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Deciphering the Role of Integrated Nutrient Management on Saffron Stigma Yield under Climatic Conditions of Quetta Balochistan

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ABSTRACT

Saffron is the most expensive spice grown in arid and semiarid regions of the globe. Integrated nutrient management has a significant impact on saffron growth and quality by improving nutrient mobilization, water hold capacity, and improvement of soil health. To evaluate the impact of organic and inorganic fertilizer on saffron stigma yield a study was conducted at Balochistan Agricultural Research and Development Center, Quetta. The study comprised of six integrated nutrient management treatments including control under randomized complete block design. Farmyard manure alone and in combination with different NP doses and NP doses alone were used to evaluate its impact on saffron yield and floral attributes. Our results showed better flowering under farmyard manure and moderate nitrogen and phosphorous treatments while the flowering delayed under high NP application. Saffron stigma, stamen and petal dry weight data showed higher yield under Farmyard Manure @ 30 tons producing 7.79, 6.93 and 102.6 milligrams of dry weight for single flower. FYM treatment also increased fresh weight of stigma, stamen and petals. FYM with balanced application of nitrogen and phosphorous also revealed positive impact on stigma and floral attributes. The correlation and PCA analysis depicted positive association of stigma with stamen 0.61 and petal dry weight 0.55 which shows that integrated nutrient management can improve saffron yield along with sustainable improvement of soil health.

INTRODUCTION

Saffron (*Crocus sativus* L.) is a perennial herbaceous plant mainly used as medicinal spicy herb and considered as one of the most expensive spices. 'Saffron' is derived from Arabic word "Zafaran" which means yellow, 'Kesar' in Hindirparan (flower of golden petal) and in Kashmiri language, it is called 'Koung' (Ayub et al., 2022) . Saffron is a triploid plant that is propagated through corms The dried crimson stigmas, which accumulate high concentrations of three glycosylated apocarotenoids, picrocrocin, crocin, and safranal, are the source of its secrets, which are more than 150 volatiles and aroma-producing compounds, contributing to the saffron's color, bitter taste, and aroma (Behdani et al., 2016) . Crocin is responsible for the color of saffron, whereas picrocin and safranal are responsible for its bitter taste and aroma (Khan & Abourashed, n.d.) Crocin is one of the major health promoting compound found in saffron stigma (Chen et al., 2008).

Global production of saffron is estimated at 418 tons per year on 121,338 hectares (توسی et al., 2024). The major Saffron producing countries includes Iran (108,000 ha) which is the largest saffron producing country with around 90% global production followed by Afghanistan (7,557 ha), India (3,674 ha) and Greece (1000 ha) (Cardone et al., 2019). To produce 1 kilogram of dry saffron it is estimated to produce 150,000 to 170,000 flowers which may require 1 to 1.2 acres of land. Environmental conditions make a major contribution in the production of saffron and its quality. Saffron is grown mainly in arid and semi-arid regions where it stays dormant in summer while active in winter season with producing flowers around 5-10ºC.

Integrated Nutrient Management (INM) is critical to increase crops yield and improve soil health for sustainable crop production. Balanced supply of nutrients, and supplementing soil to improve soil microbial health is critical in developing agricultural ecosystem. Integrated nutrient management (INM) is characterized by an environment friendly approach where a balance of organic and inorganic fertilizer is maintained for sustainable crop growth and improve soil health. Saffron quality is highly influenced by soil quality, rainfall, altitude and temperature. Well drained soil assists in improving corm size and helps in reducing soil borne diseases. Regions above 650 and 1,400 meters are considered suitable for saffron production with rainfall between 150-300 mm (Sarfraz et al., 2023). In a recent study in Kashmir, researchers demonstrated that that applying 90 kg N ha^{-1} alongside 60 t FYM ha^{-1} resulted in the highest saffron yields of 2.98 and 4.13 kg ha^{-1} over two consecutive years (Sofi et al., 2013). Likewise, saffron INM study in Iran found that integrating poultry manure, humic acid, amino acids, biofertilizers, and micronutrients resulted in significant increase in flower number and stigma yield (Ahmadian et al., 2024). Saffron flower and stigma yield were positively influenced when INM system was implemented in saffron production which improved saffron flower and stigma indices by 35-70% (Sarfraz et al., 2023). Similarly, high saffron productivity was achieved when saffron was produced under integrated nutrient management system in Iran (Kirmani et al., 2022). In a research study conducted on salina and non-saline soil at Quetta Balochistan, researchers reported increase of 44 and 41% in stigma yield of saffron after soil amendment with compost and biochar along with increase in leaf and stigma yield after using chemical fertilizer (Qasim et al., 2024).

Balochistan is largest province of Pakistan with different agroecology's with its highlands suitable for production of saffron. Due to arid to semi-arid environmental conditions, large marginal land, with well-drained soil and low humidity during flowering, Highlands of Balochistan are favorable to grow saffron. Previous studies from Balochistan on saffron crops showed that minimum research literature is available on saffron production in Balochistan and further studies required to improve saffron production in Balochistan (Ayub et al., 2022; Qasim et al., 2024). To better understand the impact of organic and inorganic fertilizer on saffron stigma production and increase in flower quality, we conducted a study to evaluate saffron production under different integrated nutrient management treatments to increase saffron flower and stigma production under climatic conditions of Balochistan.

