Morpho-physiological and yield traits of durum wheat (*Triticum durum* Desf.) response to soil-Fe deficiency

Khaled Salhi[1, 2] and Abdelmajid Krouma[2, 3*]

[1] Faculty of sciences of GAFSA, University of GAFSA, TUNISIA.

[2] Laboratory of Ecosystems and Biodiversity in Arid Land of Tunisia, Faculty of sciences, University of Sfax, TUNISIA

[3] Faculty of sciences and techniques of Sidi Bouzid, University of Kairouan, Tunisia.

* **Author for correspondence:** Abdelmajid Krouma. Email: abdelmajid.krouma@gmail.com

Abstract

Iron deficiency is a serious mineral constraint commonly observed in cultivated agrosystems. The limited Fe availability was attributed to the soil properties (pH, carbonate ions, leaching…). Sidi Bouzid agrosystem is a typical semi-arid climate where durum wheat dominates the cereal crops and soil quality differs broadly. Symptoms of iron deficiency were then observed, while the relationship between soil quality and wheat behavior at vegetative and reproductive stages remains less investigated. This study investigates the physiological and reproductive behaviors of wheat regarding Fe availability and soil quality and its impact on the keys metabolic functions and interrelationships. Three different soils (loamy calcareous: L-CS, loamy sand: LSS and sandy loam: SLS) were used to cultivating wheat during a full life cycle, under natural light and temperature. Analyses were made on the keys physiological and reproductive traits, then interrelationships were established. Compared to SLS, L-CS did not provide more than 9% of the plant need for Fe, thus decreasing significantly plant growth, photosynthesis, chlorophyll and grain yield and quality. LSS provide wheat plants by 29% of their need for Fe having, with a less extent, the same inhibitory effect on the above-mentioned parameters. Chlorophyll, photosynthesis, plant growth, yield, ear filling and grain quality are interdependent and depend closely on the Fe uptake and soil quality. Durum wheat yield depends closely on soil Fe availability that determines the key physiological functions and the subsequent plant growth and yield.

Keywords: Chlorophyll, durum wheat, grain quality, grain yield, iron deficiency, photosynthesis

1. Introduction

Wheat (*Triticum durum* Desf.) is the main agricultural crop in Tunisia. It occupies the first place with 1.6 million tons harvested from 1.27 million hectare cultivated in 2020-2021 (Ministry of Agriculture, water resources and fisheries). It occupies about 50% of the cereals area and represents almost 55% of the total cereals Product (Chebil et al, 2014). In the world, wheat feeds 40% of the population and provides 20% of the energy for human nutrition (Gupta et al, 2005). However, in addition to aridity, salinity and climate change affecting crop yield, soil quality represents a major factor hampering wheat yield. Calcareous soils are one of these problematic lands covering 45% of cultivated area in Tunisia (Mtimet, 2016). Approximately half of the agricultural crops in Tunisia are planted in calcareous soil or irrigated with water rich in calcium carbonate (pH> 7.5). Otherwise, iron solubility and availability in the soil can be affected by several factors, including pH, redox potential, microbial processes, and the amount of organic matter, leaching, and aeration (Becker and Asch, 2005). Numerous studies have demonstrated that, even if very abundant in the soil, Fe exist mainly in poorly bioavailable inorganic forms that cannot be efficiently absorbed by plants (Darbani et al, 2013; Briat et al, 2015; Tsai and Schmidt, 2017; Venutti et al, 2019). It represents a serious problem for wheat yield in Tunisian soils (Salhi et al, 2022; Zhang et al, 2020). Induced Fe deficiency was demonstrated associated to calcareous, alkaline soils where Fe availability is low (Barhoumi et al, 2021; Krouma et al, 2008; Krouma et al, 2023). The equilibrium concentration of total dissolved Fe was demonstrated lower than the concentration required for optimal growth of crops (Loeppert, 2008; Lindsay, 1979). Otherwise, Fe availability is significantly correlated with soil properties particularly pH, carbonate and bicarbonate ions and organic carbon content which majorly controls its availability (Krouma et al, 2023; Kumar et al, 2017). In sandy, acidic and light soils, nutrients and eventually iron are rapidly leached, inducing mineral (iron) deficiency (Huang and Hartemink, 2020). Mahmoud et al, (2022) stated that Fe deficiency is common in the poorly fertile soils (sandy soils) and in arid areas. These problematic soils are widely distributed globally, and particularly in the Tunisian wheat agrosystems.

