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Improving phosphorus use efficiency and quantitative and qualitative yield of sugar beet through combined application of phosphorus and iron nanoparticles under different irrigation regimes

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ABSTRACT

The main objective of this study was to investigate the interactions between phosphorus (P) and iron (Fe) fertilizers under different irrigation regimes and their effects on nutrient uptake, yield, and quality of sugar beet. The experiment was conducted at the Varamin Agricultural Research Station, Iran, during the 2021- 2022 growing seasons. The study used a split-plot design with three replications. The main factor consisted of three irrigation regimes (100%, 75%, and 50% of water requirement), and the sub-factor included six combinations of phosphorus (0, 75, and 150 kg/ha) and iron (0 and 5 kg/ha) fertilizers. Phosphorus use efficiency (PUE), phosphorus uptake efficiency (PUpE), and phosphorus utilization efficiency (PUtE) were measured. Results showed that severe water stress (50% of water requirement) reduced PUE by 25-30%, PUpE by 22-33%, PUtE by 26-37%, root yield by 26-35%, and white sugar yield by 26-37% compared to full irrigation. In contrast, the combined application of 150 kg/ha superphosphate with 5 kg/ha iron, depending on moisture conditions, increased PUE by 10-40%, PUpE by 14-55%, PUtE by 11-46%, root yield by 10-40%, and white sugar yield by 11-46% compared to the control (no fertilizer). This fertilizer combination also improved juice quality by decreasing sodium content by 25-32%, harmful nitrogen by 25-40%, and increasing potassium content by 21-25%, juice purity by 2.5-2.7%, and sucrose content by 0.4-1.3%. Overall, the balanced application of 150 kg/ha superphosphate with 5 kg/ha iron was the most effective fertilizer combination for improving phosphorus use efficiency, yield, and quality of sugar beet, even under water stress conditions.

Keywords: Sugar beet, phosphorus, iron, phosphorus use efficiency, water stress, yield, root quality

INTRODUCTION

Sugar beet (*Beta vulgaris* L.) is one of the most important industrial crops worldwide, playing a vital role in sugar production and food security (Brar *et al.,* 2015). However, sugar beet production faces numerous challenges, including soil nutrient deficiencies and water resource limitations (Wang *et al.,* 2021). Among essential nutrients, phosphorus (P) is crucial for plant growth, development, and crop production, but phosphorus use efficiency (PUE) is typically low, leading to resource waste and environmental pollution (Kusi *et al.,* 2020; Hadir *et al.,* 2020). PUE refers to the ability of plants to acquire, utilize, and convert phosphorus into biomass or harvestable yield (Ali *et al.,* 2023). Improving PUE in sugar beet is important for reducing production costs, increasing farmer profitability, and promoting sustainable agriculture (Heuer *et al.,* 2017).

Recent studies have shown that interactions between nutrients, particularly iron (Fe), can play a significant role in improving nutrient uptake and utilization (Yang *et al.,* 2024). Iron has been found to enhance phosphorus solubility and availability in the soil, potentially leading to improved PUE (Cieciuara *et al.,* 2021). However, the precise mechanisms of iron's effect on improving PUE in sugar beet are not yet fully understood. Additionally, water stress is a major challenge, as it can negatively affect the uptake and transport of nutrients, including phosphorus (He and Dijkstra, 2014). Water availability influences soil nutrient dynamics and root growth, directly impacting nutrient acquisition efficiency (Ghaly *et al.,* 2019). Understanding the interactions between nutrition management and irrigation regimes is crucial for optimizing sugar beet production under water-limited conditions.

Drought stress and iron deficiency can have a significant impact on PUE and its components, including phosphorus uptake efficiency (PUpE) and phosphorus utilization efficiency (PUtE), in sugar beet (Motalebifard *et al.,* 2016; Plaxton and Stigter, 2015). PUpE refers to the ability of plants to acquire phosphorus from the soil, while PUtE represents the efficiency with which plants use the acquired phosphorus to produce biomass or yield (Gursay and Atun, 2019). Iron plays a vital role in photosynthesis, respiration, and nitrogen and sulfur metabolism, all of which affect PUE (Kour *et al.,* 2019). Iron deficiency can alter phosphorus uptake and transport, leading to phosphorus toxicity and reduced PUtE (Yang *et al.,* 2024). Conversely, iron application can increase PUE by improving photosynthesis, root growth, and the expression of genes related to phosphorus uptake and transport (Bhat *et al.,* 2024).

In addition to PUE and its components, sugar beet crop quality is also of high importance, including parameters such as sugar content, juice purity percentage, sodium content, potassium content, and harmful nitrogen content (Gezgin *et al.,* 2017). These quality parameters directly influence sugar extraction efficiency and the overall economic value of the crop. Higher sugar content and juice purity lead to increased sugar yield, while lower levels of impurities (sodium, potassium, and harmful nitrogen) improve processing efficiency and reduce production costs (Hajiboland et al., 2018). Balanced application of phosphorus and iron fertilizers can play a crucial role in maintaining and improving these quality parameters (Ibrahim *et al.,* 2017; Makhlouf *et al.,* 2020; Bouras *et al.,* 2021;Demirbas, 2021). The main hypothesis is that the combined application of phosphorus and iron can improve PUE, PUpE, and PUtE, and consequently, the yield and quality of sugar beet, and these effects will be more pronounced under water stress conditions. We also hypothesize that iron application can mitigate the negative effects of water stress on PUpE, PUtE, and quality and yield parameters.

The main objective of this study is to investigate the effect of combined phosphorus and iron application on PUE indices (PUE, PUpE, and PUtE), yield, and quality parameters of sugar beet under different irrigation regimes. The specific objectives are: 1) To examine the effect of different levels of phosphorus and iron fertilizers on PUE, PUpE, PUtE, and quality and yield parameters of sugar beet under different irrigation regimes. 2) To determine the best combination of phosphorus and iron fertilizers to achieve maximum PUE and crop quality and yield in each irrigation regime.

MATERIALS AND METHODS

Experiment Location:

This study was conducted using a split-plot design with three replications at the Varamin, Iran, during the 2021 and 2022 growing seasons. The research station is located at 35°27' N latitude, 51°21' E longitude, and an altitude of 1180 m above sea level. The region has a semi-arid climate with an average annual temperature of 17.5°C and average annual rainfall of 244 mm, mostly occurring between November and April. The soil at the experimental site is sandy loam with a pH of 8.7, electrical conductivity of 1.2 dS/m, and organic matter content of 0.5%. The soil has a bulk density of 1.45 g/cm³, field capacity of 22% (volumetric), and permanent wilting point of 9% (volumetric) in the 0-60 cm soil layer. The available phosphorus and iron content of the soil in 2021 and 2022 were measured at 8.5 and 9.1 mg/kg for phosphorus, and 4.2 and 4.5 mg/kg for iron, respectively.

Experimental Design and Treatments:

A split-plot design with three replications was used, with irrigation regimes as the main plot factor and combinations of phosphorus (P) and iron (Fe) fertilizers as the subplot factor. Each plot measured 6 × 4 m with 1 m spacing between subplots. The experiment consisted of 18 subplots in each replication (3 irrigation regimes × 6 fertilizer treatments).

Irrigation regimes included three levels: optimal irrigation (OI): 100% ETc; moderate water stress (MWS): 75% ETc; and severe water stress (SWS): 50% ETc.

The subplot factor comprised six combinations of phosphorus (P) and iron (Fe) fertilizer treatments:

P0-Fe0: No phosphorus, no iron (0 kg P and 0 kg Fe per hectare).

P0-Fe5: No phosphorus, with iron (0 kg P and 5 kg Fe per hectare).

P75-Fe0: Low phosphorus, no iron (75 kg P and 0 kg Fe per hectare)

P75-Fe5: Low phosphorus with iron (75 kg P and 5 kg Fe per hectare)

P150-Fe0: High phosphorus, no iron (150 kg P and 0 kg Fe per hectare)

P150-Fe5: High phosphorus with iron (150 kg P and 5 kg Fe per hectare)

Phosphorus was applied as triple superphosphate (TSP, 46% P2O5) and iron as nanoparticles (Fe2O3). Phosphorus fertilizer was applied as a basal dose before planting, and iron fertilizer was applied as foliar spray in two equal applications: the first 15 days before the start of water stress treatment (30 days after planting) and the second at the start of water stress treatments (45 days after planting).

Irrigation Treatment

Irrigation treatments started 45 days after planting, corresponding to June 15, 2021, and 2022, and continued throughout the crop growth period. Irrigation water requirement was calculated based on daily reference

evapotranspiration (ETo) and crop coefficients (Kc) specific to sugar beet growth stages. ETo was estimated using the FAO Penman-Monteith method (Allen *et al.,* 1998).
Crop evapotranspiration (ETc) was calculated using the equation: ETc = Kc × ETo
Irrigation water was applied using a drip irrigation system, with drippers spaced 30 cm apart along irrigation lines. The system operated at 1.0 bar pressure with a dripper discharge rate of 2.0 L/h. Irrigation intervals were determined based on ETc and soil moisture status, monitored using tensiometers installed at 20 and 40 cm depths in each subplot.

Agronomic Practices:

The sugar beet (Beta vulgaris L.) was used in this study. Seeds were planted on May 1, 2021, and 2022, at a depth of 2.5 cm with 50 cm row spacing and 20 cm plant spacing within rows. Before planting, the land was prepared by plowing, disking, and leveling. A basal dose of nitrogen (N) at 100 kg /ha as urea (46% N) and potassium (K) at 120 kg K_2O/ha as potassium chloride (60% K_2O) was applied and mixed with the soil. Recommended agronomic practices for the region, including pest and disease management, were followed throughout the crop growth period.

Measurements:

Root yield: The sugar beet root harvest was conducted on November 15 in both years, 195 days after planting. Root yield was determined by manually harvesting and weighing roots from a 12 m² (3 × 4 m) area of each subplot and reported in tons per hectare.
Phosphorus efficiency: Plant phosphorus was measured using the wet digestion method (nitric and perchloric acid at a 3:1 ratio). Phosphorus concentration was measured using a UV-1800 spectrophotometer (Shimadzu, Japan) at 880 nm wavelength. Soil available phosphorus was extracted using the Olsen method and determined by molybdate-vanadate colorimetry. Fertilizer phosphorus was calculated based on the P_2O_5 percentage on the label and the application rate.
Phosphorus efficiency indices were calculated as follows (Dhillon *et al.,* 2017):
Phosphorus Uptake Efficiency (PUpE) = Phosphorus uptake by plant / (soil phosphorus + fertilizer phosphorus)
Phosphorus Use Efficiency (PUE) = Root yield / (soil phosphorus + fertilizer phosphorus)
Phosphorus Utilization Efficiency (PUtE) = Root yield / Phosphorus uptake by plant

Root quality:

a**) Juice Purity:** sucrose was measured using a polarimeter (P3000 Kruess, Germany) after clarifying the extract with lead acetate. Total soluble solids were determined using a digital refractometer (HI96801 Hanna Instruments, USA). Purity was calculated as the ratio of sucrose percentage to total soluble solids percentage (Bahrami *et al.,* 2020).

b) **Harmful nitrogen**: After precipitating proteins with zinc acetate (10 mL, 30%) and potassium ferricyanide (10 mL, 15%), 2 mL of ninhydrin reagent was added to the filtered solution. Samples were heated in a boiling water bath for 15 minutes and then cooled. Optical absorbance was measured with a UV-1800 spectrophotometer at 570 nm, and harmful nitrogen concentration was calculated using a calibration curve (Khalil *et al.,* 2018).

c) **Root sodium and potassium**: 5 g of dried sample was digested with 15 mL of 65% nitric acid. The resulting solution was diluted to 100 mL with distilled water. Sodium and potassium concentrations were measured using a flame photometer (PFP7 Jenway, England) (Rondevaldova *et al.,* 2023).