MATERIALS AND METHODS

The study was conducted at Balochistan agricultural Research and Development Center (BARDC), Quetta during 2021-22 season. The crop was planted under 6 different experimental treatments which include T1. Control, T2 (FYM @30 tons), T3 (FYM @ 20 tons and NP @ 50:100), T4 (FYM @ 10 tons and NP @100:100), T5 (NP@ 200:150), and T6 (NP @150:100). The Saffron genotype (local) already grown at BARDC was selected for testing purposes. The data was taken from randomly selected plants from each treatment in three replications. The following traits were measures to study the effect of integrated nutrient management using different treatments.

Days to Flower Initiation: The number of days were recorded when the first flower in the treatment emerged during the growing season of the crop.

Days to Emergence Maximum. Maximum flowering days were counted from sowing to when maximum flowers were recorded in each treatment.

Leaf Length (cm): Leaf length was recorded from randomly selected plants by taking measurements from base of leaf to the top of the leaf and recorded in cm.

Number of Leaves/plants: Number of leaves per plant was counted by selecting random plants at the time of maturity and number of leaves counted per plant.

Fresh and Dry Weight of Flowers (mg): Random sampling was done to select flowers for fresh and dry weight calculation. The fresh weight and dry weight of flowers were recorded in milligram using digital balance. After fresh weight flowers were dried under normal room conditions for 1-week duration and weight was taken from the dried flowers (mg).

Fresh and dry Weight of Stigma (mg): After picking the flowers, stigma stamen and petal were separated. Fresh weight of stigma was recorded using digital balance in milligrams. After drying of stigma at room temperature the samples were again weighed for observing dry weight of stigma (mg).

Fresh and Dry Weight of Stamen (mg): Similar procedure as conducted for stigma was used for stamen by recording fresh and dry weight of stamens after picking from the field. The separated stamens were weighed for fresh and later dried to take dry weight using digital balance and taken in milligrams.

Length of Fresh and Dry Stigma (mm): Stigma length has a major role in final yield. Separated stigma were randomly selected and measured for fresh stigma length and later dried to record dry stigma length using scale and measured in cm.

Total Flowering Period: Days from initial flower bloom to final were counted in each treatment to record total flowering days.

Statistical Analysis: The data were analyzed statistically by using one-way ANOVA with a level of significance $\alpha = 0.05$. Pearsons's correlation and Principal component analysis were used to measure the association of different measured traits. Statistical software Statistix 8.1, and Jamovi were used to analyze data (Pearson, 1920).

RESULTS

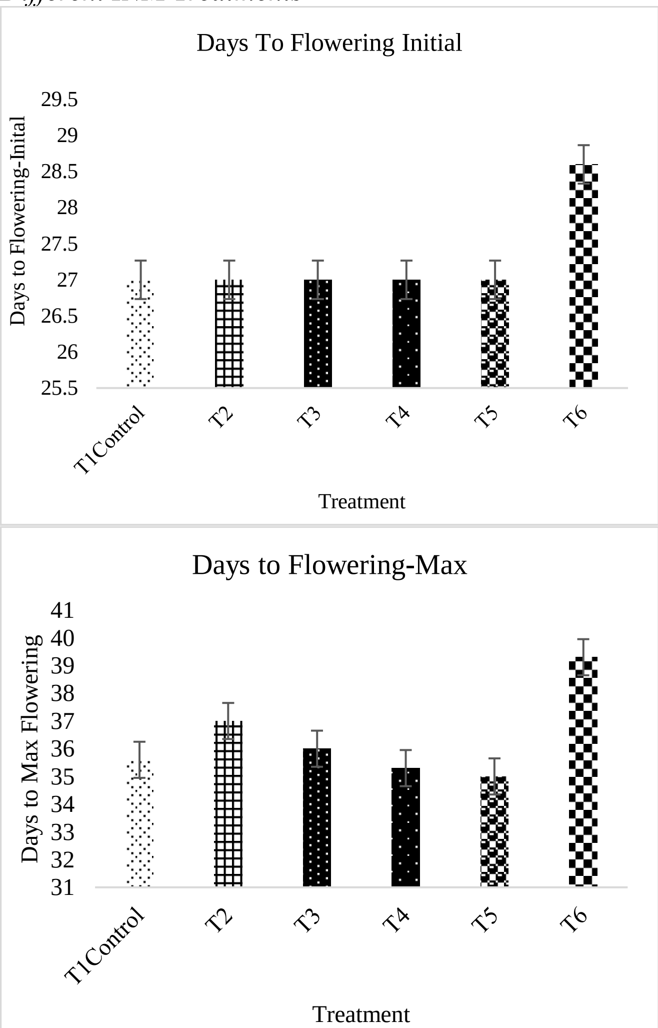
Analysis of variance showed significant (*P<0.05*) difference among tested treatments for all major traits except leaves per plant which was found to be non-significant (Table 1). The results show that integrated nutrient management has a profound impact on flower attributes in saffron.

Days to Flowering-Initial. Days from sowing to initial flowering showed all treatments flowered at same time except T6 (NP 150:100) which flowered in 28.6 days. The difference is smaller (1.5 days) but had significant impact on variability among tested treatments.