In plant, Fe plays a key role in redox reactions of numerous metabolic processes such as photosynthesis, respiration and nitrogen assimilation besides being involved in chlorophyll biosynthesis and phytohormones (Marschner, 1995). Photosynthesis, as one of the most important physiological processes on the Earth, is susceptible to iron deficiency (Salhi et al, 2022; Barhoumi et al, 2021; Ouled et al, 2022). Iron is essential for electron flow through the PSII–Cytb6f– PSI complex (Hantzis et al, 2018). When plants are Fe-deficient, photosynthesis is affected, chlorophyll cannot be produced normally; typical Fe-deficiency symptoms appeared (yellowing of young leaves), then plant growth decreased (Barhoumi et al, 2021; Krouma et al, 2008; Krouma et al, 2023; Guo et al, 2022). Other authors have shown that Fe deficiency is identified as the major reason of crop yield hampering in different plant species (Connorton et al, 2017; Pal et al, 2019; Merry et al, 2022; Dhaliwal et al, 2022). Tagliavini and Rombolà, (2001) reported that Fe deficiency causes a decline of fruit yield and quality.

In this study, sidi Bouzid agrosystem, a typical semi-arid climate, and the durum wheat cultivar karim were taken as a model system to investigate the relationship between soil type and wheat behavior at vegetative and reproductive stages. This approach allows us to highlight the problematic agrosystems, identify the most convenient soil for wheat crop, establish necessary relationships between keys metabolic reactions and identify the useful traits of tolerance. The objective was to provide a technical guidance for nutrient management of wheat in Fe-problematic soils (calcareous and sandy soils).

2. Materials and methods

2.1 Plant Material and Experimental Design

one wheat (*Triticum turgidum* ssp. *durum*) cultivar provided for us by the National Institute of field crops, widely cultivated in Tunisia (Karim) was used. Three different soils representative of the region of Sidi Bouzid agrosystems were used: Sandy loam soil reputed to be among the most fertile (SLS) sampled in the highly productive agrosystem of Gatrana (Sidi Bouzid, 35 9052.36600 N 9 40023.68900 E), loamy soil but calcareous (L-CS) sampled in the agrosystem of Faiedh (sidi Bouzid, 35 4038.53600 N 9 40032.16700 E) and loamy sand soil (LSS) sampled in the agrosystem of wergha (Sidi BouZid, 34.787203 N 9.265738 E). Crops are conducted under natural light and temperature in plastic pots of 120* 120* 70 Cm dimension (length, width, height). Three pots per soil were planted with a total of 9 pots. Healthy grains of uniform size are germinated directly in the soil in the form of 10 Cm spaced rows containing 9 plantlets each (total of 100 plants per pot) with a final number of 300 plants in each soil. Table 1 illustrated the physicochemical characteristics of used soils.

Plants were irrigated with tap water and soil humidity was maintained at field capacity. Non-destructive measurements (SPAD index and gas exchange parameters) were made at vegetative stage before ear apparition. Then, ten representative plants from each pot were harvested, separated into shoots and roots, dried at 60°C for 72 h, then pulverized into fine powder for biomass quantification and iron analysis. The experiment ends after ear filling and grain maturity to evaluate yield and associated parameters.