Statistical Analysis:

Data were subjected to analysis of variance (ANOVA) using SAS software version 9.4. Normality of data and homogeneity of variances were checked before analysis. Data were transformed when necessary to meet ANOVA assumptions. Treatment means were compared using Tukey's Least Significant Difference (LSD) test at $p \leq 0.05$.

RESULTS

Phosphorus use efficiency (PUE):

Phosphorus use efficiency (PUE) showed consistent trends across irrigation regimes, with control treatments generally outperforming phosphorus-receiving treatments (Figure 1). Under optimal irrigation (OI) in 2021, Fe0P0 treatment showed the highest PUE (2316.67 kg/kg), with F5P75 highest among phosphorus-receiving treatments (721.82 kg/kg). In 2022, Fe0P0 remained highest (2103.33 kg/kg), while F5P75 showed the highest PUE among phosphorus-receiving treatments (795.45 kg/kg), a 10.2% increase from the previous year. Under moderate water stress (MWS) in 2021, Fe0P0 had the highest PUE (1853.33 kg/kg), with F5P75 best among phosphorus-receiving treatments (626.36 kg/kg). In 2022, Fe0P0 remained highest (1646.67 kg/kg), while F5P75 showed the highest PUE among phosphorus-receiving treatments (699.09 kg/kg), an 11.6% increase from the previous year. Severe water stress (SWS) in 2021 saw Fe0P0 with the highest PUE (1510.00 kg/kg), with F5P75 highest among phosphorus-receiving treatments (533.64 kg/kg). In 2022, Fe0P0 remained highest (1343.33 kg/kg), while F0P75 showed the highest PUE among phosphorus-receiving treatments (481.90 kg/kg), 9.7% lower than the previous year's highest phosphorus-receiving treatment. PUE generally decreased with increasing water stress intensity, with moderate water stress causing a 20-22% reduction and severe water stress a 34-36% reduction compared to optimal irrigation. Phosphorus application significantly reduced PUE, with P75 treatments showing about 70-75% lower PUE than control treatments. Iron addition had variable effects on PUE, sometimes slightly improving it in P75 treatments, particularly under OI and MWS conditions.

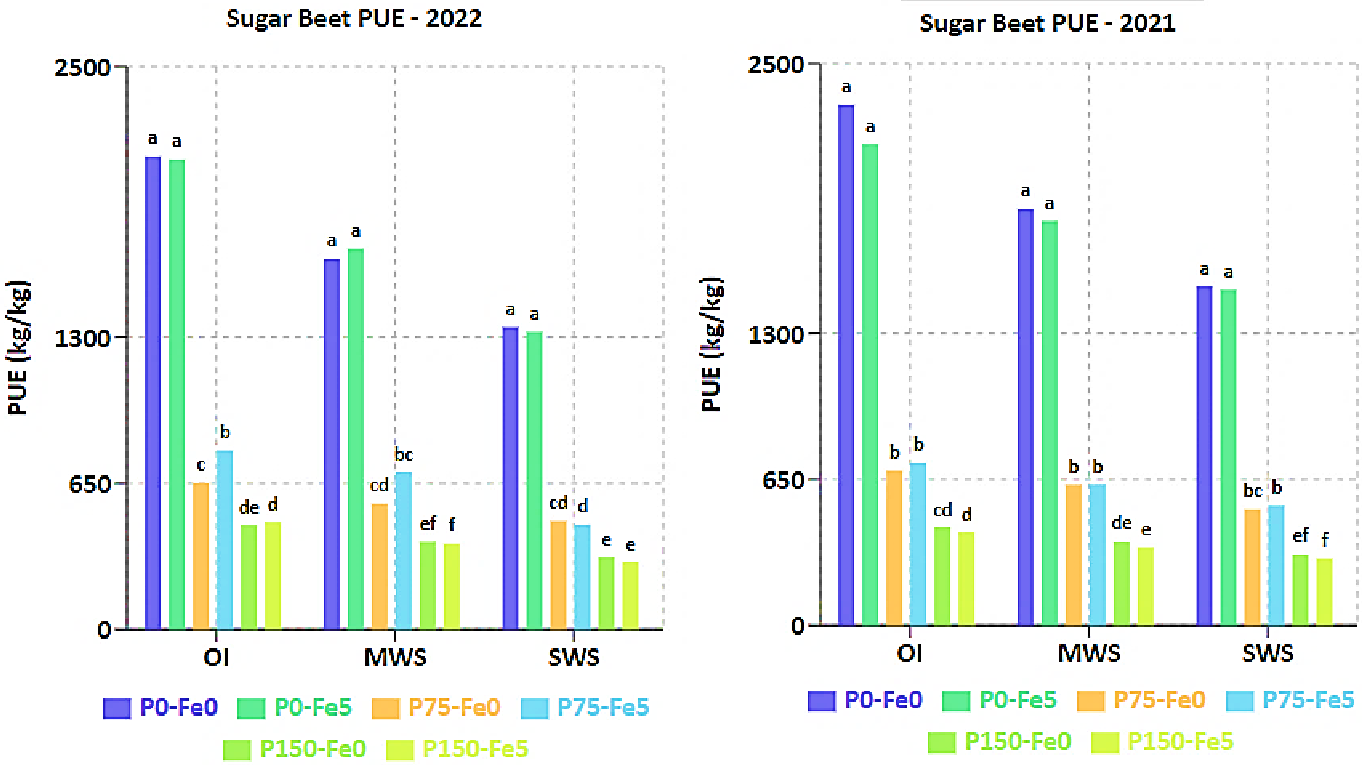

Fig. 1. Sugar beet phosphorus use efficiency (pue) under different irrigation regimes and phosphorus-iron treatments in 2021 and 2022

PUpE (Phosphorus Uptake Efficiency):

Phosphorus uptake efficiency (PUpE) was highest in control treatments (Fe0P0 and Fe5P0) across all irrigation regimes (Figure 2). Under optimal irrigation (OI) in 2021, Fe0P0 showed the highest PUpE (5.35 kg/kg), while P75 treatments had the highest PUpE (1.70 kg/kg) among phosphorus-receiving treatments, 68.2% lower than the control. In 2022, P75Fe5 slightly outperformed P75Fe0 (1.74 vs. 1.65 kg/kg). Under moderate water stress (MWS) in 2021, Fe0P0 had the highest PUpE (5.08 kg/kg), with P75 treatments performing best among phosphorus-receiving treatments (~1.65 kg/kg). In 2022, P75Fe5 slightly outperformed P75Fe0 (1.69 vs. 1.61 kg/kg). Severe water stress (SWS) in 2021 saw Fe0P0 with the highest PUpE (5.02 kg/kg) and P75 treatments best among phosphorus-receiving treatments (~1.60 kg/kg). In 2022, no significant difference was observed between P75Fe0 and P75Fe5 (both 1.59 kg/kg). Overall, PUpE decreased with increasing phosphorus application rates and water stress intensity, with P75 treatments generally showing higher PUpE than P150 treatments. Water stress reduced PUpE in all treatments, while iron addition had variable effects, sometimes slightly improving PUpE.

PUtE (Phosphorus Utilization Efficiency)

Phosphorus utilization efficiency (PUtE) showed varying trends across irrigation regimes (Figure 3). Under optimal irrigation (OI) in 2021, F5P0 treatment showed the highest PUtE (446.43 kg/kg), with F5P75 highest among phosphorus-receiving treatments (424.60 kg/kg). In 2022, F5P75 showed the highest PUtE (456.79 kg/kg), a 2.3% increase from the previous year. Under moderate water stress (MWS) in 2021, F5P0 had the highest PUtE (387.69 kg/kg), with F5P75 best among phosphorus-receiving treatments (381.67 kg/kg). In 2022, F5P75 showed the highest PUtE (413.51 kg/kg), an 8.3% increase from the previous year. Severe water stress (SWS) in 2021 saw F5P75 with the highest PUtE (335.43 kg/kg), while in 2022, F0P150 showed the highest PUtE (303.16 kg/kg), 9.6% lower than the previous year's highest. PUtE generally decreased with increasing water stress intensity, with moderate water stress causing a 10-15% reduction and severe water stress a 25-30%

reduction. Phosphorus application had variable effects on PUtE, while iron addition was generally positive, leading to a 3-8% increase under OI and MWS conditions.

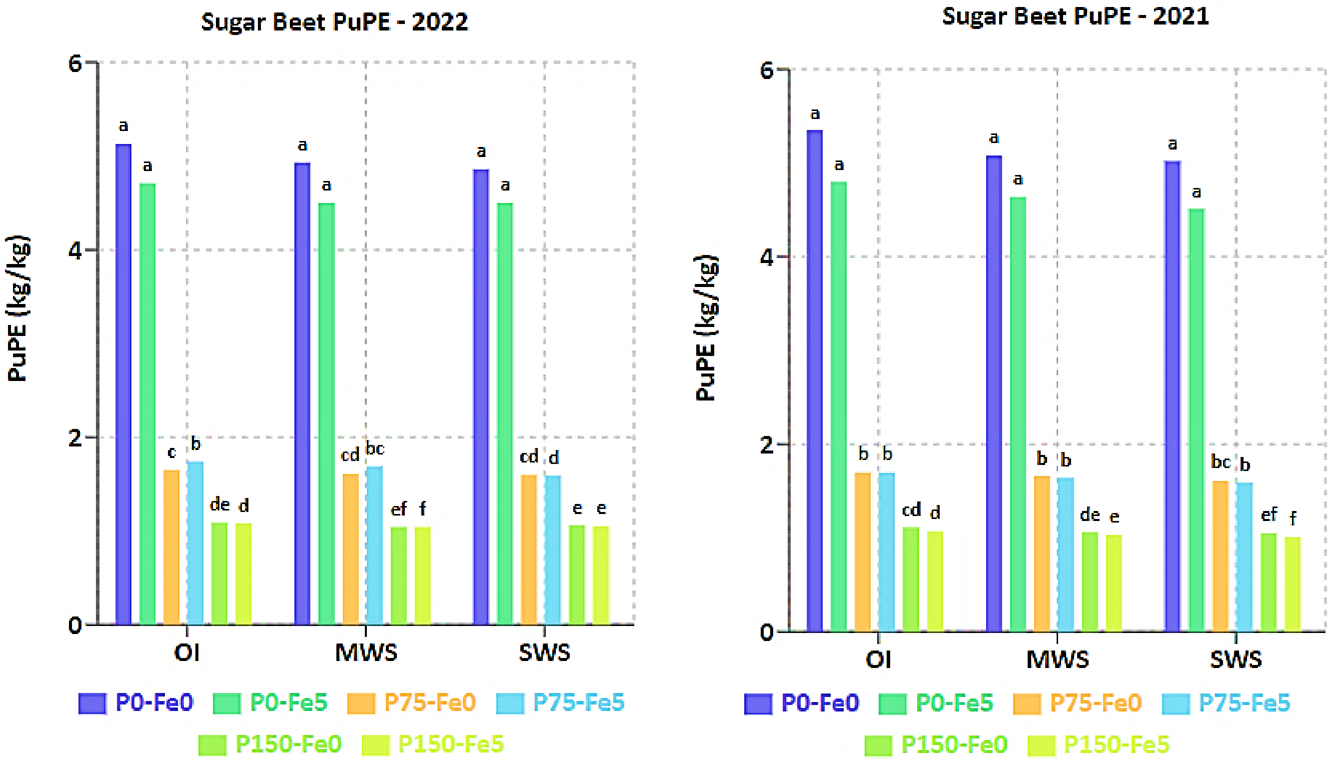

Fig. 2. Sugar beet phosphorus uptake efficiency (pupe) under different irrigation regimes and phosphorus-iron treatments in 2021 and 2022

