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Evaluation of Factors Influencing the Yield Gap of Sugar Beet in Northern Khuzestan Using the CPA Method

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ABSTRACT

Reducing the yield gap is a critical challenge in modern agriculture. Accurate estimation of this gap can play a vital role in enhancing productivity and increasing agricultural production. This study aimed to evaluate the yield gap in sugar beet fields in Shush, Dezful, Andimeshk, and Shushtar counties and identify the key management factors affecting it. During the 2022–2023 agricultural year, data on agricultural management practices from 197 sugar beet farms in the region were collected through farmer interviews and detailed questionnaires. These data encompassed all aspects of farm management, including seedbed preparation, fertilization, weeding, pest and weed control, irrigation, and harvesting operations. Data were processed using Excel, and final analysis was performed with SAS software. Stepwise regression and the Comparative Performance Analysis (CPA) model were used to identify relationships between agronomic practices and actual crop yield. The results revealed that among 82 management variables, six independent variables—poultry manure application, potassium fertilizer application, farmer experience, total top-dress nitrogen fertilizer application, micronutrient application, and insecticide application frequency—were identified as the key factors limiting sugar beet yields in northern Khuzestan. The yield gap was estimated to be 12 t ha^{-1}, resulting from the difference between the average actual yield (74 t ha^{-1}) and the optimal yield (86 t ha^{-1}). Insufficient poultry manure and potassium fertilizer application and limited farmer experience accounted for 26%, 23%, and 22% of the yield gap, respectively. Other factors, including micronutrient application, top-dress nitrogen fertilizer, and insecticide application frequency, accounted for 13%, 9%, and 7% of the gap, respectively. The efficient use of poultry manure, potassium, micronutrients, and nitrogen fertilizers, enhancing farmer experience, and improving pest management can help reduce the yield gap and increase sugar beet production. These findings emphasize the importance of these critical factors and provide recommendations for improving farm management and policymaking.

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1. Introduction

Sugar beet (*Beta vulgaris*) is a key crop in sugar production, playing a significant role in ensuring food security (Dmitriyev *et al*., 2024). This crop is cultivated as a fall crop in northern Khuzestan, where its growth period coincides with the rainy season, enhancing its importance (Hasanvandi *et al*., 2022). However, optimizing its production has become a major challenge due to poor resource management. Given the rapid growth of the global population and the increasing demand for food, improving agricultural yields has gained paramount importance. Predictions indicate a substantial rise in the global population by 2050, which will further intensify the need for increased food production. A key strategy to address this growing demand is enhancing crop yields and minimizing food waste (Van Ittersum *et al*., 2013; Nuss and Tanumihardjo, 2010). In this context, the concept of the yield gap defined as the difference between actual and potential crop yields—has emerged as a

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critical issue in agriculture. This gap is primarily attributed to insufficient water resource management, inappropriate use of chemical fertilizers, and issues related to genetic diversity of crops (Mohammadzadeh *et al*., 2023).

In recent years, concerns about food security have led to a significant increase in yield gap-related research worldwide (Van Ittersum *et al*., 2013; Van Wart *et al*., 2013; Rong *et al*., 2021) and in Iran (Mohammadzadeh *et al*., 2023; Absalan *et al*., 2023; Mootab Laleh *et al*., 2023). Van Ittersum et al. (2013), along with Van Wart et al. (2013), highlighted that improving agricultural productivity by reducing yield gaps is an effective approach to enhancing food security and mitigating environmental impacts (Van Ittersum *et al*., 2013; Van Wart *et al*., 2013). Rong et al. (2021) conducted a comprehensive study analyzing yield gaps and resource use efficiency in three major food crops—wheat, maize, and rice. The study revealed that global potential yields for these crops were 7.7, 10.4, and 8.5 tons per hectare, respectively, while actual yields were reduced to 4.1, 5.5, and 4 tons per hectare. Limiting factors included climatic conditions, nutrients, moisture, and crop type (Rong *et al*., 2021). The findings emphasized the necessity of improving resource management and adopting advanced technologies to reduce yield gaps.

In Iran, one of the earliest studies on crop yield gaps was conducted by Torabi et al. (2011), who analyzed wheat production constraints in Golestan Province. Using 20 years of meteorological data from 10 stations and simulation methods, they assessed the yield potential of rainfed wheat on three soil types and identified limiting factors. In another study, Soltani et al. (2023) applied the Comparative yield Analysis (CPA) method to investigate the yield gap of cotton in western Golestan Province. They identified nine key factors, including nitrogen application, planting date, and irrigation volume, as major contributors to the yield gap, which reached 3,119.5 kg ha^{-1} (Soltani *et al*., 2023). CPA has proven to be a powerful tool for assessing yield gaps and identifying limiting factors in crop production (Mootab Laleh *et al*., 2023; Salarian and Salari, 2021; Matourian *et al*., 2021; Javaheri *et al*., 2005). Other studies utilizing CPA in Iran include Torabi et al. (2011) and Nekahi et al. (2014), which examined wheat and maize yields, respectively, identifying similar constraints (Torabi *et al*., 2011; Nekahi *et al*., 2014). Habibi et al. (2019), using CPA, reported that the average actual yields in Amol and Rasht were 4,821 and 4,467 kg ha^{-1}, respectively, with significant yield gaps of 1,707 and 1,934 kg ha^{-1} (Habibi *et al*., 2019).