2.2 SPAD index measurements

Relative leaf chlorophyll concentrations were estimated in vivo using a SPAD-502 (Konica-Minolta, Japan) before gas exchange measurements on the median fully expanded leaves. Measurements were made on ten plants for each pot and soil. Results are presented as means of 30 replicates per soil. Values are expressed as SPAD units.

2.3 Gas exchange measurements

Were made with a portable photosynthesis system CI- 340- USA. The induction of photosynthesis was censured by a saturating light of 1000 µmol m^{-2} s^{-1}. The other parameters were maintained constant, sample pCO_2 at 362 mbar, flow rate at 500 µmol $^{s-1}$, and temperature at 25°C.

2.4 *Active Fe determination*

Fe was extracted from powdered shoot and root samples digested using the HCl method; 25 mg of fine powder was digested in 5 mL of 1N hydrochloric acid solution for 3 days according to Köseoglu and Açikgöz, (1995), and then filtered. Fe content was determined by the atomic absorption spectrophotometer method.

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2.5 Yield evaluation

At maturity, ear of each soil plants were harvested, and a number of representative parameters are measured:

Ear length (Cm)
Number of grains per ear
Mean weight of 100 grains (g)
Percentage of ear filling (%)

Yield (quintals hectare^{-1}, q ha^{-1})

2.6 *Statistical Analysis*

The software StatPlus Pro was used to analyze data and statistics. All data are presented as the mean ± standard deviation error. An analysis of variance (ANOVA) was performed to determine whether the differences between factors are significant. Fisher's least significant difference test (LSD) at 5% was used. Significance was assigned when the difference between any two treatments was greater than the LSD value generated from the ANOVA. They are marked by different letters in the figures.

3. Results

After 30 days of cultivation, young leaves of plants grown on the loamy calcareous soil developed specific Fe chlorosis which increased gradually with time. Many days later, these symptoms appeared, even weak, in the loamy sand soil. No chlorosis was observed on plants cultivated on sandy loam soil. The SPAD index which reflects the chlorophyll level in leaves confirmed these observations. Figure 1A clearly showed that SPAD index decreased significantly on L-CS (- 35.2%) and with less effect on LSS (- 27.3%), as compared to SLS. Otherwise, plants grown on SLS displayed clearly a better development than those grown on LSS and L-CS. The quantification of biomass production demonstrated that plants growth decreased significantly on LSS (- 33.5%) and on L-CS (- 75%), as compared to SLS soil (Figure 1B).

The measurements made on gas exchange parameters demonstrated that wheat cultivation on L-CS and LSS significantly inhibited net photosynthetic assimilation (*Pn*), as compared to SLS soil. In fact, *Pn* decreased by 47.4% and 29.2%, respectively on L-CS and LSS, as compared to SLS (Figure 2). Stomatal conductance showed the same behavior with significant decrease in LSS (- 15%) and much more decrease on L-CS (- 25%), as compared to SLS (Figure 3).

In order to progress in the elucidation of the link between the observed physiological dysfunctions and the soil quality, we analyzed the active form of iron (Fe^{2+}) in plant organs. Figure 4 demonstrated that, compared to SLS, cultivation of wheat plants on L-CS and LSS decreased drastically Fe nutrition. In shoots, Fe concentration decreased by 60% in LSS and by 65.2% in L-CS, as compared to SLS. In roots, Fe concentration decreased by 48% in LSS and by 72% in L-CS, as compared to SLS.

When correlating plant growth with plant Fe content (Figure 5A) we obtained a strict positive relationship (R^2= 0.88) demonstrating the interdependence of biomass production and the available Fe in the plant. When comparing used soils, we reported the highest plant growth and Fe content in SLS, succeeded by LSS whereas L-CS provided plants with the lowest quantities of Fe producing lesser biomass accumulation.

In the same way, when correlating net photosynthesis with shoot Fe, we obtained the same behavior (R^2= 0.84, Figure 5B) demonstrating the close relationship between these two parameters. In addition, (Figure 5C) showed a stricter and positive relationship between plant growth and net photosynthesis (R^2= 0.99). Plants expressing higher photosynthetic activity developed better biomass production; condition seems accomplished in SLS but disturbed in LSS and particularly in L-CS.