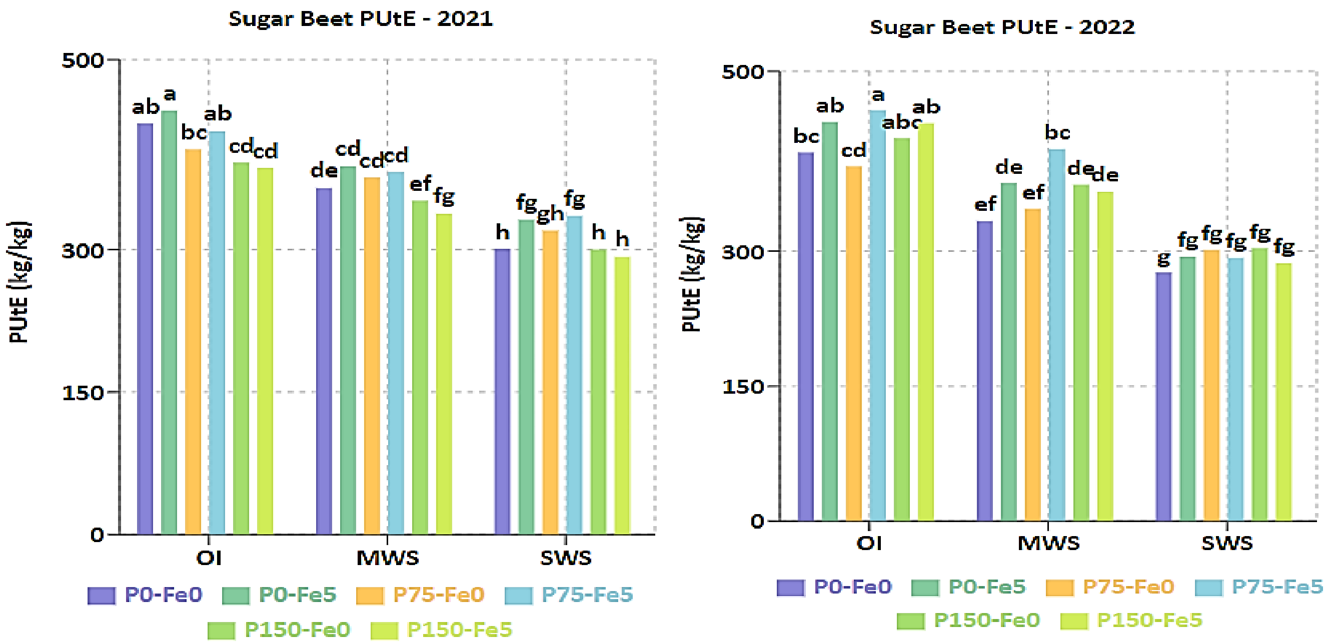

Fig. 3. Sugar Beet Phosphorus Utilization Efficiency (PUtE) Under Different Irrigation Regimes and Phosphorus-Iron Treatments in 2021 and 2022

Potassium Content

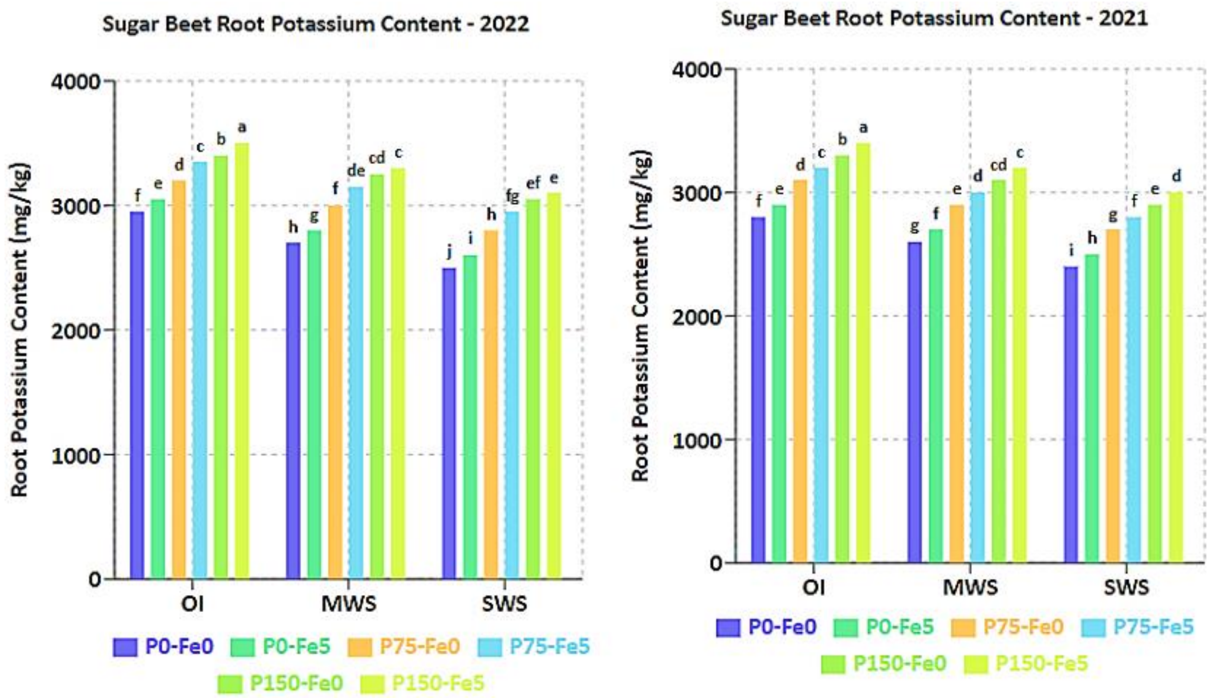

Fig. 4. Sugar beet potassium contnet under different irrigation regimes and phosphorus-iron treatments in 2021 and 2022

Potassium content in sugar beet roots increased with phosphorus and iron application rates across all irrigation regimes (Figure 4). Under optimal irrigation (OI), P150Fe5 treatment showed the highest potassium content in both years. In 2021, P150Fe5 recorded 3400 mg/kg (21.4% higher than control), while P75Fe5 showed a 14.3% increase compared to the control. In 2022, P150Fe5 showed 3500 mg/kg (18.6% higher than control), and P75Fe5 showed a 13.6% increase. Under moderate (w8% lower than control). In 2022, P0Fe0 showed 230 mg/kg, and P150Fe5 showed 160 mg/kg (30.4% lower). Under moderate water stress (MWS) in 2021, P0Fe0 had the highest sodium content (245 mg/kg), with P150Fe5 lowest at 175 mg/kg (28.6% lower than control stress (MWS). In 2021, P150Fe5 showed the highest potassium content (3200 mg/kg, 23.1% higher than control), while in 2022, it showed 3300 mg/kg (22.2% higher than control). P75Fe5 showed a 15.4% increase in 2021 and a 16.7% increase in 2022. Severe water stress (SWS) in 2021 saw P150Fe5 with the highest potassium content (3000 mg/kg, 25% higher than control), and in 2022, it showed 3100 mg/kg (24% higher than control). P75Fe5 showed a 16.7% increase in 2021 and an 18% increase in 2022. Water stress generally reduced potassium content, with a 6-8% reduction under MWS and 12-15% under SWS. Iron addition led to a 3-5% increase in potassium content across all conditions.

Sodium Content:

Sodium content in sugar beet roots decreased with increasing phosphorus and iron application rates across all irrigation regimes (Figure 5). Under optimal irrigation (OI) in 2021, P0Fe0 showed the highest sodium content (220 mg/kg), while P150Fe5 had the lowest (150 mg/kg, 31. rol). In 2022, P0Fe0 showed 255 mg/kg, and P150Fe5 showed 185 mg/kg (27.5% lower). Severe water stress (SWS) in 2021 saw P0Fe0 with the highest sodium content (270 mg/kg) and P150Fe5 lowest at 200 mg/kg (25.9% lower than control). In 2022, P0Fe0 showed 280 mg/kg, and P150Fe5 showed 210 mg/kg (25% lower). Water stress increased sodium content, with 11-16% increase under MWS and 22-33% under SWS. Iron addition led to a 4-7% decrease in sodium content across all conditions.

Harmful Nitrogen Content:

Harmful nitrogen content in sugar beet roots decreased with increasing phosphorus and iron application rates across all irrigation regimes (Figure 6). Under optimal irrigation (OI) in 2021, P0Fe0 showed the highest HarmN content (3.2 mg/100 g), while P150Fe5 had the lowest (2.2 mg/100 g, 31.3% lower than control). In 2022, P0Fe0 showed 2.6 mg/100g, and P150Fe5 showed 1.5 mg/100g (42.3% lower). Under moderate water stress (MWS) in 2021, P0Fe0 had the highest HarmN content (3.5 mg/100 g), with P150Fe5 lowest at 2.5 mg/100 g (28.6% lower than control). In 2022, P0Fe0 showed 2.9 mg/100g, and P150Fe5 showed 1.8 mg/100g (37.9% lower). Severe water stress (SWS) in 2021 saw P0Fe0 with the highest HarmN content (3.8 mg/100 g) and

P150Fe5 lowest at 2.8 mg/100 g (26.3% lower than control). In 2022, P0Fe0 showed 3.2 mg/100g, and P150Fe5 showed 2.1 mg/100g (34.4% lower). Water stress increased HarmN content, with a 9–12% increase under MWS and 19–23% under SWS. Iron addition led to a 5-10% decrease in HarmN content across all conditions. Generally, HarmN content in 2022 was lower than in 2021, with a 15-20% decrease in most treatments.