Mootab Laleh et al. (2023) analyzed wheat yield gaps in 104 farms in Varamin County using CPA. Their results showed actual wheat yields ranging from 2,600 to 7,600 kg ha^{-1}, with a yield gap of 3,748 kg ha^{-1} (40.23%). Key factors included leaf chlorophyll content, irrigation, and soil salinity. CPA was introduced as an inexpensive and straightforward tool for identifying yield gaps and their causes in developing countries (Mootab Laleh *et al*., 2023). In Dehloran County, Ilam Province, Absalan et al. (2023) investigated canola yield gaps and found that the difference between farmers' actual yields and the predicted yields was 833.54 kg ha^{-1}. Variables such as potassium fertilizer, sulfur application, irrigation frequency, and micronutrient use were the most influential factors, with irrigation frequency alone accounting for approximately 53% of the yield gap (Absalan *et al*., 2023). Regarding sugar beet yield gaps in Iran, Hesadi et al. (2022) analyzed 220 spring sugar beet farms nationwide, estimating yield and sugar content gaps at 57.2% and 21.7%, respectively. Their findings indicated that water resource management, seed rate, plant density, and physiographic conditions such as altitude and longitude played significant roles in yield gaps. Improving agronomic management could reduce these gaps and enhance sugar beet productivity (Hesadi *et al*., 2022).

Moreover, Mohammadzadeh et al. (2023) used the SSM-iCrop2 model to estimate sugar beet's potential yield (Yp) in Iran at 103 tons ha^{-1}, compared to an actual yield (Ya) of 47 tons ha^{-1}, resulting in a yield gap (Yg) of 56 tons ha^{-1}. They concluded that with current management, less than half of the potential yield is achieved. By improving agronomic practices and achieving 80% of the potential yield, production could reach 82 tons ha^{-1} (Mohammadzadeh *et al*., 2023). In northern Khuzestan, yield gap factors for sugar beet not only reduce sugar production but also negatively influence the local economy and food security. This study aimed to assess the yield gap of sugar beet in northern Khuzestan and identify key factors contributing to this gap. The results can help improve productivity, reduce waste in sugar beet production, and promote sustainable agriculture in northern Khuzestan and similar regions. Furthermore, this research can assist policymakers and farmers in designing effective strategies to optimize production and resource management.

2. Materials and methods

2.1. Study areas

This study was conducted in the counties of Shush, Dezful, Andimeshk, and Shushtar in northern Khuzestan. Shush, positioned at 48°15' E longitude and 32°10' N latitude, spans 120,000 ha of cultivable land, a large portion of which is allocated to sugar beet farming. Dezful, located at a longitude of 48°20' E and latitude of 32°22' N, has 110,000 ha of arable land. Shushtar also plays a considerable role in sugar beet production. In the 2022-2023 growing season, the total area under sugar beet cultivation in Khuzestan was 18,000 ha, with more than 17,000 hectares in northern Khuzestan (Ministry of Agricultural Jihad, 2022). Of the total area, Shush contributed 56%, Dezful 18%, Andimeshk 16%, and Shushtar 7% to the overall sugar beet cultivation area (Ministry of Agricultural Jihad, 2022) (Fig. 1).

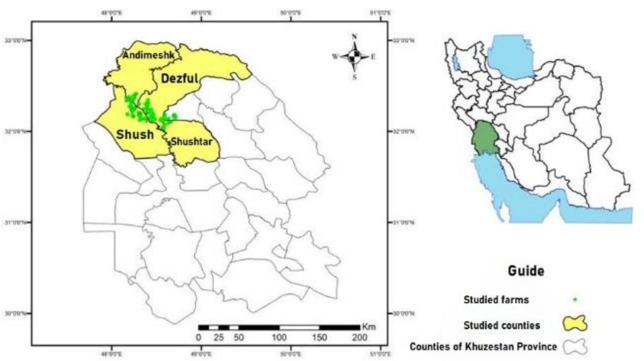

Figure 1. Map of the distribution of the studied sugar beet fields

2.2. Climatic conditions

The majority of precipitation in northern Khuzestan occurs between November and March. The dry season typically coincides with the summer months, during which the lowest rainfall is observed. The peak monthly rainfall in various northern Khuzestan cities usually occurs in December, January, and February, with lower amounts in the autumn and spring. The annual average rainfall in these areas does not vary significantly. Specifically, the long-term average annual precipitation at the meteorological stations in Shush, Dezful, and Andimeshk has been recorded as approximately 300, 250, and 280 millimeters, respectively (Fig. 2).