Days to Flowering Maximum. The days to flowering when maximum flowers were recorded showed minimum days was recorded by treatment T5 (NP 200:150) where maximum flowers were produced in 35 days while maximum days to flower was recorded for treatment T6 (NP 150:100) with 39.3 days followed by treatment T2 (FYM @ 30 tons) with 37 days. The results show 4 days difference between treatment T5 and T6 while other treatments were within this range with control and T4 also flowered in 35.6 and 35.3 days.

Figure 1

Days to Flowering (Initial and Maximum) under Different INM Treatments

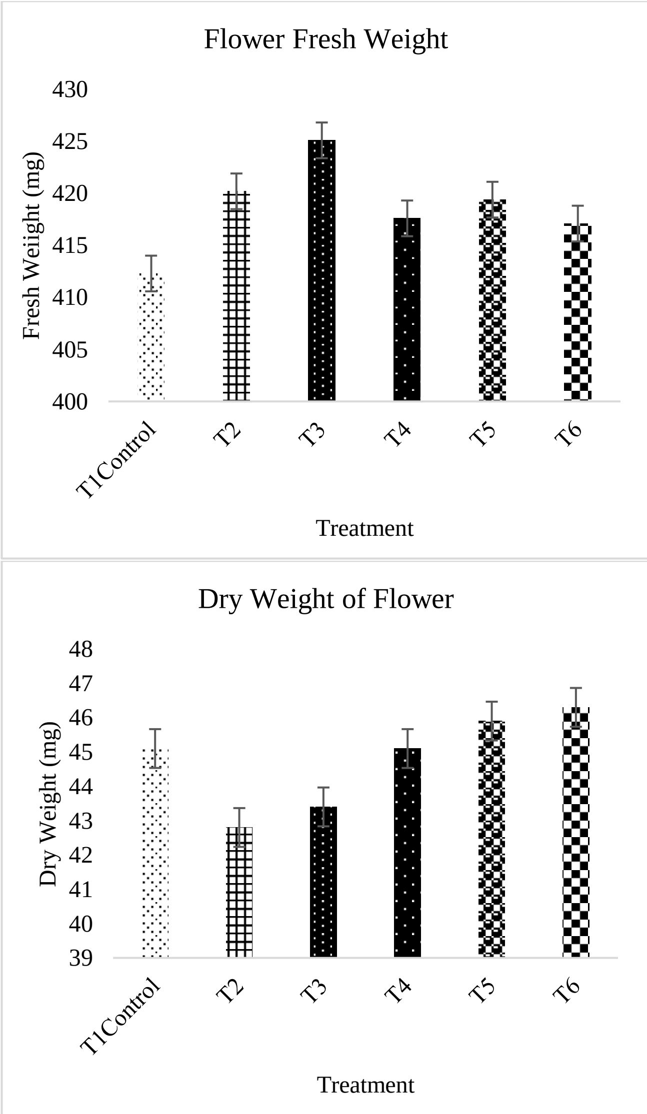


Flower Fresh Weight. Fresh weight of single flower data depicts maximum fresh weight under treatment T3 (FYM @ 20 tons and NP @ 50:100) with 425.1 milligrams followed by treatment T2 with 420.2 milligrams weight. Minimum weight was observed for control treatment with 412.3 milligrams of fresh flower weight.

Dry Weight of Flower. Dry weight of single flower taken by averaging multiple flowers showed maximum dry weight under treatment T6 (NP 150:100) with 46.3 milligrams while lowest was for treatment T2 (FYM@ 30 tons) with 42.8 milligrams of dry weight. Treatment T5 closely followed T6 by producing 45.9 mg dry weight of flower. Large differences were observed in fresh and dry weight for flowers after drying which changed the ranking of the treatments.