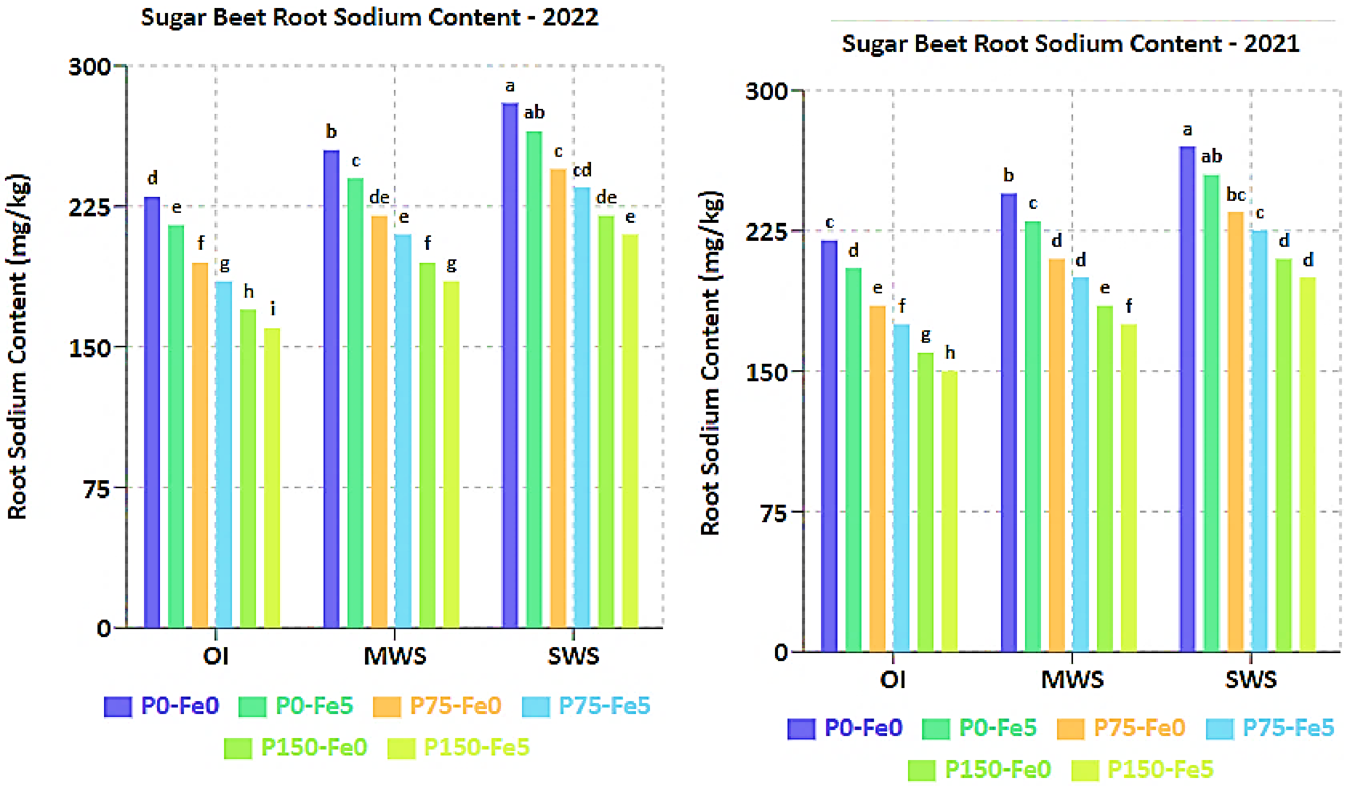

Fig. 5. Sugar beet sodium contnet under different irrigation regimes and phosphorus-iron treatments in 2021 and 2022

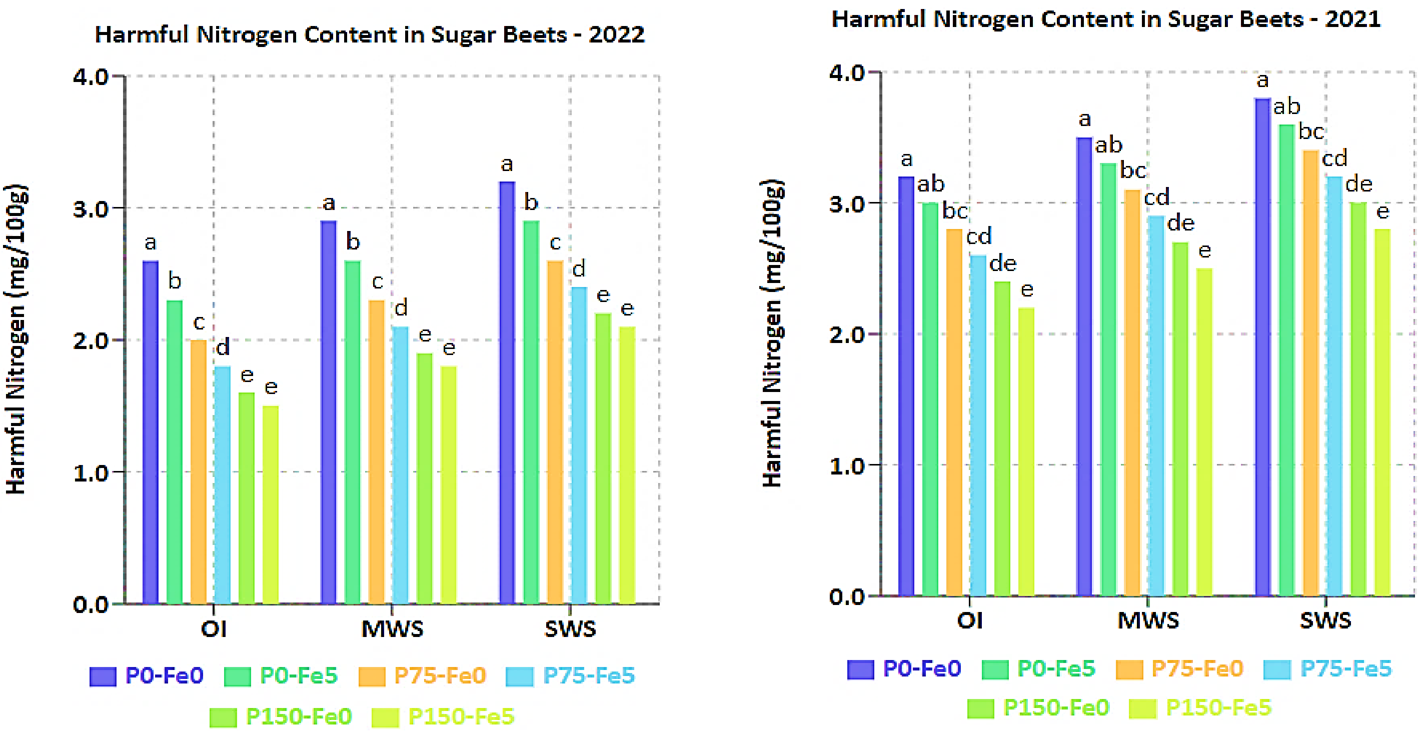

Fig. 6. Sugar beet harmful nitrogen under different irrigation regimes and phosphorus-iron treatments in 2021 and 2022

Juice Purity:

Juice purity percentage in sugar beet increased with phosphorus and iron application rates across all irrigation regimes (Figure 7). Under optimal irrigation (OI) in 2021, P150Fe5 showed the highest juice purity (94.5%), while P0Fe0 had the lowest (92.0%, 2.7% lower than highest). In 2022, P150Fe5 showed 95.5%, and P0Fe0 showed 93.0% (2.6% lower). Under moderate water stress (MWS) in 2021, P150Fe5 had the highest purity (93.5%), with P0Fe0 lowest at 91.0% (2.7% lower than highest). In 2022, P150Fe5 showed 94.5%, and P0Fe0 showed 92.0% (2.6% lower). Severe water stress (SWS) in 2021 saw P150Fe5 with the highest purity (92.5%) and P0Fe0 lowest at 90.0% (2.7% lower than highest). In 2022, P150Fe5 showed 93.5%, and P0Fe0 showed 91.0% (2.7% lower). Water stress reduced juice purity, with 1.0-1.1% reduction under MWS and 2.1-2.2% under SWS. Iron addition led to a 0.5% increase in purity across all conditions. Generally, juice purity in 2022 was higher than in 2021, with about a 1.0% increase in most treatments.

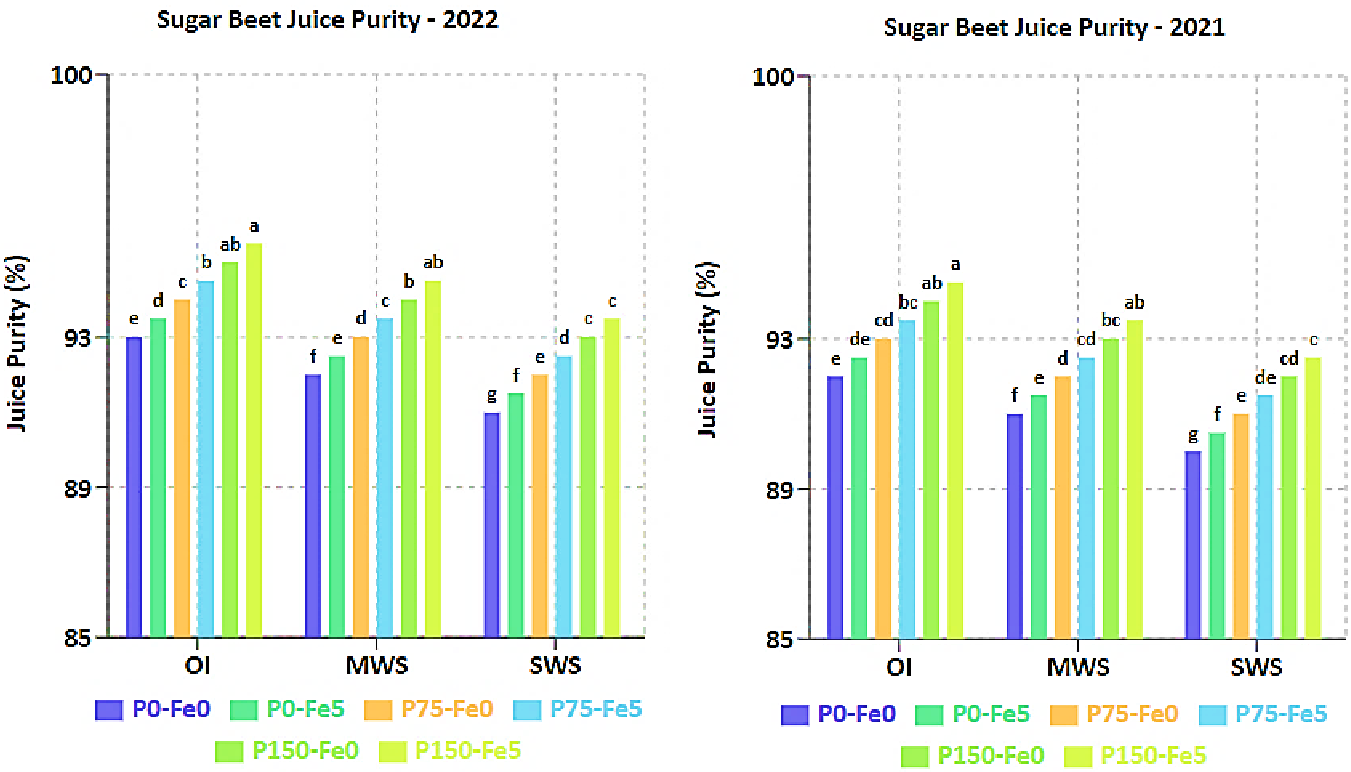

Fig. 7. Sugar beet juice purity nder different irrigation regimes and phosphorus-iron treatments in 2021 and 2022

Root Yield:

Root yield in sugar beet was influenced by phosphorus and iron application rates and irrigation regimes (Figure 8). Under optimal irrigation (OI) in 2021, P75Fe5 showed the highest root yield (79.4 t/ha), while P0Fe0 had the lowest (69.5 t/ha, 12.5% lower than highest). In 2022, P150Fe5 showed the highest yield (88.3 t/ha, 11.2% higher than the previous year's highest). Under moderate water stress (MWS) in 2021, P75Fe5 had the highest yield (68.9 t/ha), with P0Fe0 lowest at 55.6 t/ha (19.3% lower than highest). In 2022, P75Fe5 showed the highest yield (76.9 t/ha, 11.6% increase from the previous year). Severe water stress (SWS) in 2021 saw P75Fe5 with the highest yield (58.7 t/ha) and P0Fe0 lowest at 45.3 t/ha (22.8% lower than highest). In 2022, P150Fe0 showed the highest yield (57.8 t/ha, similar to the previous year's highest). Root yield decreased with increasing water stress intensity, with MWS causing a 13-20% reduction and SWS a 26-35% reduction. Phosphorus and iron application generally increased root yield, with P75Fe5 and P150Fe5 treatments showing the highest yields in most cases.