2.3. Data collection

In selecting the sugar beet farmers and fields, efforts were made to ensure the highest diversity in the management practices employed by the farmers. To this end, in coordination with experts from the Agricultural Jihad centers, the Agricultural Farmers' Association of the four counties of Shush, Dezful, Andimeshk, and Shushtar, as well as representatives from the sugar factories that sign contracts with beet farmers annually, approximately 398 farmers were selected. To determine the sample size, Cochran's formula (Equation 1) was applied, and ultimately, 197 sugar beet farmers from these four counties were chosen.

$$n = \frac{\frac{z^2pq}{d^2}}{1 + \frac{1}{N}[\frac{z^2pq}{d^2} - 1]} \quad (1)$$

p and q, a z-value of 1.96, and d of 0.05 were considered. N represents the population size, and n represents the sample size. All information, including the age and experience of the farmers, farm size, and details related to agricultural management such as seedbed preparation (type, number, and timing of plowing, disking, and other operations), planted varieties, planting dates, fertilization (type, amount, and timing of fertilizer application), pest, disease, and weed control, irrigation (number of times and scheduling), and harvest-related issues (irrigation cutoff timing before harvest, harvest timing, harvesting method, and root yield) were collected. These data were gathered through face-to-face interviews, direct farm observation, and completion of questionnaires with 82 variables.

2.4. Data analysis

The collected data from the farm monitoring in each county were analyzed separately. To analyze this data, first, after entering it into Excel 2019, qualitative data such as the use or non-use of sub-soilers were recorded as binary codes (zero and one). Additionally, using October 1st as a reference, planting dates, timing of fertilizer and pesticide applications, and other agricultural operations were coded according to plant growth stages based on the BBCH (Biologische

Bundesanstalt Bundessortenamt) system. Finally, these codes, along with quantitative data, were used in the final analysis conducted with SAS software version 9.4 (Soltani, 2015). After performing correlation analysis on the 82 initial variables, 64 variables remained and were used as independent variables to determine the yield model. To define the yield model, the relationship between all measured variables (both quantitative and qualitative) and yield was examined using stepwise regression analysis (Mootab Laleh *et al.*, 2023; Matourian *et al.*, 2021; Torabi *et al.*, 2011). Once the yield model was determined, the observed means of the variables in the farms of each region were input into the corresponding model, and the average yield was calculated using this model. Then, the best-observed values for the variables, representing the best farming and management practices of the farmers, were entered into the yield model, allowing for the calculation of the maximum achievable yield (Mootab Laleh *et al.*, 2023) (Fig. 3).