Figure 2

Saffron Flower Fresh and Dry weight under Different INM Treatments

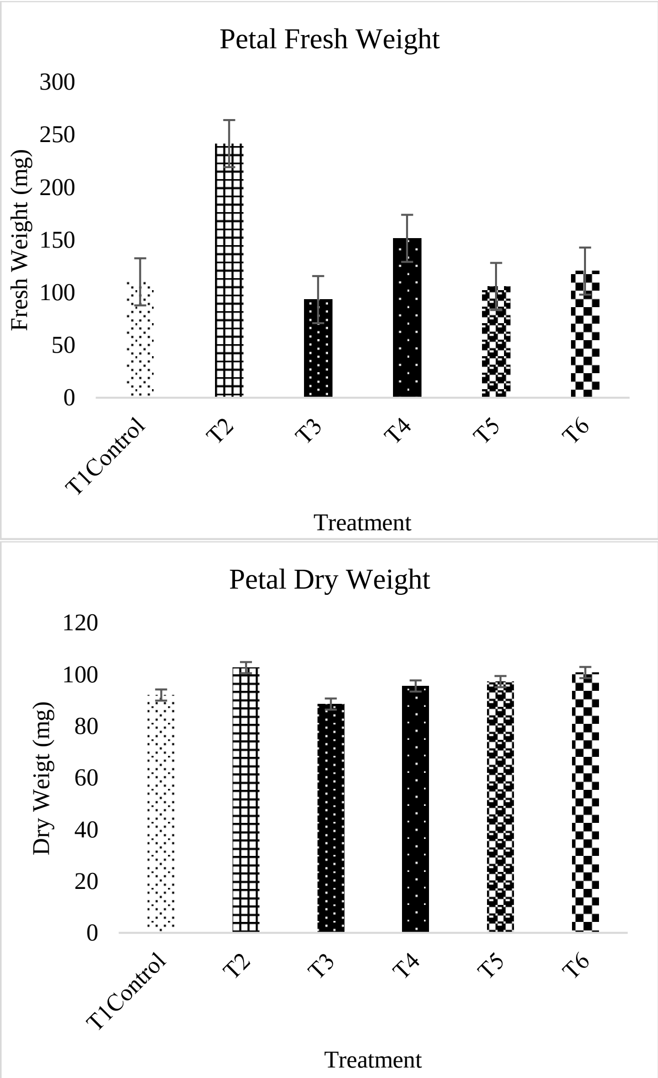


Petal Fresh Weight (mg). Petal fresh weight was recorded after removing petals from each flower to evaluate which treatment has maximum impact on petal fresh weight. On average single flower petal fresh weight data shows T2 (FYM @ 30 tons) as the best performing treatment with 241.4 milligrams of fresh petal weight followed by T4 (FYM @ 10 tons and NP @100:100) with 151.4 milligrams. Lowest petal fresh weight was recorded for treatment T3 (FYM @ 20 tons and NP @ 50:100).

Petal Dry Weight (mg). Petal dry weight data showed variability in weight with maximum dry weight recorded under treatment T2 (FYM @ 30 tons) with 102.6 grams of petal dry weight followed by treatment T6 (NP 150:100) with 100.7 milligrams of petal dry weight. The control treatment produced a petal dry weight of 92 milligrams. Minimum petal dry weight was recorded for treatment T3 which produced an 88.5 milligram weight for petals from single flower.

Figure 3

Saffron Petal fresh and Dry weight under Different INM Treatments

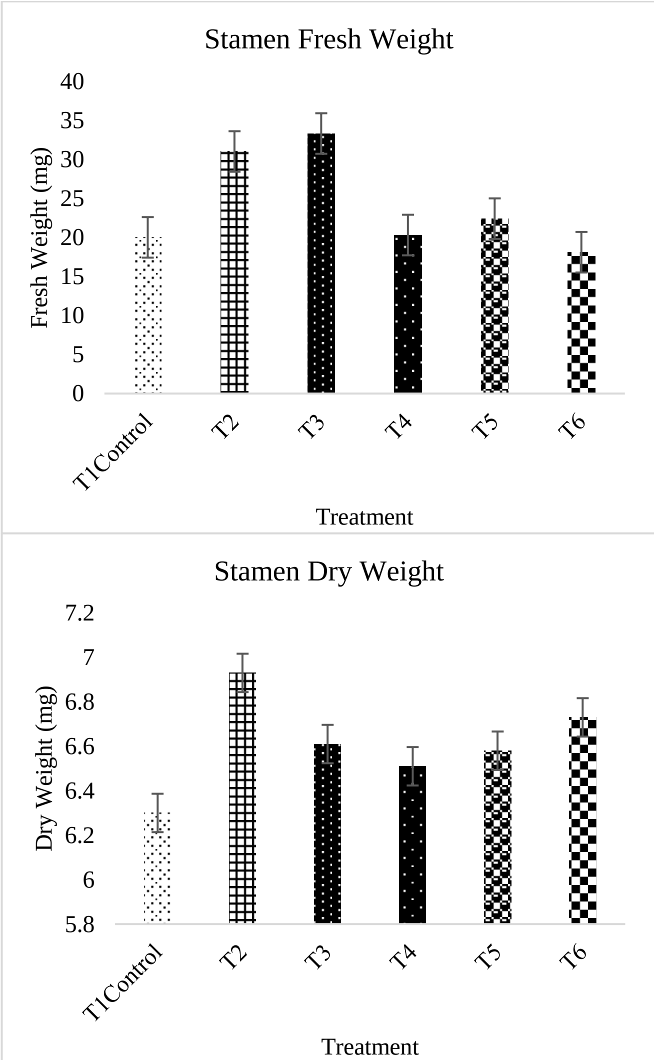


Stamen Fresh Weight. Stamen fresh weight was also recorded to check the effect of integrated nutrient management on stamen yield under fresh and dry weight. Maximum stamen fresh yield was observed for treatment T3 (FYM @ 20 tons and NP @ 50:100) with 33.3 milligrams weight while minimum was for T6 (NP 150:100) with 18.1 milligrams weight.

Stamen Dry Weight. Stamen dry weight data showed maximum yield for T2 (FYM @ 30 tons) with 6.93 milligram dry weight followed by T6 (NP 150:100) with 6.73 weight. Minimum dry weight was observed for control treatment with 6.3 milligrams of stamen weight.