White Sugar Yield

White sugar yield in sugar beet followed similar trends to root yield across treatments and irrigation regimes (Figure 9). Under optimal irrigation (OI) in 2021, P75Fe5 showed the highest white sugar yield (15.1 t/ha), while P0Fe0 had the lowest (13.1 t/ha, 13.2% lower than highest). In 2022, P150Fe5 showed the highest yield (16.8 t/ha, 11.3% higher than the previous year's highest). Under moderate water stress (MWS) in 2021, P75Fe5 had the highest yield (13.0 t/ha), with P0Fe0 lowest at 10.4 t/ha (20% lower than highest). In 2022, P75Fe5 showed the highest yield (14.6 t/ha, 12.3% increase from the previous year). Severe water stress (SWS) in 2021 saw P75Fe5 with the highest yield (11.1 t/ha) and P0Fe0 lowest at 8.5 t/ha (23.4% lower than highest). In 2022, P150Fe0 showed the highest yield (10.9 t/ha, 1.8% lower than the previous year's highest). White sugar yield decreased with increasing water stress intensity, with MWS causing a 13-20% reduction and SWS a 26-37% reduction. Phosphorus and iron application generally increased white sugar yield, with P75Fe5 and P150Fe5 treatments showing the highest yields in most cases.

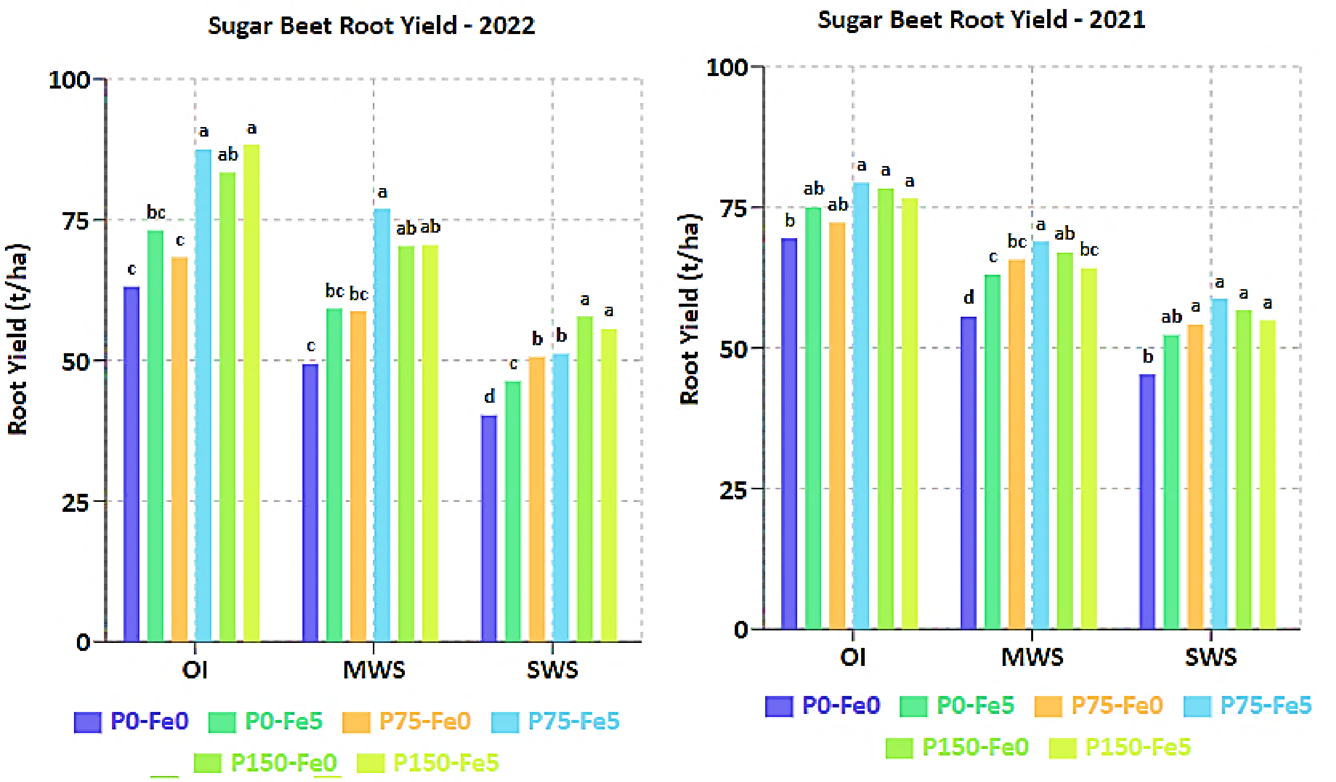

Fig. 8. Sugar beet root yield under different irrigation regimes and phosphorus-iron treatments in 2021 and 2022

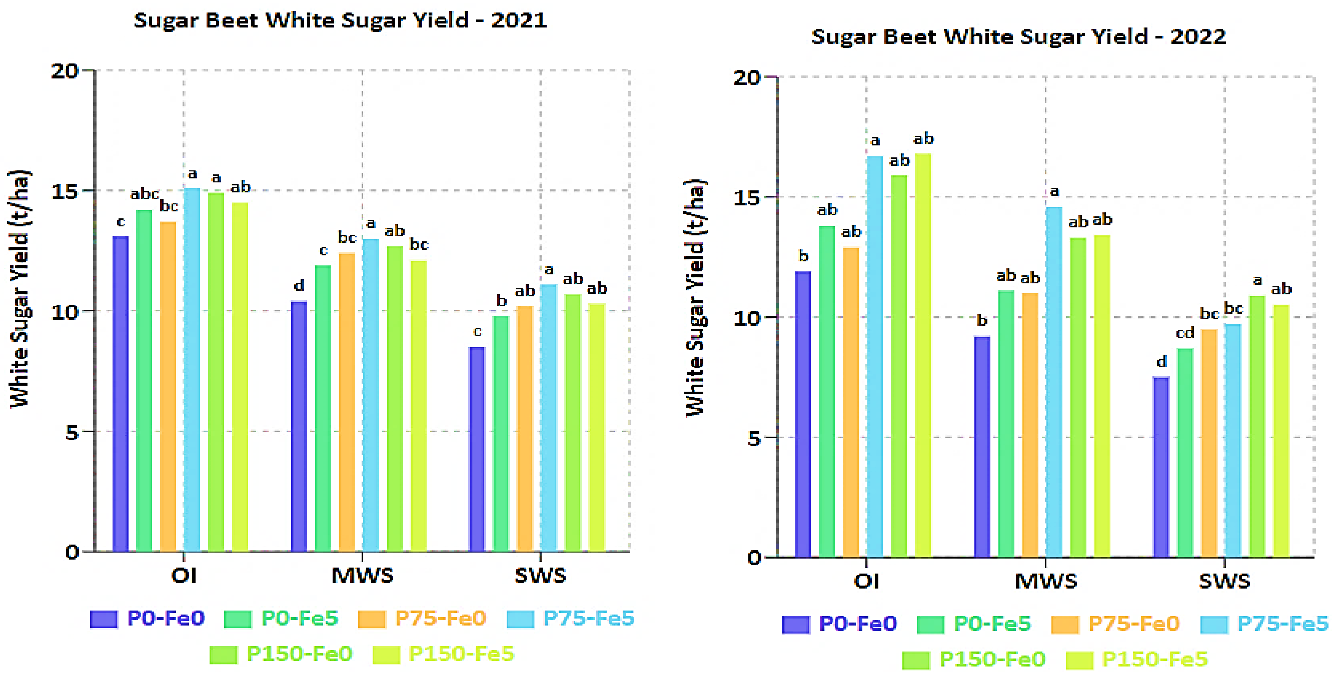

Fig. 9. Sugar beet white sugar different irrigation regimes and phosphorus-iron treatments in 2021 and 2022

Sucrose Content:

Sucrose content in sugar beet showed slight variations across treatments and irrigation regimes (Figure 10). Under optimal irrigation (OI) in 2021, P75Fe5 showed the highest sucrose content (18.99%), while P0Fe0 had the lowest (18.88%, 0.58% lower than highest). In 2022, P75Fe5 showed the highest content (19.04%, 0.26% higher than the previous year). Under moderate water stress (MWS) in 2021, P75Fe5 had the highest sucrose content (18.93%), with P0Fe0 lowest at 18.78% (0.79% lower than highest). In 2022, P75Fe5 showed the highest content (19.01%, 0.42% increase from the previous year). Severe water stress (SWS) in 2021 saw P75Fe5 with the highest sucrose content (18.93%) and P0Fe0 lowest at 18.71% (1.16% lower than highest). In 2022, P150Fe0 showed the highest content (18.92%, 0.05% lower than the previous year's highest). Sucrose content decreased slightly with increasing water stress intensity, with MWS causing a 0.3-0.5% reduction and SWS a 0.6-0.9% reduction. Phosphorus and iron application slightly increased sucrose content, with P75Fe5 treatment generally showing the highest sucrose content. However, differences between treatments were relatively small compared to other parameters.

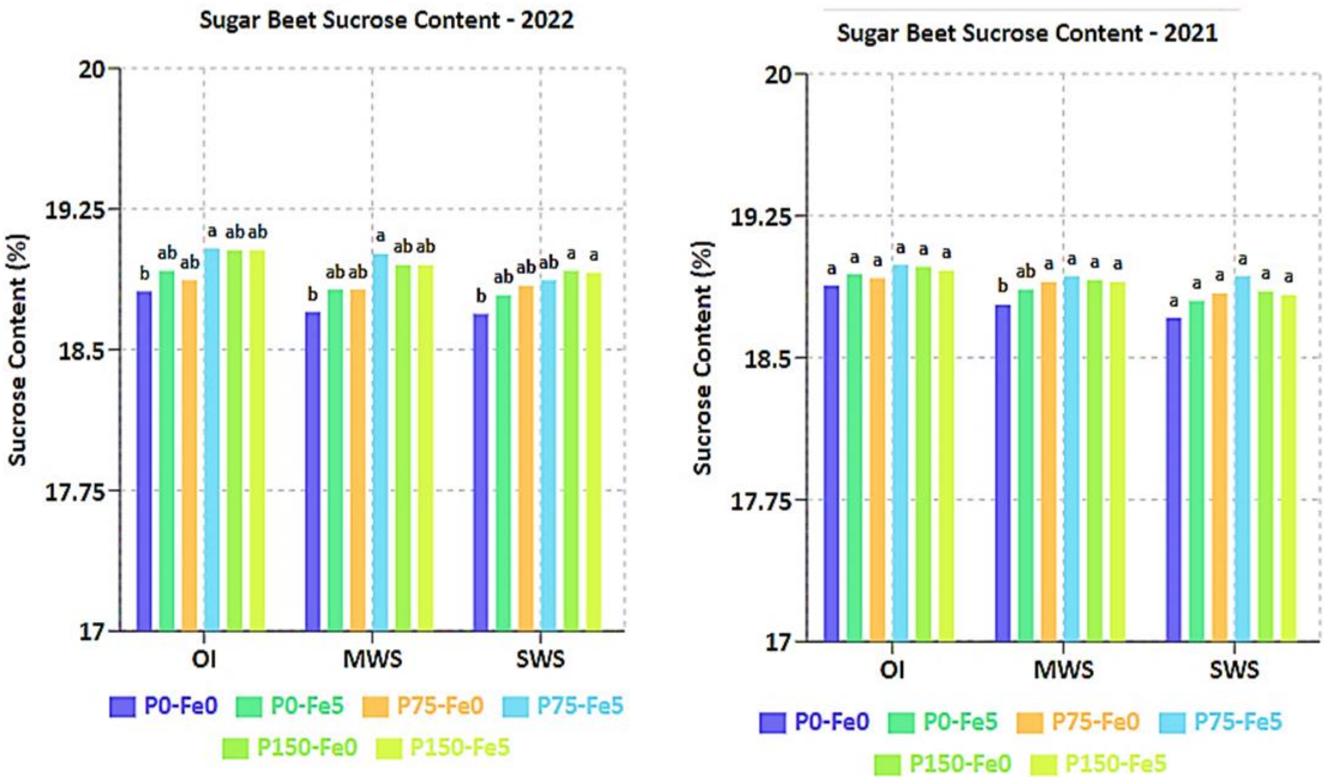

Fig. 10. Sugar beet sucrose content different irrigation regimes and phosphorus-iron treatments in 2021 and 2022