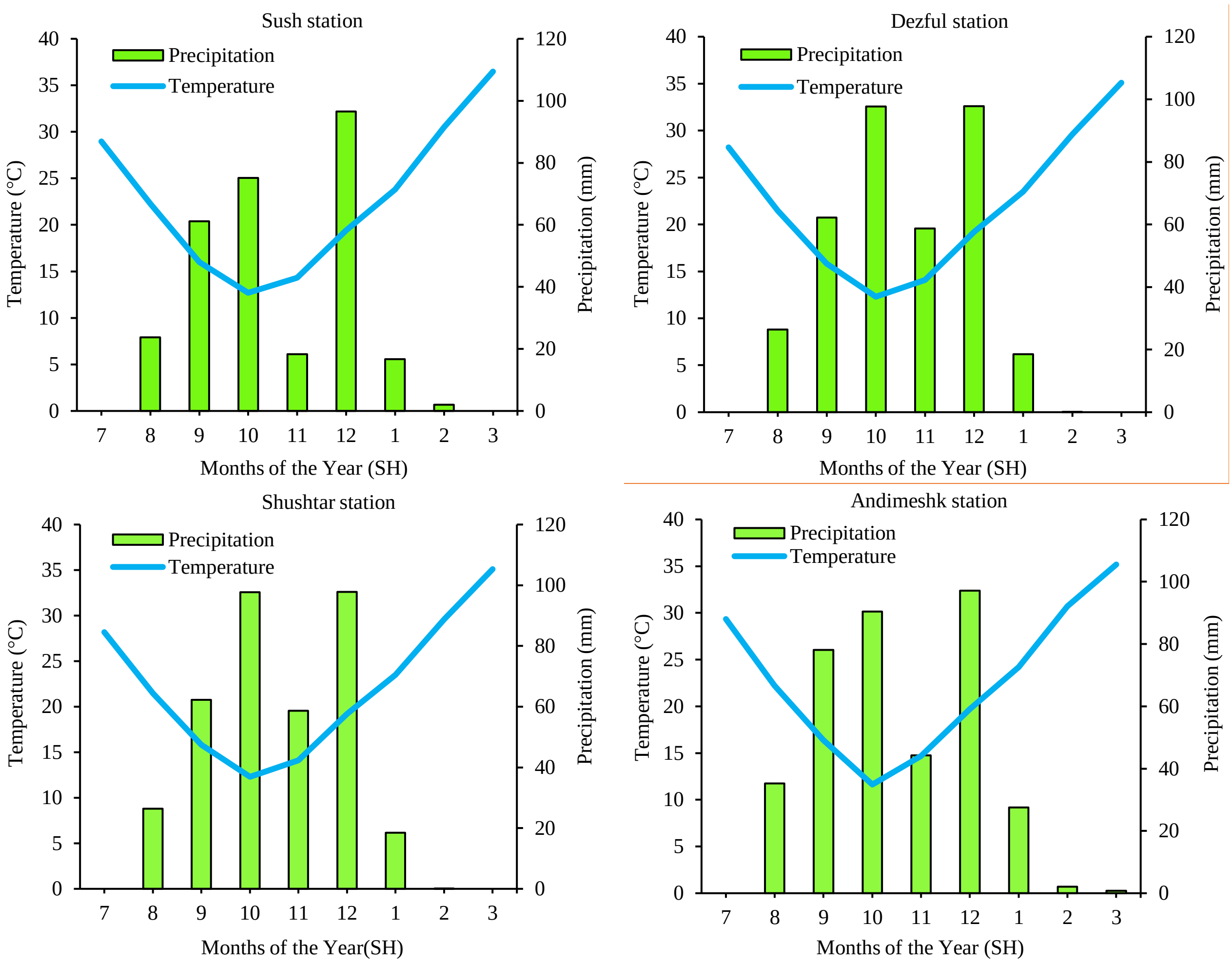

Figure 2. Precipitation and temperature in sugar beet growth in synoptic stations

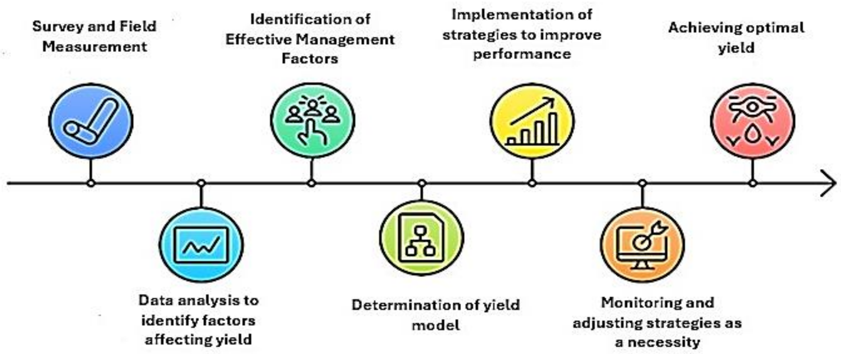

Figure 3. Steps of agricultural performance improvement through data management and evaluation

3. Results and discussion

The statistical results of the studied variables in 197 sugar beet farms are presented in Table 1. The average experience of the farmers in sugar beet cultivation was 10.79 years, indicating the high level of experience of farmers in the region. The use of various fertilizers, including potassium, phosphorus, and nitrogen fertilizers, showed considerable diversity. On average, 117.26 kg ha^{-1} of potassium fertilizer, 124.37 kg ha^{-1} of phosphorus fertilizer, and 95.69 kg ha^{-1} of nitrogen fertilizer were used as base fertilizers in these farms. Regarding the varieties, the highest cultivated area was occupied by the Antek variety, with 46.7%. This was followed by the Hani variety with 19.3% and Betaseed with 9.6%. Cadillac and Silveta each accounted for 6.1%, while Levante, Callas, and Amaldi had the smallest cultivated areas. The Antek and Hani varieties had the highest yields, while Cadillac and Levante had the lowest averages (Fig. 4). The average planting date was on day 277 of the year 2022 (approximately early October).

In terms of herbicide management, farmers used herbicides an average of 1.90 times, reflecting their focus on weed control. The average final plant density was 9.79 plants per square meter. The optimal plant density for sugar beet, resulting in the highest yield, was around 9 to 11 plants per square meter. Additionally, the average thinning date was on day 316, and the growth period lasted an average of 246.49 days. The average root yield of sugar beet was 73.59 tons per hectare, with significant variability across different farms (Fig. 5).

Table 1. Descriptive statistics of variables studied in 197 sugar beet fields

Variable	Maximum	Minimum	Mean	C.V.	S.E.
Years of sugar beet cultivation experience (years)	31.00	0.00	10.79	83.20	0.64
Manure application (tons ha^{-1})	3.00	0.00	1.76	82.46	0.07
Basal potassium fertilizer application (kg ha^{-1})	250.00	0.00	117.26	51.19	4.28
Basal phosphorus fertilizer application (kg ha^{-1})	250.00	50.00	124.37	36.58	3.24
Basal nitrogen fertilizer application (kg ha^{-1})	200.00	0.00	95.69	40.64	2.77
Sowing date (days since 2022/01/01)	308.00	263.00	277.92	3.24	0.64
Herbicide usage (L ha^{-1})	8.00	0.00	3.94	49.29	0.14
Number of herbicide applications (count)	5.00	0.00	1.90	52.15	0.07
Total top-dress nitrogen fertilizer application (kg ha^{-1})	450.00	100.00	295.20	34.12	7.18
Thinning date (days since 2022/01/01)	358.00	294.00	316.20	4.48	1.01
Final plant density (plants m^{-2})	15.00	6.00	9.79	18.20	0.13
Number of hand-weeding events (count)	2.00	1.00	1.69	27.42	0.03
Number of cultivator passes (count)	3.00	0.00	1.40	53.45	0.05
Foliar application date (days since 2022/01/01)	436.00	0.00	400.25	20.76	5.92
Micronutrient application (kg ha^{-1})	4.50	0.00	2.35	28.30	0.04
Number of insecticide applications (count)	3.00	2.00	2.62	18.59	0.03
Number of fungicide applications (count)	4.00	0.00	2.39	30.63	0.05
Irrigation cut-off (days before harvest)	19.00	8.00	13.16	17.94	0.17
Growth duration (days)	278.00	179.00	246.49	8.93	1.57
Harvest date (days since 2022/01/01)	278.00	179.00	246.49	8.93	1.57
Root yield (tons ha^{-1})	110.00	48.00	73.59	15.73	0.82