To evaluate the impact of Fe-dependent soil quality on the different yield and grain quality parameters, we summarized the relevant traits in Table 1. The quantified yield demonstrated a very significant decrease in L-CS (- 87%) and significant decrease in LSS (- 51%), as compared to SLS. Ear length decreased by 23% in LSS and 46% in L-CS, Ear filling decreased by 8% in LSS and 52% in L-CS, and mean weight 100 grains decreased by 27% in LSS and 44% in L-CS, as compared to SLS.

In order to understand the mechanisms influencing Wheat yield in these problematic soils, a number of relationships were established between the key physiological functions and yield parameters. Figure 6 which correlates yield with plant growth (Figure 6A), net photosynthesis (Figure 6B) and with plant Fe content (Figure 6C) Showed a positive close relationship between all these parameters ($R^2 > 0.9$). Higher values of all these parameters are registered in SLS whereas the lowest values are registered in L-CS. Thus, we can suggest that soils providing plants with sufficient Fe developed important plant growth, higher photosynthesis and better yield.

To study the behavior of grain quality, we correlated mean weight 100 grains (MW100) with shoot Fe (Figure 7A) and with net photosynthesis (Figure 7B). In all case we obtained the same close relationship ($R^2 > 0.9$) suggesting that grain enlargement and lengthening is highly dependent on photosynthesis and available Fe. Thus, iron deficiency induced in L-CS, less pronounced in LSS, seems to affect wheat yield through the reduction of ear filling (number of grains per ear, Table 2) and the grain development.

4. Discussion

This study was conducted on Durum wheat cultivated on three different soils. At vegetative stage, loamy calcareous soil, and with a less extent loamy sandy soil was revealed problematic regarding iron nutrition. As compared to SLS, plant growth, SPAD index and photosynthesis are significantly hampered in parallel to a clear decline in Fe availability. Furthermore, plant growth, photosynthesis and iron nutrition have been shown to be interdependent (Fig 5). Grain yield and quality decreased significantly in LSS and L-CS, as compared to SLS, and remains highly dependent on plant growth, photosynthesis, and Fe uptake (Figs 6 and 7). It becomes clear that the general behavior of wheat plants depends closely on the soil quality, regarding iron availability. LSS and L-CS provide plants with insufficient Fe; thus, Fe-dependent metabolic reactions are slowed down with serious consequences on plant growth, and of course yield and grain quality. Despite the high total concentrations of Fe in all soils, this micronutrient undergoes oxidation and precipitates as compounds of low solubility, limiting its availability to plants (Kämpf et al, 2000). Numerous Authors reported similar results on the effect of iron deficiency on plant growth and grain yield (Audebert and Fofana, 2009; Chérif et al, 2009). The state of Fe oxidation and its bond to soil components, as well as the degree of crystallinity of the mineral, also affect its availability (Abreu et al, 2007). In fact, if we consider that SLS provide plants with the optimum needed iron, we can conclude that LSS provide plants by only 29% of its need for Fe whereas L-CS did not provide more than 9% of the plant's need for Fe. In accordance with these results, Mortvedt, (1991) reported that calcareous soil did not provide more than 10% of the plant need for Fe. Neutral and alkaline soils make the problem of Fe availability even worse. However, when this micronutrient is not available to the plants, frequent detection of yellowing of the upper leaves and a lower growth rate occurs (Jeong and Connolly, 2009). Connorton, (2017) stated that perturbations of Fe uptake, transport, or storage affects plant growth as well as crop yield. In fact, even if highly abundant in the soil, Fe exists mainly as oxyhydroxide polymers such as $Fe(OH)^{2+}$, $Fe(OH)_3$ and $Fe(OH)^-_4$. Low Fe solubility limits its uptake and accumulation by plants (Tsai and Schmidt, 2017).