DISCUSSION

Phosphorus Nutrition Status:

The interaction between phosphorus (P) and iron (Fe) plays a crucial role in determining the phosphorus nutrition status of sugar beet, primarily reflected in the phosphorus use efficiency (PUE). This study revealed a synergistic interaction between P and Fe, particularly at moderate P levels (P75) combined with Fe application (Fe5). This synergy was most evident in phosphorus utilization efficiency (PUtE), while phosphorus uptake efficiency (PUpE) showed a more complex relationship. The synergistic effect may be attributed to iron's role in enhancing phosphorus solubility in the soil and improving root growth, which collectively facilitate phosphorus uptake and translocation within the plant (Sun *et al.,* 2024).The P75Fe5 treatment consistently outperformed P75Fe0, especially under optimal irrigation (OI) and moderate water stress (MWS) conditions, indicating a positive interaction between P and Fe on overall phosphorus nutrition status. These findings align with previous studies that have reported synergistic effects of P and Fe on nutrient uptake and utilization in various crops (Xue *et al.,* 2016; Bhat *et al.,* 2024).

The synergistic effect can be attributed to the complementary roles of P and Fe in plant metabolism. Phosphorus is crucial for energy transfer and root development, while iron is essential for chlorophyll synthesis

and enzyme activation (Stigter & Plaxton, 2015; Gisbert *et al.,* 2020). Additionally, iron plays a key role in the formation of iron-phosphate complexes, which can enhance phosphorus solubility and availability in the soil (Marajan *et al.,* 2020). The combined application of these nutrients likely enhances root growth and increases the plant's capacity to utilize absorbed P more efficiently. This synergy may involve enhanced root development due to adequate P supply, leading to increased P uptake capacity, improved photosynthetic efficiency facilitated by Fe, providing more energy for P uptake and assimilation, and optimized P allocation and utilization within plant tissues due to enhanced metabolic processes (Etienne *et al.,* 2018 Yuan *et al.,* 2023;)
However, it's important to note that higher P rates (P150) did not always result in further improvements, suggesting that the P-Fe synergy has an optimal range beyond which benefits may diminish. This underscores the importance of balanced nutrient management for maximizing PUE and overall P nutrition status, as highlighted by Heuer *et al .,* (2017) and Kusi *et al.* (2021).

Under water stress conditions, the P-Fe interaction showed a mitigating effect on the negative impacts of water limitation on P nutrition status. While water stress generally reduced PUE, the combined application of P and Fe (particularly P75Fe5 treatments) helped to alleviate these negative effects, especially under moderate water stress. This mitigation effect can be attributed to improved root growth and function, enhancing both water and P uptake efficiency under stress conditions (Ahanger *et al.,* 2016; Kour *et al.,* 2019)**.** These findings suggest that integrated P-Fe fertilization strategies could be particularly beneficial in drought-prone regions or under predicted climate change scenarios, potentially reducing fertilizer waste and improving crop resilience to water scarcity (Valdiuia Vega *et al.,* 2022).

The decrease in phosphorus use efficiency (PUE) under water stress is attributed to impaired phosphorus uptake and reduced utilization within the plant. Limited soil moisture restricts root growth and phosphorus mobility, reducing absorption capacity (Motalebifard *et al.,* 2016). Drought also alters enzyme activity involved in phosphorus metabolism, hindering efficient utilization (Plaxton and Stigter, 2015). Furthermore, water stress disrupts photosynthesis and carbon allocation, weakening the plant's overall phosphorus-related processes and contributing to the decline in PUE (He and Dijkstra, 2014). However, the synergistic P-Fe interaction can partially mitigate these negative effects by enhancing root development, maintaining photosynthetic efficiency, and supporting osmotic regulation, thereby improving the plant's ability to acquire and utilize phosphorus even under water-limited conditions (Von Tucher *et al.,* 2018)

Reduced PUpE under drought is linked to restricted root growth and exploration, limiting phosphorus absorption (Motalebifard *et al.,* 2016). The P-Fe interaction enhances root development and function, mitigating this effect (Etienne *et al.,* 2018; Gisbert et al., 2020). Changes in PUtE are tied to root enzyme activity - drought stress impairs phosphorus metabolism (Plaxton and Stigter, 2015), while iron supplementation supports optimal enzyme function for efficient phosphorus utilization (Kour *et al.,* 2019; Yang *et al.,* 2024). Iron is a crucial component of many enzymes involved in phosphorus metabolism, such as acid phosphatases and phytase, and its adequate supply helps maintain their activity even under drought stress conditions (Zhaksbayeva *et al.,* 2021). These root-level adaptations underlie the observed trends in overall phosphorus use efficiency under different nutrient and water stress treatments.

The synergistic interaction between phosphorus and iron plays a crucial role in nutrient uptake and utilization. The combined application of P and Fe enhances root growth and function, improving the plant's capacity for phosphorus absorption (Etienne *et al.,* 2018;Gisbert *et al.,* 2020). Iron also supports photosynthesis and enzyme activity, optimizing phosphorus metabolism and allocation within the plant (Kour *et al.,* 2019; Yang et al., 2024). This P-Fe synergy leads to increased phosphorus use efficiency, uptake, and utilization compared to either nutrient alone, ultimately enhancing sugar beet quality parameters such as sugar content and juice purity (Zhaksbayeva *et al.,* 2022)

Root Quality Parameters:

The interaction between P and Fe significantly influenced various root quality parameters in sugar beet, including potassium (K) content, sodium (Na) content, harmful nitrogen content, and juice purity percentage. These interactions were predominantly synergistic for desirable traits and antagonistic for undesirable traits, .collectively contributing to improved root quality.

For potassium content, the P-Fe interaction showed a strong synergistic effect. The P150Fe5 treatment consistently resulted in the highest K content across all irrigation regimes, with substantial increases compared to treatments without Fe or with lower P levels. This synergy suggests that the combined application of P and Fe enhances the plant's ability to uptake and accumulate K, consistent with findings by Rondevaldova *et al.* (2023) and Aghdam & Valilue (2023). The mechanism behind this synergy likely involves improved root growth and function due to adequate P supply, coupled with enhanced photosynthetic efficiency facilitated by Fe. This interaction leads to increased energy availability for active K uptake and translocation. The improved K status resulting from this P-Fe synergy can contribute to better osmotic regulation and enzyme activation in sugar beet, potentially improving stress tolerance and overall plant health (Etienne *et al.,* 2018; Yaqing *et al.,* 2023)**.** Higher K content in sugar beet typically leads to improved sugar yield and quality by enhancing sucrose translocation and reducing impurities in the extracted juice (Ali *et al.,* 2023)

Regarding sodium content, the P-Fe interaction exhibited an antagonistic effect, which is beneficial for sugar beet quality. The P150Fe5 treatment consistently showed the lowest Na content across all irrigation regimes. This antagonistic effect on Na accumulation may be due to improved selectivity of root membranes for K over Na, enhanced by the combined application of P and Fe (Wang *et al.,* 2021; Yaqing *et al.,* 2023). The P-Fe interaction likely improves the plant's ability to exclude Na and maintain a favorable K/Na ratio in tissues. This effect is particularly beneficial under water stress conditions, where Na exclusion becomes crucial for maintaining cellular functions and preventing salt stress. The reduced Na content resulting from this P-Fe antagonism contributes to improved root quality and potentially enhances sugar beet's tolerance to saline conditions (Bouras *et al.,* 2021; Gisbert *et al.,* 2020)**.** Lower Na content in sugar beet roots directly improves juice purity and sugar extraction efficiency, leading to higher quality sugar and reduced processing costs (Sun *et al.,* 2024).

For harmful nitrogen content, the P-Fe interaction showed an antagonistic effect, which is beneficial for sugar beet quality. The P150Fe5 treatment consistently resulted in the lowest HarmN content across all irrigation regimes. This antagonism suggests that the combined application of P and Fe enhances the plant's nitrogen metabolism, promoting the conversion of inorganic nitrogen to organic forms (Gezgin *et al.,* 2017;Makhlouf *et al.,* 2021). The mechanism behind this interaction may involve improved nitrogen assimilation due to enhanced photosynthetic efficiency (facilitated by Fe) and increased energy availability for nitrogen metabolism (provided by P). This more efficient nitrogen utilization results in lower accumulation of harmful nitrogenous compounds, contributing to improved root quality and potentially higher sugar content (El-Mansoub & Mohamed;2014; Kusi *et al.,* 2021)**.** Lower harmful nitrogen content in sugar beet roots significantly improves juice purity and reduces the formation of undesirable color compounds during processing, leading to higher quality sugar and improved factory performance (Ghaly *et al.,* 2019).

The P-Fe interaction exhibited a synergistic effect on juice purity percentage. The P150Fe5 treatment consistently showed the highest juice purity across all irrigation regimes. This synergy indicates that the combined application of P and Fe enhances the plant's ability to accumulate sucrose while reducing impurities in the root, as observed in previous studies on sugar beet and other crops (Bahrami *et al.,* 2020; Hadir et al., 2020). The mechanism behind this synergy likely involves improved photosynthesis and carbon allocation (facilitated by both P and Fe), coupled with more efficient exclusion of impurities like Na and harmful nitrogen compounds. The increased juice purity resulting from this P-Fe synergy directly contributes to improved sugar beet quality and potentially higher sugar extraction efficiency during processing (Brar *et al.,* 2015; Khalil *et al.,* 2018)**.** Higher juice purity translates to reduced processing costs, increased sugar yield, and ultimately higher profitability for both farmers and sugar processors (Gursay and Atun, 2019).

The P-Fe interaction exhibits synergistic effects on potassium content, with P150Fe5 resulting in the highest K levels (Aghdam & Valilue, 2023; Rondevaldova *et al.,* 2023). Conversely, it shows antagonistic effects on sodium and harmful nitrogen accumulation, with P150Fe5 having the lowest Na and N (Gezgin *et al.,* 2017; Makhlouf *et al.,* 2021; Wang et al., 2021; Yaqing *et al.,* 2023). These nutrient interactions optimize root quality parameters, contributing to improved crop performance, even under water stress. The resulting nutrient profile—higher K and lower Na and harmful N—significantly enhances sugar beet processing quality, potentially leading to improved sugar extraction efficiency, reduced processing costs, and higher-quality end products (Cieciura *et al.,* 2021).