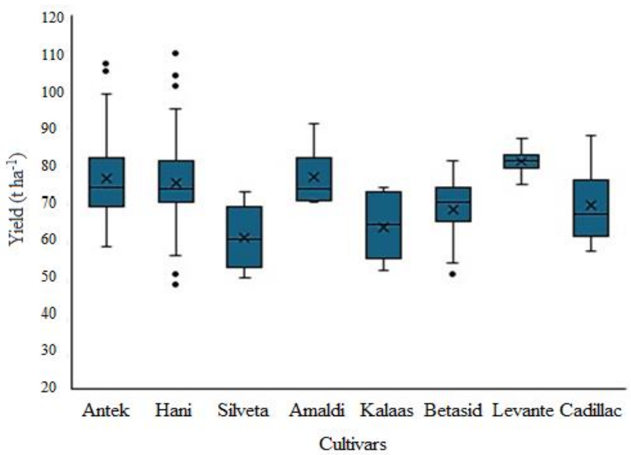

Figure 4. Comparison of the average yield of the cultivars.

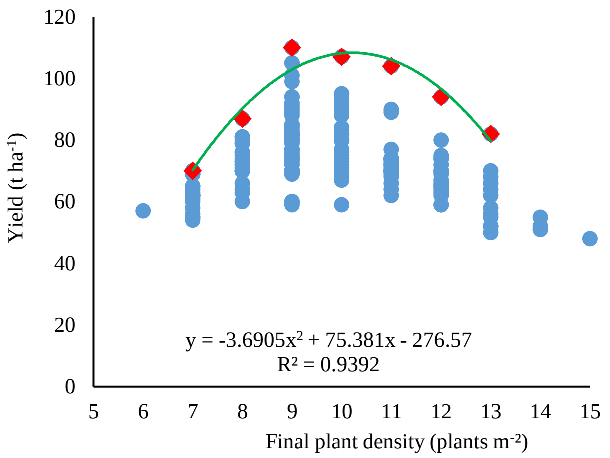

Figure 5. The relationship between final plant density and yield

Table 2 shows the yield gap and the impact of various variables on the yield of sugar beet. The calculated model determines the yield gap based on different variables with specific coefficients. The consumption of poultry manure (X_2), with a coefficient of 2.590, is the most significant factor contributing to 26% of the yield gap. The optimal value for this variable is 3 tons per hectare, and its average is 1.76 tons, creating a yield gap of 2.3 tons per hectare. Potassium fertilizer (X_3), with a coefficient of 0.860, accounts for 23% of the yield gap. The yield gap for this variable is 2.8 tons per hectare. The optimal value is 150 kg ha^{-1}, and the observed average is 117.26 kg ha^{-1}, causing a yield gap.

Farmer experience (X_1), with a coefficient of 0.289, contributes to 22% of the yield gap. The optimal value for this variable is 20 years, and the average is 10.79 years, resulting in a yield gap of 2.7 tons per hectare. Additionally, micronutrient fertilizers (X_5), with a coefficient of 1.332, account for 13% of the yield gap. The optimal value is 3.5 kg ha^{-1}, and the average is 2.35 kg ha^{-1}, creating a yield gap of 1.5 t ha^{-1}. Side-dress nitrogen fertilizer (X_4), with a coefficient of 0.019, contributes 9% to the yield gap. The optimal value is 350 kg ha^{-1}, and the average is 295.2 kg ha^{-1}, leading to a yield gap of 1.1 t ha^{-1}. Finally, the frequency of insecticide use (X_6), with a coefficient of 2.365, accounts for 7% of the yield gap. The optimal value is 3 applications, and the average is 2.62 applications, leading to a yield gap of 0.9 tons per hectare. Overall, the total yield gap in this study is 12 tons per hectare, resulting from the difference between the optimal and observed yields in the sugar beet farms (Fig. 6).

Table 2. Quantification of yield gap in autumn sugar beet in northern Khuzestan

Variable	Coef	Observed			Predicted		Yield gap	
		Best	Max	Min	Average	Best	Yield gap (%)	Yield gap (ton ha^{-1})
X_1	0.289	20	31	0	3	6	3	22
X_2	2.590	3	3	0	5	8	3	26
X_3	0.086	150	250	0	10	13	3	23
X_4	0.019	350	450	100	6	7	1	9
X_5	1.332	3.5	4.5	0	3	5	2	13
X_6	2.365	3	4	2	6	7	1	7
Yield			110	48	74	86	12	100

X1, X2, X3, X4, X5, X6 are as follows: farmer experience, amount of poultry manure, amount of potassium fertilizer, total amount of side-dress nitrogen fertilizer, micronutrient fertilizers, and frequency of insecticide application.

