward vegetative proliferation rather than reproductive development. At moderate to high concentrations (25–100 mg.kg^{-1}), plant responses gradually transitioned toward reproductive enhancement, culminating at approximately 250 mg.kg^{-1}, which proved to be the optimal dose for maximizing floral and stigma yield parameters. Corm priming at 250 mg.kg^{-1} significantly increased flower number, stigma length, stigma dry weight, and total stigma yield per 100 corms. At this concentration, auxin likely optimized cellular division and differentiation in reproductive tissues, improved assimilate partitioning toward floral organs, and enhanced the sink strength of developing flowers and stigmas. Additionally, this treatment favored the production of larger replacement corms, improving propagation quality and potential yield for subsequent cycles. However, further increases in auxin concentration (≥500 mg.kg^{-1}) again reduced most growth and yield traits, indicating the onset of auxin-induced inhibition, possibly through stress responses, hormonal imbalance, or disrupted polar transport. Overall, these findings confirm that the physiological effects of auxin on saffron growth are highly concentration-dependent and tissue-specific, reflecting auxin's dual role in balancing vegetative and reproductive development.

From a practical standpoint, pre-planting priming of saffron corms with approximately 250 mg.kg^{-1} NAA can be recommended to improve reproductive performance and corm quality under aeroponic culture, whereas lower concentrations (5–10 mg.kg^{-1}) may be more suitable when the objective is rapid propagation through small corm production.

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