Figure 4

Saffron Stamen fresh and Dry weight under Different INM treatments



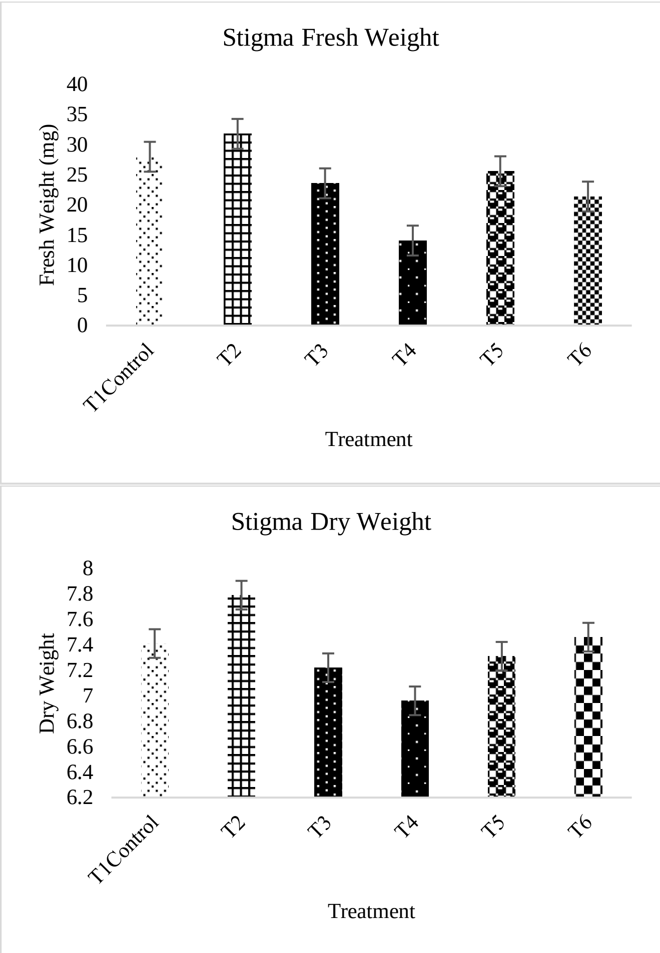
Stigma Fresh Weight. Stigma fresh weight, which is the main component in this study showed maximum stigma fresh yield for treatment T2 (FYM@ 30 tons) with 31.8 milligrams followed by control treatment with 28 milligrams of fresh weight. Minimum fresh stigma weight was recorded for treatment T4 (FYM @ 10 tons and NP @100:100) with only 14.1 milligrams of weight. The data was averaged from different flowers and taken as single flower stigma weight.

Stigma Dry Weight. Final yield of dry stigma exhibited that treatment T2 (FYM @ 30 tons) produced maximum yield of stigma (7.79) milligrams followed by Treatment

T6 (NP @150:100) with 7.46 milligrams of dry stigma while treatment control followed closely by producing 7.41 milligrams of stigma weight. Minimum stigma yield was observed for treatment T4 with 6.96 milligrams of dry stigma weight.

Figure 5

Stigma fresh and dry weight under Different INM treatments



Leaf Length (cm). Leaf length data showed maximum length for treatment T2 (FYM @ 30 tons) with 17.5 cm length followed by T5 (NP@ 200:150) which produced 16.6 cm. Minimum leaf length was observed for T1 (Control) which produced 13.6 cm leaf.

Leaves per Plant. Leaf numbers were counted when maximum leaves were observed around maturity stage. T1 (Control and T2 (FYM@ 30 tons) showed maximum leaves per plant with production of 4 followed by treatment T3. Minimum leaves per plant were recorded for T6 (NP @ 150:100).

Figure 6

Leaf length and Leaves per Plant under Different INM Treatments

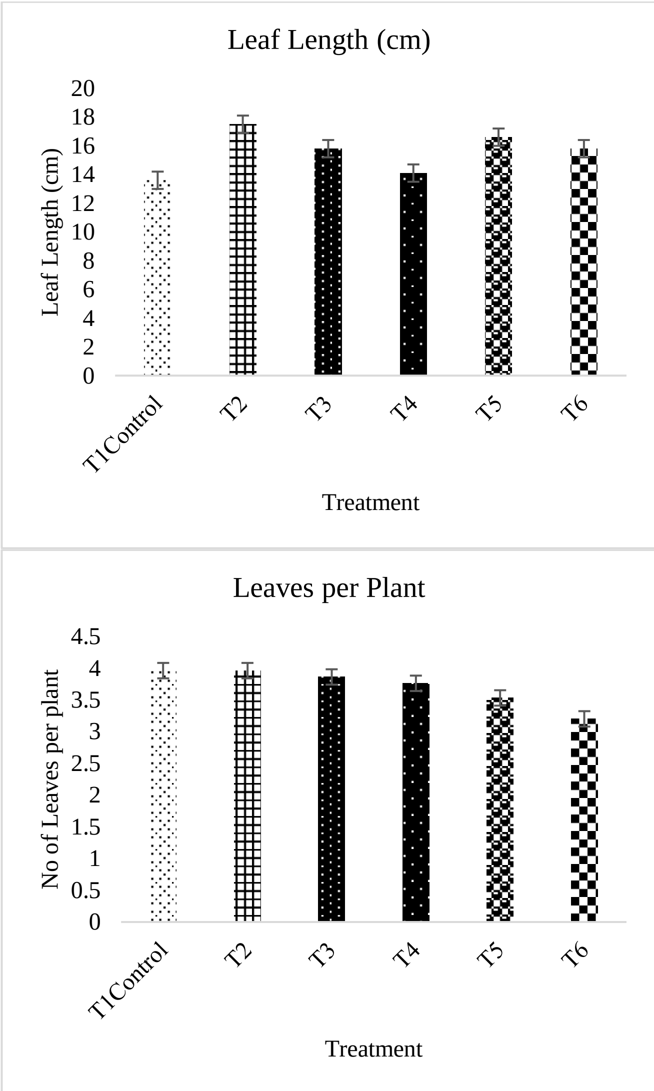


Table 1

Analysis of variance of different traits tested under Integrated nutrient management system in saffron.