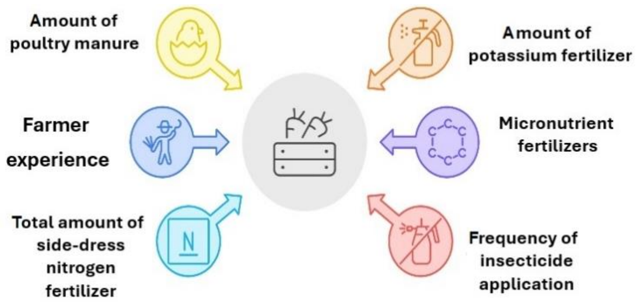

Figure 6. Management factors affecting the yield gap of sugar beet in the study area

In Fig. 7, the relationship between the predicted yield by the model and the observed yield is visible. The coefficient of determination (R^2) is 0.8486, indicating that the model has been able to predict approximately 85% of the changes in the observed yield. Additionally, the RMSE value is 4.87 tons per hectare, which reflects the high accuracy of the model in predicting the actual yield. These values confirm that the model is highly capable of predicting yield and can serve as a useful tool for assessing yield gaps and optimizing production conditions.

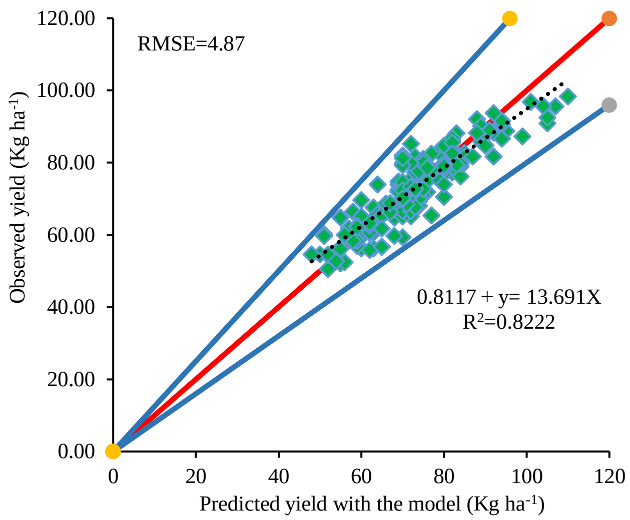

Figure 7. The relationship between predicted and observed yield values

The use of organic fertilizers, such as poultry manure, plays a significant role in improving the chemical and biological properties of the soil, which consequently increases crop yield. Based on the findings of this study and the regression relationship between yield (tons per hectare) and the amount of poultry manure used (tons per hectare), the yield of sugar beet increased linearly with the increase in poultry manure application (Fig. 8). The results of this research also indicate that the application of poultry manure before planting is one of the key factors in reducing the yield gap in sugar beet. These findings align with the study by Kobierski et al. (2017), which examined the effect of poultry manure application on the chemical and biochemical properties of soil. They showed that the application of poultry manure can improve soil properties, such as increasing organic matter and nutrient elements in the soil, which ultimately leads to better plant growth and higher yield. These results emphasize the importance of using organic fertilizers, like poultry manure, for soil management and enhancing crop productivity (Kobierski *et al.*, 2017). Potassium is one of the essential elements for improving sugar beet yield, especially under environmental stress conditions such as salinity. According to the results obtained, the relationship between potassium fertilizer application (kg ha^{-1}) and sugar beet yield (tons per hectare) shows that with the increase in potassium fertilizer application up to 150 kg ha^{-1}, the yield improves and then reaches a constant value (Fig. 8). Based on the research of El-Mageed et al. (2022), potassium improves the physiological and biochemical activities of plants, enhancing photosynthesis, water use efficiency, and dry matter accumulation. These effects ultimately reduce the negative impacts of environmental stresses and improve both the quantity and quality of the crop (El-Mageed *et al.*, 2022). Therefore, proper potassium management could be an effective strategy for reducing the yield gap in sugar beet under challenging environmental conditions. The role of potassium as a key factor in improving the quantity and quality of sugar beet yield has been emphasized in various studies. Javaheri et al. (2005) conducted a study in the Bardsir region and demonstrated that using potassium fertilizers in combination with organic manure could lead to significant improvements in the yield and quality of sugar beet. They found that proper potassium application increased root weight and sugar percentage in sugar beet (Javaheri *et al.*, 2005). These results underline the importance of optimal potassium fertilizer management in improving crop yield and reducing the yield gap.