In the current study, the significant decrease of iron uptake and accumulation in plants cultivated in L-CS and LSS can be explained by its oxidized-unavailable form. In fact, Fe availability is severely limited in calcareous soils due to their low solubility at high pH and bicarbonate concentration which reduces Fe uptake by plants (Najafi-Ghiri et al, 2013), whereas sandy soils often have low field capacity and high permeability and are susceptible to nutrients leaching (Huang and Hartemink, 2020). Mahmoud et al, (2022) stated that Fe deficiency is common in the poorly fertile soils (sandy soils) and in arid areas. Thus, we can suggest that the problematic soils in this study (LSS and L-CS) are clearly inducible of iron deficiency regarding the above-mentioned reasons. The observed symptoms of Fe chlorosis and the subsequent decline of chlorophyll, photosynthesis, biomass, and yield confirm our suggestion. Accordingly, chlorotic soybean plants often are substantially shorter than nonchlorotic plants, have reduced biomass, produced fewer seeds, and had lower yields (Froehlich and Fehr, 1981; Penas et al, 1990; Hansen, 2003). Several studies show that subjecting plants to direct iron deficiency leads to a significant reduction in growth and inhibition of chlorophyll (Barhoumi et al, 2021). Other studies have shown that this effect is essentially linked to the fact that Fe is directly involved in the biosynthesis of chlorophyll and therefore any reduction in the availability of this nutrient leads to a disturbance in the biosynthesis of this pigment (Pestana et al, 2001). The same behavior was described by Jolley and Brown, (1987) and Jolley et al, (2008) in soybean plants. Li et al, (2021) showed that iron deficiency directly leads to chloroplast degeneration and decreased chlorophyll biosynthesis. Assefa et al, (2020) showed that chlorosis caused by calcareous soils or high soil pH limits iron availability and adversely affects soybean (Glycine max) yield. Photosynthetic organisms convert light energy into chemical energy and store it in carbohydrates. To carry out this process, an acceptable rate of essential minerals, e.g. Fe, is a prerequisite in the chloroplast. Since iron plays a key role in electron transport and chlorophyll conformation, iron deficiency alters photosynthesis and promotes leaf chlorosis (Therby-Vale et al, 2022). Our finding suggests that iron deficiency observed in LSS and L-CS alters photosynthesis not only through its effect on chlorophyll biosynthesis and electron transport as previously discussed, but also through limited stomatal conductance (SC) that restrict C availability for Kelvin cycle. The significant decrease of SC observed in this study supported our suggestion (Fig 3). In fact, stomata are a basic plant-specific organelle for transpiration and respiration, and Fe significantly affected the stomatal size and upper epidermis thickness of leaves (Soundararajan et al, 2013; Shi et al, 2014). Fe-deficiency caused a smaller stomatal size, decreased the degree of stomatal opening, and affected the gas exchange of plants (Silva et al, 2020). Xiao et al, (2021) demonstrated that stomatal density increased with supplementary Fe treatments and indicates that Fe and pH influence stomatal density simultaneously. Otherwise, iron is an important cofactor for enzymes, plays an important role in plant photosynthesis, mitochondrial respiration, nucleotide synthesis and repair, regulation of metal homeostasis, and maintaining the structural integrity of various proteins (Mahender et al, 2019). Thus, any disturbance of plant Fe nutrition could have a direct consequence on photosynthesis, plant growth and subsequent yield and grain quality. Riaz, (2021) suggested that the impairment of Fe uptake, transport, or storage affect not only plant growth, but also crop yield and quality.