There is a delicate balance between optimizing nutrient use efficiency and enhancing water stress tolerance. While the P-Fe interaction improves phosphorus uptake and utilization, it also plays a role in maintaining root function, photosynthesis, and metabolic processes under drought (Gisbert *et al.,* 2020; Etienne *et al.,* 2018; Kour *et al.,* 2019). This synergistic effect helps mitigate the negative impacts of water stress on nutrient use efficiency (He and Dijkstra, 2014; Motalebifard *et al.,* 2016), showcasing the trade-offs involved in managing these competing priorities for optimal crop performance. This balance underscores the importance of precision nutrient management, where fertilizer applications are tailored to specific soil conditions, water availability, and crop growth stages (Marajan *et al.,* 2020).

Root Yield, Sucrose Content and Sugar Yield

The interaction between P and Fe had significant impacts on root yield, sucrose content, and ultimately, sugar yield in sugar beet. These interactions were predominantly synergistic, contributing to improved overall productivity and quality: For root yield, the P-Fe interaction showed a strong synergistic effect. The P75Fe5 and P150Fe5 treatments generally resulted in the highest root yields across different irrigation regimes, particularly under optimal irrigation and moderate water stress conditions. This synergy suggests that the combined application of P and Fe enhances overall plant growth more than either nutrient alone, consistent with findings by Ibrahim (2017) and Aghdam & Valilue (2023). The mechanism behind this synergy likely involves enhanced root development due to adequate P supply, leading to better nutrient and water uptake, improved photosynthetic efficiency facilitated by Fe, providing more energy for biomass production, and optimized carbohydrate allocation to the root, resulting in increased root biomass (Gisbert *et al.,* 2020; Yuan *et al.,* 2023)**.** This increase in root yield directly translates to higher sugar production potential per hectare, significantly improving the economic returns for farmers and the overall efficiency of sugar beet cultivation (Gursay and Atun, 2019).

The P-Fe interaction on sucrose content showed a positive but relatively small synergistic effect compared to its impact on root yield. The P75Fe5 treatment generally showed the highest sucrose content across irrigation regimes, but the differences between treatments were less pronounced than for other parameters. This mild synergy suggests that while the P-Fe interaction does enhance sucrose accumulation, its effect on sucrose concentration is less dramatic than its effect on overall yield. The mechanism may involve improved photosynthetic efficiency, leading to increased sugar production, enhanced translocation of sugars to the root, facilitated by improved vascular function, and optimized metabolic processes that favor sucrose accumulation over other carbon sinks (Khalil *et al.,* 2018; Bahrami *et al.,* 2020). However, it's important to note that other factors such as genetic potential and environmental conditions may play a more significant role in determining the final sucrose concentration (Brar *et al.,* 2015 **;**Mirzaei & Ghadami Firouzabadi, 2022)**.** Despite the modest increase in sucrose content, when combined with the substantial improvement in root yield, the P-Fe interaction still contributes to a significant increase in total sugar yield per hectare, underlining its importance for overall sugar production (Marajan *et al.,* 2020).

The interaction between P and Fe showed a strong synergistic effect on sugar yield, which is a function of both root yield and sucrose content. The P75Fe5 and P150Fe5 treatments generally resulted in the highest sugar yields across different irrigation regimes. This synergy is largely driven by the substantial increases in root yield, combined with the modest improvements in sucrose content. The mechanism behind this synergy integrates the effects on both root yield and sucrose content. Increased root biomass provides a larger storage capacity for sucrose, improved photosynthetic efficiency leads to greater overall sugar production, and enhanced nutrient uptake and utilization support the metabolic demands of high sugar production and storage (Kusi *et al.,* 2021; Khalil *et al.,* 2018)**.** This significant increase in sugar yield per hectare translates directly to improved economic returns for farmers and enhanced processing efficiency for sugar factories, potentially leading to more sustainable and profitable sugar beet production (Ali *et al.,* 2023).

Under water stress conditions, the P-Fe interaction showed a mitigating effect on the negative impacts of water limitation on yield parameters. While water stress generally reduced yields, the combined application of P and Fe (particularly P75Fe5 and P150Fe5 treatments) helped to alleviate these negative effects, especially under moderate water stress. This mitigation effect can be attributed to improved water use efficiency, better osmotic regulation, and maintained photosynthetic activity under stress conditions (Motalebifard *et al.,* 2016; Yaqing *et al.,* 2023)**.** These findings offer promising strategies for maintaining sugar beet productivity in drought-prone regions or areas facing increasing water scarcity due to climate change, potentially enhancing food security and economic stability in these vulnerable agricultural systems (Hajiboland *et al.,* 2018).

This study challenges the conventional wisdom that simply increasing phosphorus inputs can linearly improve nutrient use efficiency in sugar beet (Kusi *et al.,* 2021; Heuer *et al.,* 2017). Instead, it demonstrates the synergistic benefits of moderate P levels combined with iron supplementation, outperforming higher P rates (Kusi *et al.,* 2021). Additionally, the mitigating effect of the P-Fe interaction under water stress (Ahanger et al., 2016; Kour *et al.,* 2019) challenges the siloed approach of managing irrigation and nutrients, highlighting the importance of integrated strategies to enhance sugar beet resilience (He and Dijkstra, 2014). These findings underscore the potential for more sustainable and cost-effective sugar beet production through optimized nutrient management, potentially reducing environmental impacts associated with excessive fertilizer use while maintaining or improving crop yields (Sun *et al.,* 2024).

The P150Fe5 treatment, while requiring higher input costs, provides substantial yield and quality gains under optimal irrigation, potentially offsetting expenses. Under moderate stress, the more cost-effective P75Fe5 can still maintain productivity and quality improvements. For severe stress, the P75Fe5 treatment emerges as the most practical option, significantly enhancing PUE, yields, and quality at reduced input levels. Tailoring the P-Fe combination to water availability balances costs with the potential for increased profits through higher yields, improved quality, and enhanced resource use efficiency. This adaptive approach not only optimizes economic returns but also promotes environmental sustainability by reducing unnecessary nutrient applications and improving water use efficiency, aligning with long-term goals for sustainable intensification in agriculture (Ghaly *et al.,* 2019).

In conclusion, the interactions between phosphorus and iron in sugar beet cultivation are predominantly synergistic for root yield, sucrose content, and sugar yield. These interactions contribute to improved overall productivity and quality, particularly under optimal and moderately stressed conditions. The benefits of P-Fe synergy highlight the importance of balanced nutrient management in sugar beet production, especially in the face of variable water availability (Demirbaş, 2021; Ibrahim, 2017). Under optimal irrigation, apply P150Fe5 for the highest PUE and yields, and under moderate stress, P75Fe5 can mitigate negative impacts, maintaining efficient nutrient use, yields, and quality. For severe stress, the more practical P75Fe5 is recommended, as it significantly improves PUE, yields, and quality even under extreme drought. Integrating strategic P-Fe application with irrigation management optimizes productivity and resource use efficiency. These findings not only offer a pathway to more resilient and productive sugar beet cultivation but also exemplify the potential for precision nutrient management to address broader challenges in sustainable agriculture, such as resource conservation and adaptation to climate variability (Cieciura *et al.,* 2021).

CONCLUSION

This study demonstrates the significant synergistic effects of the interaction between phosphorus (P) and iron (Fe) on sugar beet productivity and quality under varying irrigation regimes. The combined application of P and Fe, particularly at moderate P levels (75 kg/ha P) with Fe supplementation (5 kg/ha Fe), consistently improved key performance indicatorsCompared to treatments without the P-Fe combination, the P75Fe5 treatment increased phosphorus use efficiency (PUE) by up to 40%, phosphorus uptake efficiency (PUpE) by up to 55%, and phosphorus utilization efficiency (PUtE) by up to 46%. These efficiency gains were observed across different irrigation conditions, with the P-Fe interaction showing a protective effect against the negative impacts of water stress. The P-Fe synergy also had a positive impact on root quality parameters. It enhanced potassium (K) content by up to 25%, while reducing undesirable elements like sodium (Na) by up to 32% and harmful nitrogen (N) by up to 40%. These interactions resulted in improved juice purity by up to 2.7%, higher root yields by up to 40%, and increased white sugar yields by up to 46%, especially under optimal irrigation and moderate water stress conditions,While higher P rates (150 kg/ha) showed some benefits, the results suggest an optimal range for the P-Fe synergy, beyond which the returns may diminish. This highlights the importance of precise nutrient application strategies to maximize agronomic efficiency and minimize environmental impacts, as excessive nutrient inputs can lead to resource waste and pollution.

REFERENCES

Aghdam, M. Z., & Valilue, R. (2023). Effect of iron, zinc and boron on sugar beet yield and quality. *Cross Current International Journal of Agriculture and Veterinary Sciences*, *5*(1), 1-7.

Ahanger, M. A., Morad-Talab, N., Abd-Allah, E. F., Ahmad, P., & Hajiboland, R. (2016). Plant growth under drought stress: Significance of mineral nutrients. *Water stress and crop plants: a Sustainable Approach*, *2*, 649-668.

Ali, A. M., Mahdy, A. Y., Al-Sayed, H. M., & Bayomi, K. M. (2023). Phosphorus sources and sheep manure fertilization for soil properties enhancement and sugar beet yield. *Gesunde Pflanzen*, *75*(6), 2785-2795.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). FAO Irrigation and drainage paper No. 56. *Rome: Food and Agriculture Organization of the United Nations*, *56*(97), e156.

Bahrami, M. E., Honarvar, M., Ansari, K., & Jamshidi, B. (2020). Measurement of quality parameters of sugar beet juices using near-infrared spectroscopy and chemometrics. *Journal of Food Engineering*, *271*, 109775.

Bhat, M. A., Mishra, A. K., Shah, S. N., Bhat, M. A., Jan, S., Rahman, S., ... & Jan, A. T. (2024). Soil and Mineral Nutrients in Plant Health: A Prospective Study of Iron and Phosphorus in the Growth and Development of Plants. *Current Issues in Molecular Biology*, *46*(6), 5194-5222.

Bouras, H., Bouaziz, A., Bouazzama, B., Hirich, A., & Choukr-Allah, R. (2021). How phosphorus fertilization alleviates the effect of salinity on sugar beet (Beta vulgaris L.) productivity and quality. *Agronomy*, *11*(8), 1491.

Brar, N. S., Dhillon, B. S., Saini, K. S., & Sharma, P. K. (2015). Agronomy of sugarbeet cultivation-A review. *Agricultural Reviews*, *36*(3), 184-197.

Cieciura-Włoch, W., Borowski, S., & Domański, J. (2021). Dark fermentative hydrogen production from hydrolyzed sugar beet pulp improved by nitrogen and phosphorus supplementation. *Bioresource Technology*, *340*, 125622.

Demirbaş, A. (2021). The effect of different phosphorus doses application on yield and nutrient uptake of sugar beet (Beta vulgaris L.) plant.

Dhillon, J., Torres, G., Driver, E., Figueiredo, B., & Raun, W. R. (2017). World phosphorus use efficiency in cereal crops. *Agronomy Journal*, *109*(4), 1670-1677.

El-Mansoub, M. M. A., & Mohamed, H. Y. (2014). Effect of sowing dates and phosphorus fertilizer on root rot and quality of some sugar beet varieties. *Journal of Plant Production*, *5*(5), 745-764.