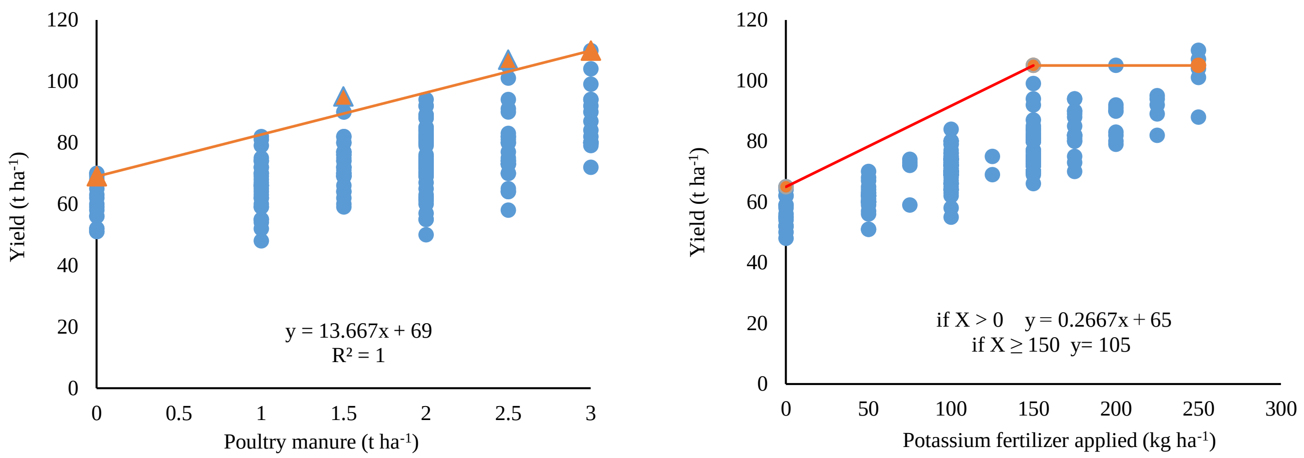

Figure 8. The relationship between maximum yield and poultry manure (left) and potassium fertilizer (right)

Micronutrients play a vital role in improving crop yield and quality. Although these elements are required in small amounts, they have significant effects on plant growth and can enhance product quality by increasing nutrient content and disease resistance (Ortel *et al.*, 2024). Additionally, farmers' experience and their learning process significantly affect crop yield improvement. According to the results obtained, the relationship between farmers' experience (years) and sugar beet yield (tons per hectare) indicates that with increasing farmers' experience, yield also increases (Fig. 9). This finding is consistent with the study by Goodwin et al. (2002), who showed that experienced farmers, who improve their skills through experiential learning, achieve higher yields in agricultural products. This finding directly aligns with the results of this study and highlights the role of farmers' experience in improving sugar beet yield (Goodwin *et al.*, 2002). In the assessment of the yield gap in sugar beet, farmers' experience has been identified as a key factor affecting crop yield. These findings align with those of Nidumolu et al. (2015), who explored the role of farmers' experience in managing climatic risks in dryland agricultural systems. They demonstrated that more experienced farmers have higher capabilities to adapt to climate change. These findings can also be applied to sugar beet cultivation, especially in regions like northern Khuzestan, where environmental conditions play a significant role in crop yield. Regarding the relationship between micronutrient fertilizer application and yield, it is observed that with increasing application up to 3 kg ha^{-1}, sugar beet yield also increases (Fig. 9). The results of this study are consistent with the findings of Salarian and Salari (2021), who investigated the effect of micronutrient foliar application on the technological quality of sugar beet. They demonstrated that using micronutrient combinations like iron, zinc, manganese, magnesium, and molybdenum significantly increased sugar yield, white sugar, and improved extractable sugar percentage. These results emphasize the importance of proper micronutrient management in improving both the quantity and quality of sugar beet and reducing the yield gap (Salarian and Salari, 2021).

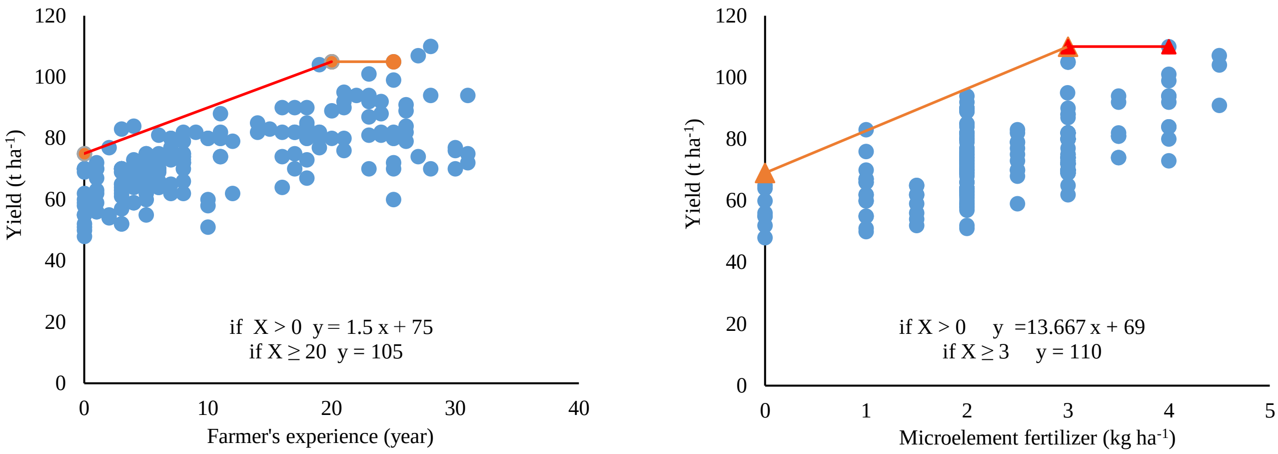

Figure 9. The relationship between maximum yield and farmer's experience (left) and microelement fertilizer (right)