The overall observed physiological behavior of Durum wheat on LSS and L-CS, as compared to SLS remain strictly dependent on the available Fe from root uptake. The appearance of specific iron chlorosis and the associated keys metabolic reactions dysfunction (chlorophyll, photosynthesis, plant growth) takes a toll on yield and grain quality. In fact, Figure 6 has shown a strict relationship between yield and plant growth, yield and photosynthesis and between yield and accumulated Fe, whereas Figure 7 has shown a close relationship between grain quality (MW100) and shoot Fe, and between grain quality and photosynthesis. Thus, we can suggest that Durum wheat yield and grain quality is determined by the proper functioning of a system whose components are interdependent. Grain yield and quality is determined by plant growth which depends on the functioning of chlorophyll biosynthesis and photosynthetic activity whose remains strictly dependent on Fe supply. This last factor remains in close relationship with soil quality. The decreased ear length and ear filling reflects a clear effect on grain production (number of grains per ear) whereas the declined MW100 grains reflect the effect of Fe on grain quality. LSS and L-CS produced less and smaller grains, thus less yield, as compared to SLS. Merry et al, (2022) stated that Fe deficiency in soybean has been identified as the major reason of crop growth hampering with serious impact on productivity. Several studies have reported significant reductions in growth and yield of different plant species grown under Fe-deficient conditions (Mahmoudi et al, 2005; Norvell and Adams, 2006; Yousfi et al, 2007). Dhaliwal et al, (2022) reported that Soybean crop has shown high sensitivity to iron deficiency, and thus recorded major yield and nutritional quality losses. Froehlich and Fehr, (1981) evaluated 15 soybean genotypes on calcareous and noncalcareous soils and concluded that the highest-yielding genotypes on noncalcareous soil were among the lowest-yielding on the calcareous soil.

Taken together, our results demonstrated that in limited iron-availability soils, chlorophyll biosynthesis and photosynthesis are among the main repressed functions resulting in reduced vegetative growth and declined grain yield and quality. Thus, the significant decrease in wheat yield might be attributed to the decreased Fe availability for plant nutrition which hampered Fe- dependent physiological functions having an impact on grain yield and quality.

5. Conclusion

The present study focused on the physiological response of Durum wheat (*Triticum turgidum* ssp. *durum*) to the availability of iron in the rhizosphere regarding soil quality, and the subsequent grain yield. Obtained results demonstrated the close relationship between soil quality, plant behavior and crop yield. This system functions as a consistent continuum where the physiological behavior of the plant reflects strictly the available iron in the rhizosphere and determines yield. Iron deficiency observed in calcareous and sandy soils affect the overall Fe-dependent physiological parameters among which chlorophyll and photosynthesis influences plant growth and having expanses on yield. The limited iron availability in LSS and L-CS affect wheat yield by two ways: A significant decline of grain production, estimated by ear length and ear filling (%); and a drastic decrease of grain quality, estimated by MW100 grain. The two components lead to reducing yield, estimated by qxha^{-1}.

Conflict of interest

The authors declare that they have no conflict of interest.

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Tables

Table 1. physicochemical characteristic of used soils. SLS: Sandy loam soil, LSS: Loamy sand soil, L-CS: loamy calcareous soil

Parameters	**SLS**	**LSS**	**L-CS**
pH	7.9	8.9	9
Organic matter (%)	2.26	2.99	4.93
Active lime (%)	4.6	-	17.3
Total carbonates (%)	10.45	-	33.02
K (%)	1.148	1.14	0.632
Mg (%)	0.498	0.49	0.831
N (%)	0.62	0.62	0.42
C (%)	0.93	1.76	1.25
P (%)	0.144	0.19	0.22
Fe (%)	0.590	0.387	0.449
Clay (%)	7.6	11.2	8.2
Limon (%)	22.9	6.3	41.7
Sand (%)	69.5	82.5	50.1

Table 2. Yield and grain quality traits in durum wheat cultivated on sandy loam soil (SLS, loamy sand soil (LSS) and loamy calcareous soil (L-CS).