Treatment	DF	SS	MS	F	P
DTF-I	5	6.9444	1.388	25.0	0.000***
DTF-M	5	58.444	11.689	36.28	0.000***
FW-Flower	5	1.281E-04	2.563E-05	4.87	0.0162*
DW-Flower	5	3.290E-05	6.579E-06	173.65	0.000***
Leaf Length	5	31.9444	6.3888	8.27	0.0025*
Leaves per Plant	5	1.3516	0.2703	1.59	0.248Ns
Petal Fresh Weight	5	0.04499	0.00900	67.24	0.0000***
Petal Dry Weight	5	0.00116	2.317E-04	29.78	0.0000***
Stigma Fresh Weight	5	5.512E-04	1.102E-04	38.29	0.000***
Stamen Fresh Weight	5	6.028E-04	1.205E-04	17.55	0.000***
Stigma Dry Weight	5	1.405E-06	2.812E-07	55.94	0.000***
Stamen Dry Weight	5	6.618E-07	1.324E-07	8.61	0.0022**

Table 2

Means for different tested traits under integrated nutrient management in Saffron

Treatment	DTFI	DTFM	FWF	DWF	StmFW mg	StmDW mg	StgFW mg	StgDW mg
T1-Control	27	35.6	412.3	0.0451	20.0	6.30	28.0	7.41
T2	27	37	420.2	0.0428	31.0	6.93	31.8	7.79
T3	27	36	425.1	0.0434	33.3	6.61	23.6	7.22
T4	27	35.3	417.6	0.0451	20.3	6.51	14.1	6.96
T5	27	35	419.4	0.0459	22.4	6.58	25.6	7.32
T6	28.6	39.3	417.1	0.0463	18.1	6.73	21.4	7.40

DTFI: Days to Flowering-Initial, DTFM: Days to Flowering Maximum, FWF: Fresh Weight of Flower, DWF: Dry Weight of Flower, StmFW: Stamen Fresh Weight, StmDW: Stamen Dry Weight, StgFW: Stigma Fresh Weight, StgDW: Stigma dry Weight

Table 3

Means for different tested traits under integrated nutrient management in Saffron

Treatment	PFW (mg)	PDW (mg)	LL	LPP
T1-Control	110.1	92.0	13.6	3.96
T2	241.4	102.6	17.5	3.96
T3	93.2	88.5	15.8	3.86
T4	151.4	95.5	14.1	3.76
T5	105.7	97.2	16.6	3.53
T6	120.3	100.7	15.8	3.20

PFW: Petal Fresh Weight, PDW: Petal Dry Weight, LL: Leaf length: LPP: Leaves per Plant

Correlation Analysis

Pearsons correlation analysis (Pearson, 1920) was applied to observe the association of different tested traits under variable integrated nutrient management. Stigma yield is the major objective of our study, and the results revealed stigma dry weight has high correlation with stamen dry weight (0.78), and petal dry weight (0.45). Stigma dry weight also has high correlation with stigma fresh weight (0.60). The dry weight of flowers showed high negative correlation with stigma stamen and petal fresh weight with -0.30, -0.85 and -0.56 correlation respectively (Table 4). Days to flowering maximum showed positive correlation with stigma yield (0.49). Days to initial flowering and Max flowering also showed maximum correlation (0.88).

Table 4

Pearsons correlation for tested traits under different INM treatments

Trait	*LL*	*DTFI*	*DTFM*	*Lpp*	*FWF*	*DWF*	*StgFW*	*StmnfW*	*PetalFW*	*StgdW*	*stmdW*	*PetaldW*
LL	1.00											
DTFI	0.02	1.00										
DTFM	0.23	0.88	1.00									
LPP	-0.05	-0.54	-0.38	1.00								
FWF	0.20	-0.37	-0.31	0.17	1.00							
DWF	-0.47	0.43	0.13	-0.34	-0.56	1.00						
StgFW	0.38	-0.20	-0.04	0.26	0.26	-0.30	1.00					
StmnFW	0.43	-0.44	-0.22	0.47	0.65	-0.85	0.39	1.00				
PetalFW	0.41	-0.11	0.14	0.23	-0.14	-0.56	0.31	0.26	1.00			
StgDW	0.78	0.23	0.49	-0.06	0.09	-0.45	**0.60**	0.38	**0.65**	1.00		
StmDW	0.59	0.26	0.43	-0.09	0.16	-0.49	0.18	**0.43**	**0.61**	**0.78**	1.00	
PetalDW	0.21	0.33	0.31	-0.30	-0.51	0.24	0.15	-0.40	**0.55**	**0.45**	0.42	1.00