Nitrogen, as one of the key elements for improving sugar beet yield, plays a significant role in crop growth and quality. According to the data obtained in this study, applying urea nitrogen fertilizer above 100 kg ha^{-1} increased sugar beet yield (Fig. 10). Several studies have confirmed this effect, including the research by Tsialtas and Maslaris (2005), who showed that increasing nitrogen fertilizer application significantly boosted root yield. This effect is especially important in Mediterranean climates, like northern Khuzestan, where similar conditions exist. The findings of this study are consistent with those of Majidi and Tabeiezad (2018), who showed that different nitrogen sources and levels could significantly improve root yield and the quality characteristics of sugar beet. These results indicate that a balanced and precise nitrogen fertilization strategy can maximize productivity and improve product quality in specific climatic conditions such as those in northern Khuzestan (Hoffmann and Märländer, 2005; Malnou *et al*., 2006; Su *et al*., 2024).

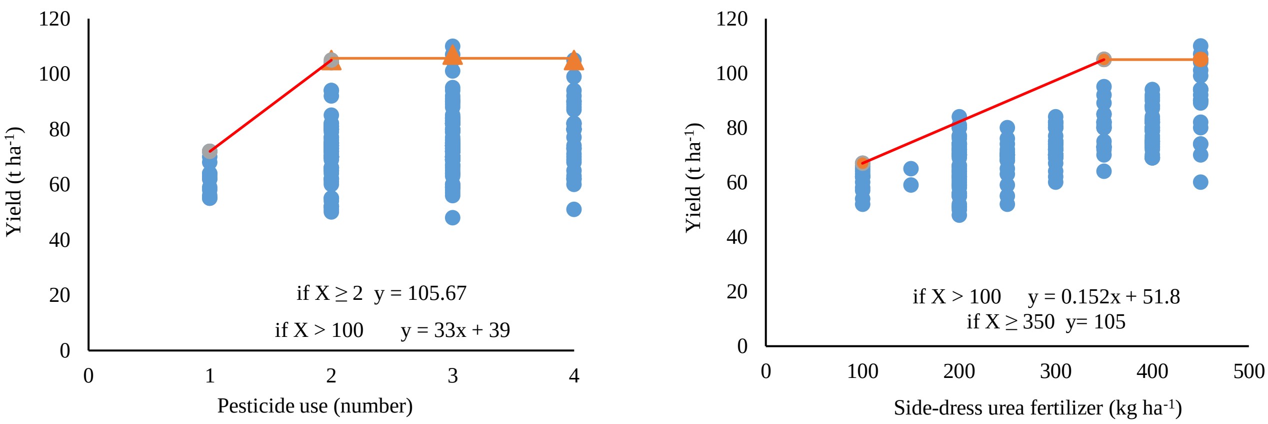

Figure 10. The relationship between maximum yield and pesticide use (left) and side-dress urea fertilizer (right)

Another significant factor identified in this study as influencing the yield gap in sugar beet was the frequency of insecticide application. Based on the obtained results, the relationship between the frequency of insecticide use and sugar beet yield shows that increasing insecticide application up to two times enhances the yield (Fig. 10). The findings of this research align with those of Bocianowski et al. (2022), who investigated the effects of different insecticide treatments on *Agrotis spp.* and the technological performance of sugar beet. Using AMMI analysis, they demonstrated that various insecticide methods significantly affect the final yield. These results underscore that the optimal and balanced use of insecticides can play a crucial role in reducing the yield gap (Bocianowski *et al*., 2022).

4. Conclusion

The findings of this study reveal that the yield gap of sugar beet in northern Khuzestan is predominantly influenced by various factors, including poultry manure application, potassium fertilizer usage, farmer experience, and the frequency of insecticide applications. Based on the computed model, poultry manure was identified as the most critical factor contributing to the yield gap, followed by potassium fertilizer and farmer experience. Enhancing the management of these inputs, particularly the optimal use of potassium and organic fertilizers, could help reduce the yield gap and improve crop productivity. Additionally, the results indicate that precise management of micronutrients and nitrogen fertilizers, especially in appropriate quantities and timing, has a significant impact on improving sugar beet yield. A balanced application of nitrogen and potassium fertilizers, combined with leveraging farmers' experience and adopting advanced techniques such as precision irrigation and optimal pesticide use, can enhance both the quality and quantity of the crop under the challenging climatic conditions of northern Khuzestan. Finally, it is recommended that future research further investigate the synergistic effects among potassium fertilizers, micronutrients, and modern farm management practices. Long-term experiments under diverse climatic conditions could also provide more comprehensive strategies for closing the yield gap. These approaches can contribute to sustainable production and greater agricultural efficiency in the region.

Conflict of interests

All authors declare no conflict of interest.

Ethics approval and consent to participate

No humans or animals were used in the present research. The authors have adhered to ethical standards, including avoiding plagiarism, data fabrication, and double publication.

Consent for publications

All authors read and approved the final manuscript for publication.

Availability of data and material

All the data are embedded in the manuscript.

Authors' contributions

All authors had an equal role in study design, work, statistical analysis and manuscript writing.

Informed consent

The authors declare not to use any patients in this research.

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