Etienne, P., Diquelou, S., Prudent, M., Salon, C., Maillard, A., & Ourry, A. (2018). Macro and micronutrient storage in plants and their remobilization when facing scarcity: the case of drought. *Agriculture*, *8*(1), 14.

Gezgin, S., Yilmaz, F. G., Dursun, N., Yazgan, M. G., Harmankaya, M., & Hamurcu, M. (2017). Effects of different nitrogen, phosphorus and potassium rates on quality and yield of sugarbeet. (2017), 323-324.

Gisbert, C., Timoneda, A., Porcel, R., Ros, R., & Mulet, J. M. (2020). Overexpression of BvHb2, a class 2 non-symbiotic hemoglobin from sugar beet, confers drought-induced withering resistance and alters iron content in tomato. *Agronomy*, *10*(11), 1754.

Gisbert, C., Timoneda, A., Porcel, R., Ros, R., & Mulet, J. M. (2020). Overexpression of BvHb2, a class 2 non-symbiotic hemoglobin from sugar beet, confers drought-induced withering resistance and alters iron content in tomato. *Agronomy*, *10*(11), 1754.

Hadir, S., Gaiser, T., Hüging, H., Athmann, M., Pfarr, D., Kemper, R., ... & Seidel, S. (2020). Sugar beet shoot and root phenotypic plasticity to nitrogen, phosphorus, potassium and lime omission. *Agriculture*, *11* (1), 21.

He, M., & Dijkstra, F. A. (2014). Drought effect on plant nitrogen and phosphorus: a meta-analysis. *New Phytologist*, *204* (4), 924-931.

Heuer, S., Gaxiola, R., Schilling, R., Herrera-Estrella, L., López-Arredondo, D., Wissuwa, M., ... & Rouached, H. (2017). Improving phosphorus use efficiency: a complex trait with emerging opportunities. *The Plant Journal*, *90*(5), 868-885.

Ghaly, F., Abd-Hady, M., & Abd-Elhamied, A. (2019). Effect of varieties, phosphorus and boron fertilization on sugar beet yield and its quality. *Journal of Soil Sciences and Agricultural Engineering*, *10* (2), 115-122.

Gürsoy, Ö. N. D. E. R., & Atun, R. (2019). Using remote sensing in detecting sugar beet fields treated with different doses of phosphorus. *Fresenius Environmental Bulletin*, *28* (2A), 1247-1253.

Hajiboland, R., Shekari, S., Sadeghzadeh, N., & Poschenrieder, C. (2018). Sugar beet profits from intercropping with wheat both under optimum and deficient phosphorus supply. *Acta Agriculturae Slovenica*, *111* (1), 85-100.

Ibrahim, M. E. M. (2017). Influence of iron levels and foliar application times on productivity and quality of sugar beet. *Journal of Plant Production*, *8* (9), 923-927.

Khalil, M. R., Mubarak, M. H., AbdEl-Razek, A. M., & Abdalla, M. Y. (2018). Quality of some sugar beet varieties under different environmental conditions. *Sinai Journal of Applied Sciences*, *7* (1), 17-34.

Kour, D., Rana, K. L., Yadav, A. N., Yadav, N., Kumar, V., Kumar, A., ... & Saxena, A. K. (2019). Drought-tolerant phosphorus-solubilizing microbes: biodiversity and biotechnological applications for alleviation of drought stress in plants. *Plant growth promoting rhizobacteria for sustainable stress management: Volume 1: Rhizobacteria in Abiotic Stress Management*, 255-308.

Kusi, N. Y. O., Stevens, W. B., Sintim, H. Y., y Garcia, A. G., & Mesbah, A. O. (2021). Phosphorus fertilization and enhanced efficiency products effects on sugarbeet. *Industrial Crops and Products*, *171*, 113887.

SUN, H. R., ZHANG, J. P., GANG, L. H., WANG, S. B., & WANG, Z. D. (2024). Criteria of soil available phosphorous and the corresponding phosphorus application rates for sugar beet in China. *Journal of Plant Nutrition and Fertilizers*, *30*(8), 1529-1538.

Makhlouf, B. S., Ibrahim, M. E. M., & Eanar, A. K. (2021). Additional Chelated Iron and Organic Amendment Influence on Yield and Quality of Sugar Beet under Various Plant Populations. *Journal of Plant Production*, *12*(5), 567-575.

Marajan, W. A., Idris, B. E. M., & Adam, A. H. (2021). Response of sugar beet (Beta vulgaris L.) growth, yield and yield components to compost and phosphorus fertilizers. *Journal of Agronomy Research*, *4*, 14-22.

Mirzaei, M. R., & Ghadami Firouzabadi, A. (2022). Evaluation of the Effective Drought Stress Level for Drought Tolerance of Sugar Beet Genotypes. *Iranian Journal of Irrigation and Drainage*, *16*(5), 1055-1065.

Motalebifard, R., Najafi, N., & Oustan, S. (2016). Effects of zinc and phosphorus on nutrients, starch and reducing sugar concentrations of potato tubers under with or without water deficit stress. *Water and Soil*, *30*(2), 497-510.

Rondevaldova, J., Novy, P., Tauchen, J., Drabek, O., Kotikova, Z., Dajcl, J., ... & Kokoska, L. (2023). Determination of antioxidants, minerals and vitamins in Cambodian underutilized fruits and vegetables. *Journal of Food Measurement and Characterization*, *17*(1), 716-731.

Stigter, K. A., & Plaxton, W. C. (2015). Molecular mechanisms of phosphorus metabolism and transport during leaf senescence. *Plants*, *4*(4), 773-798.

Vega, S. V., Cabrejos, J. P., & Salazar, S. V. (2022). Phosphorus balance in a saline soil cultivated with sugar beet (Beta vulgaris L. subsp. Vulgaris var. altissima döll). *Ciencia y Tecnología Agropecuaria*, *23* (3).

von Tucher, S., Hörndl, D., & Schmidhalter, U. (2018). Interaction of soil pH and phosphorus efficacy: Long-term effects of P fertilizer and lime applications on wheat, barley, and sugar beet. *Ambio*, *47*, 41-49.

Wang, N., Fu, F. Z., Ji, J. F., Wang, P., He, S. P., Shao, H. Y., ... & Zhang, X. M. (2021). Dry matter accumulation & phosphorus utilization efficiency in sugar beet (Beta vulgaris) under varied irrigation and phosphorus supply.

Wang, Ning, Feng-zhen Fu, Jin-feng Ji, Peng Wang, Shu-ping He, Hong-ying Shao, Zhen Ni, and Xing-mei Zhang. "Dry matter accumulation & phosphorus utilization efficiency in sugar beet (Beta vulgaris) under varied irrigation & phosphorus supply." (2021), 513-520.

Xue, Y., Xia, H., Christie, P., Zhang, Z., Li, L., & Tang, C. (2016). Crop acquisition of phosphorus, iron and zinc from soil in cereal/legume intercropping systems: a critical review. *Annals of Botany*, *117*(3), 363-377.

Yang, X., Liu, C., Liang, C., Wang, T., & Tian, J. (2024). The Phosphorus-Iron Nexus: Decoding the Nutrients Interaction in Soil and Plant. *International Journal of Molecular Sciences*, *25*(13), 6992.

Yaqing, S., Shaoying, Z., Xiaojiao,W., Xue, L., Ningning,L., & Guolong, L. (2023). Overexpression of AVP1 Gene Improved the Tolerance to Low Phosphorus, Salt and Drought Stress in Sugar Beet. Acta Bot. Boreal.-Occident. Sin., 43(11), 1827-1833.

Yuan, H., Wang, Y., Sun, Z., Shi, N., Li, B., Ma, C., ... & Li, Y. (2023). Increasing iron use efficiency by controlling emitter clogging in drip irrigation systems. *Agricultural Water Management*, *290*, 108601.

Zhaksybayeva, G., Balgabayev, A., Vassilina, T., Shibikeyeva, A., & Malimbayeva, A. (2022). Yield of sugar beet and changes in phosphorus fractions in relation to long term P fertilization in chestnut soil of Kazakhstan. *Eurasian Journal of Soil Science*, *11*(1), 25-32.

Zhaksybayeva, G., Umbetov, A., Balgabayev, A., Suleimenov, Y., & Shibikeyeva, A. (2021). IOT process for sugar beet productivity by long-term use of phosphorus fertilisers on irrigated light chestnut soil. *International Journal of Agricultural Resources, Governance and Ecology*, *17*(2-4), 165-182.

تحسين كفاءة استخدام الفوسفور والإنتاجية الكمية والنوعية لبنجر السكر من خلال التطبيق المشترك لجزيئات الفوسفور والحديد النانوية تحت أنظمة ري مختلفة

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تؤثر تفاعلات الفوسفور والحديد تحت ظروف الإجهاد المائي على امتصاص المغذيات في بنجر السكر. يمكن أن يوفر التحقيق في هذه التفاعلات استراتيجيات لتحسين كفاءة استخدام الفوسفور، وزيادة مقاومة الجفاف، وتعزيز إنتاجية المحصول وجودته. تم إجراء التجربة كقطع منشقة في تصميم القطاعات الكاملة العشوائية بثلاثة مكررات على مدى موسمين زراعيين في عامي 2021 و2022. تكون العامل الرئيسي من ثلاثة أنظمة ري (100٪ و75٪ و50٪ من الاحتياج المائي)، وتضمن العامل الفرعي ستة توليفات من أسمدة الفوسفور (0 و75 و150 كجم/هكتار) والحديد (0 و5 كجم/هكتار). أظهرت النتائج أن الإجهاد المائي الشديد (50٪ من الاحتياج المائي) مقارنة بالري الكامل قلل من كفاءة استخدام الفوسفور بنسبة 25-30٪، وكفاءة امتصاص الفوسفور بنسبة 22-33٪، وكفاءة استخدام الفوسفور بنسبة 26-37٪، وإنتاجية الجذور بنسبة 26-35٪، وإنتاجية السكر الأبيض بنسبة 26-37٪. في المقابل، أدى التطبيق المشترك لـ 150 كجم/هكتار من السوبر فوسفات مع 5 كجم/هكتار من الحديد، اعتمادًا على ظروف الرطوبة، إلى زيادة كفاءة استخدام الفوسفور بنسبة 10-40٪، وكفاءة امتصاص الفوسفور بنسبة 14-55٪، وكفاءة استخدام الفوسفور بنسبة 11-46٪، وإنتاجية الجذور بنسبة 10-40٪، وإنتاجية السكر الأبيض بنسبة 11-46٪ مقارنة بالشاهد (بدون سماد). كما أدت هذه التوليفة السمادية إلى خفض محتوى الصوديوم بنسبة 25-32٪ والنيتروجين الضار بنسبة 25-40٪، مع تحسين محتوى البوتاسيوم بنسبة 21-25٪، ونقاوة العصير بنسبة 2.5-2.7٪، ومحتوى السكروز بنسبة 0.4-1.3٪. بشكل عام، أظهرت نتائج هذه الدراسة أن التطبيق المتوازن لـ 150 كجم/هكتار من السوبر فوسفات مع 5 كجم/هكتار من الحديد كان أفضل توليفة سمادية لتحسين كفاءة استخدام الفوسفور وإنتاجية وجودة بنجر السكر، حتى في ظروف الإجهاد المائي.

الكلمات المفتاحية: بنجر السكر، الفوسفور، الحديد، كفاءة استخدام الفوسفور، الإجهاد المائي، الإنتاجية، جودة الجذور.