Principal Componenet Analysis

Principal component analysis developed by Pearsons is a dimensionality reduction method for reducing the large data variables into meaningful components (Karamizadeh et al., 2013). The analysis asists in identifying features which have major contribution and assign similar group to traits which have similar impact together. In our study we analyzed 12 traits under PCA with the first three PCs out of twelve resulted in more than 76.8 % of the total variation with eigenvalues of 4.25, 3.52 and 1.43, respectively (Table 5). The results from scree plot revealed that first three components in the PCA analysis were with Eigen values above one as required (Figure 2). The components loading reveal that PC1 is strongly realted with variables like stigma dry weight (0.949), stamen dry weight (0.856), petal fresh weight (0.749), and leaf length (0.786) representing stigma and floral dry weight accumulation along with leaf length. Results were also confirmed by PCA Biplot which shows stigma dry weight, stamen dry weight, petal fresh weight, and leaf length grouped together with some assocaiton with days to flower maximum and petal dry weight (Figure 7). PC2 show strong assocaition with days to flowering at initial stage (0.845), days to flowering at maximum flowers (0.729), and petal dry weight (0.655). The PCA Biplot exhibit stigma fresh weight, petal fresh weight and leaves per plant grouping together which show better associaiton of these traits. The vector length in the Figure 7. showed the extent of variation explained by each variable in the PCA.

Table 5
Eigenvalues and % variance explained using PCA analysis for tested Traits

Componenet	Eigenvalue	% of Variance	Cumulative %
1	4.257	35.476	35.5
2	3.520	29.336	64.8
3	1.436	11.967	76.8
4	0.900	7.505	84.3
5	0.752	6.274	90.6
6	0.453	3.781	94.3
7	0.323	2.693	97.0
8	0.196	1.633	98.7
9	0.069	0.583	99.3
10	0.050	0.418	99.7
11	0.030	0.257	99.9
12	0.008	0.070	100.0

Table 6
Component Loading for different tested Traits

Trait	PC1	PC2	Uniquness
Days To Flowering-Initial		0.845	0.2785
Days To Flowering-Max	0.366	0.729	0.3340
Leaf Length (cm)	0.786		0.3823
Leaves per Plant		-0.641	
Stigma Fresh Weight	0.538		0.6471
Stigma Dry Weight	0.949		0.0674
Stamen Fresh Weight	0.555	-0.732	0.1559
Stamen Dry Weight	0.856		0.2404
Petal Fresh Weight	0.749		0.4381
Petal Dry Weight	0.389	0.655	0.4202
Flower Fresh Weight		-0.687	0.4852
Flower Dry Weight	-0.657	0.617	0.1879

Figure 7
Principal Componenet Analysis

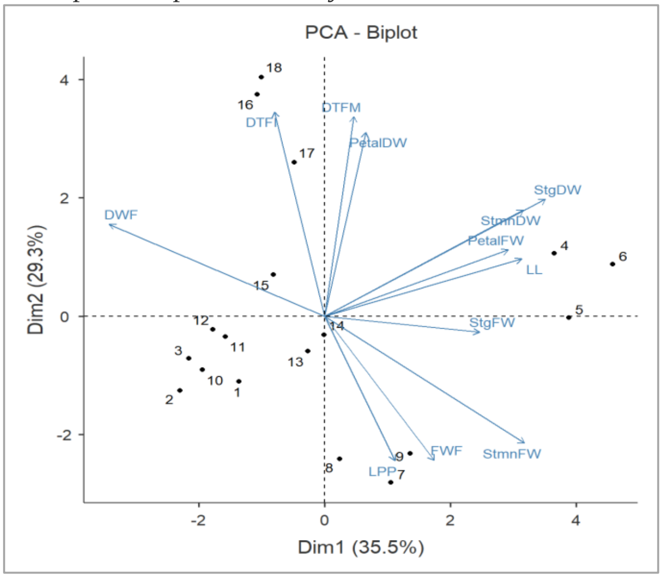
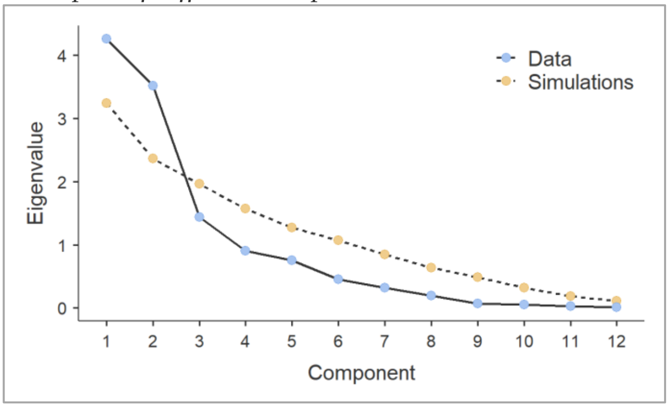


Figure 8
Scree plot of different components



DISCUSSION

Integrated nutrient management (INM) refers to the system where both crop productivity and soil health are improved by maintaining a suitable balance of organic and inorganic inputs. Balanced organic and in-organic fertilizer improve availability of plant nutrients and play role in enhancement of crop production along with increasing physicochemical and biological properties of the soil (K. & S., 2012; Sarfraz et al., 2023). Soil in arid and semi-arid regions are characterized by low organic matter and lack nutrients or the nutrient depletion is faster (Mukherjee et al., 2014). Researchers showed that application of organic amendments not only enhance crop production and soil health but also improve nutrient use efficiency (Diacono & Montemurro, 2010). The present study was conducted to evaluate saffron productivity under variable integrated nutrient management strategies under arid-semi arid region of Quetta Balochistan. Results showed that high dose of NP without any organic matter amendments resulted in late emergence of flowers, and which also delayed reaching maximum flower. Research show that high concentration of N and P in soil can lead to osmotic stress resulting reduced water uptake and also cause ammonia toxicity which can negatively impact corm growth (Khatri & Rathore, 2022).

The results of this study demonstrate that integrated nutrient management significantly influences key flower attributes in saffron. The analysis of variance revealed significant (*P<0.05*) differences among tested treatments for most of the major traits, except for the number of leaves per plant, which remained non-significant. These findings indicate that nutrient availability plays a crucial role in saffron flowering, fresh and dry biomass accumulation, and overall floral component development.

Days to initial flowering varied among treatments, with T6 (NP 150:100) inducing the earliest flowering at 28.6 days after sowing. This slight difference of 1.5 days from other treatments was statistically significant and suggests that specific nutrient combinations may enhance early flowering. The maximum flowering time varied, with T5 (NP 200:150) showing the shortest duration of 35 days, while T6 (NP 150:100) required the longest duration of 39.3 days. This variability aligns with previous studies that suggest optimal nitrogen and phosphorus levels are essential for regulating flowering phenology in saffron (Cardone et al., 2019; Krouk & Kiba, 2020).

The fresh weight of a single flower was highest under T3 (FYM @ 20 tons and NP @ 50:100) at 425.1 mg, followed by T2 (FYM @ 30 tons), whereas the control treatment recorded the lowest fresh weight. This indicates that the addition of farmyard manure (FYM) and an optimal combination of nitrogen and phosphorus improves flower biomass. Similar trends were observed for petal fresh and dry weight, where T2 exhibited the highest values. The significant effect of FYM application aligns with studies emphasizing the role of organic amendments in improving soil fertility and nutrient uptake in saffron (Salas et al., 2020; Zhang et al., 2022).

Since saffron stigma yield is a primary determinant of economic value, our findings highlight the importance of nutrient management in optimizing stigma production. The highest stigma fresh and dry weight was recorded in T2 (FYM @ 30 tons), confirming that organic amendments improve yield quality. Interestingly, the control treatment ranked second in stigma dry weight, suggesting that saffron plants may have an inherent ability to perform well under nutrient-deficient conditions. However, minimum stigma yield was observed for T4 (FYM @ 10 tons and NP @100:100), indicating that excess nitrogen may not always be beneficial. Previous research has also reported that balanced organic and inorganic fertilization is crucial for achieving optimal stigma production in saffron (Abbasi & Sepaskhah, 2022; Jahan & Jahani, 2007).

The longest leaf length was recorded for T2 (FYM @ 30 tons), supporting the hypothesis that organic amendments promote vegetative growth. However, leaf number per plant did not show significant variation across treatments, which could suggest that saffron leaf proliferation is genetically controlled rather than nutrient-dependent. This is consistent with prior studies that report the marginal effects of fertilizers on saffron leaf count (Chaudhary et al., 2023).

Pearson correlation analysis revealed a strong positive association between stigma dry weight and stamen dry weight (r = 0.78), and moderate positive correlations with petal dry weight (r = 0.45) and stigma fresh weight (r = 0.60). This suggests that treatments enhancing stamen and petal biomass also improve stigma yield. Conversely, dry flower weight negatively correlated with stigma, stamen, and petal fresh weight, indicating a shift in biomass allocation post-drying. These findings agree with previous studies highlighting the interdependence of floral traits in saffron (Shah et al., 2024). Principal component analysis further supported these associations, with the first three components explaining 76.8% of total variation. The high loadings of stigma dry weight, stamen dry weight, and petal fresh weight in PC1 confirm their contribution to saffron floral biomass accumulation. The strong association of PC2 with flowering time traits suggests that early and late-flowering genotypes cluster distinctly based on nutrient treatments (Eftekhari et al., 2023; Rather et al., 2020) (Eftekhari et al., 2023; Irfan et al., 2020). The PCA biplot effectively visualized these trait groupings, supporting the reliability of nutrient impact assessments.

CONCLUSION

Overall, this study highlights the significance of integrated nutrient management in improving saffron flower quality and yield. Treatments enriched with FYM, particularly T2 (FYM @ 30 tons), consistently performed well across multiple traits, demonstrating the importance of organic amendments in saffron cultivation. The results also suggest that optimal nitrogen and phosphorus levels enhance flower biomass but must be balanced to prevent excessive vegetative growth at the expense of stigma yield. Future studies should focus on long-term field evaluations and molecular assessments to further validate these findings.

Authors Contribution

MS: Performed the research, Data curation; analysis; investigation; writing. MRS: Investigation, methodology and editing. ARR: review and editing. NS: funding acquisition, review and editing. MAK: analysis, review and editing. NK: review and editing. A: methodology, review and editing. NU: review and editing, MN: writing—review. SRA: writing, analysis and editing, and JK: Investigation; assist in research and methodology; analysis; writing, review and editing.

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