Yield parameters	**Yield (qx ha^{-1})**	**Ear lengh (Cm)**	**Earfilling (%)**	**MW100 grains (g^{-1})**
SLS	34.3± 2.4^{a}	13± 0.91^{a}	87.5± 6.7^{a}	5,6± 0.45^{a}
LSS	16.8± 1.01^{b}	10± 0.86^{b}	80.5± 6.5^{b}	4,1± 0.33^{b}
L-CS	4.6± 0.31^{c}	7± 0.57^{c}	42.4± 2.3^{c}	3,7± 0.21^{c}

Figures

Figure 1. Effect of induced iron deficiency on SPAD index (A) and dry weight production (B) in Tunisian wheat (*Triticum turgidum* ssp. *durum*) grown on different Fe- deficient soils. SLS: sandy loam soil, LSS: loamy sand soil, L-CS: loamy calcareous calcareous soil. Within columns, means with the same letter are not significantly different at α = .05 according to Fisher's least significant difference. Bars on the columns represent the standard error of the mean (n = 10).

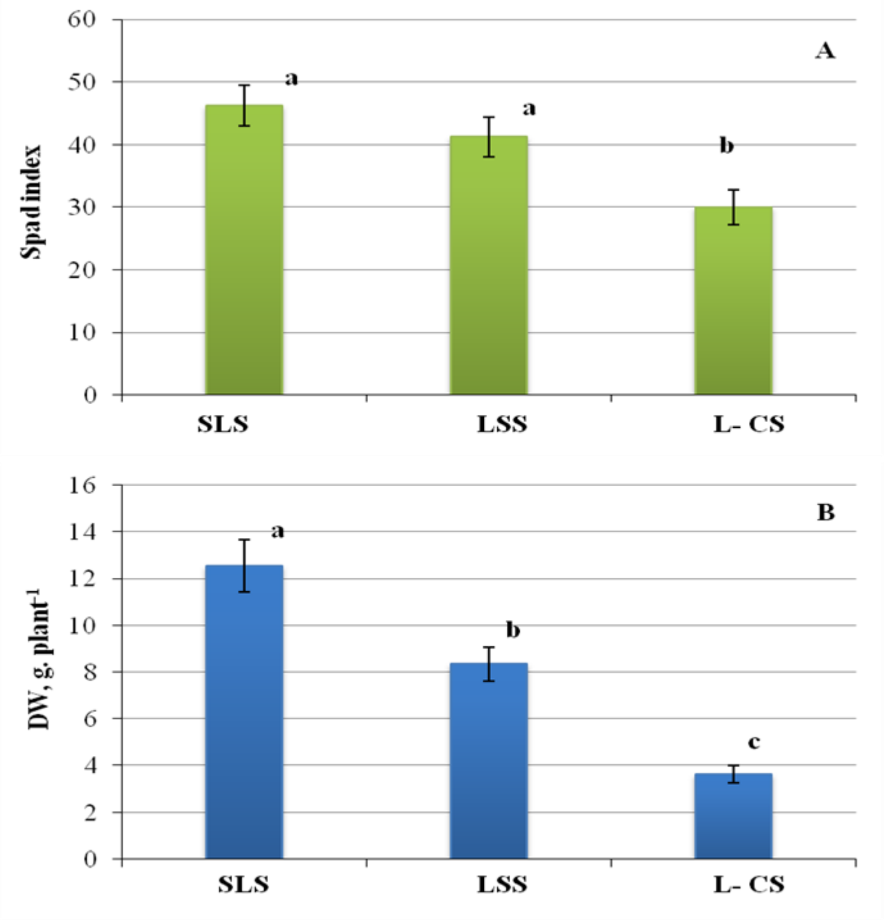

Figure 2. Net photosynthesis activity (*Pn*, µmol CO_2 m^{-2s-1}) in Tunisian wheat (cultivar karim) grown on different Fe- deficient soils. SLS: sandy loam soil, LSS: loamy sand soil, L-CS: loamy calcareous calcareous soil. Within columns, means with the same letter are not significantly different at α = .05 according to Fisher's least significant difference. Bars on the columns represent the standard error of the mean (n = 10).

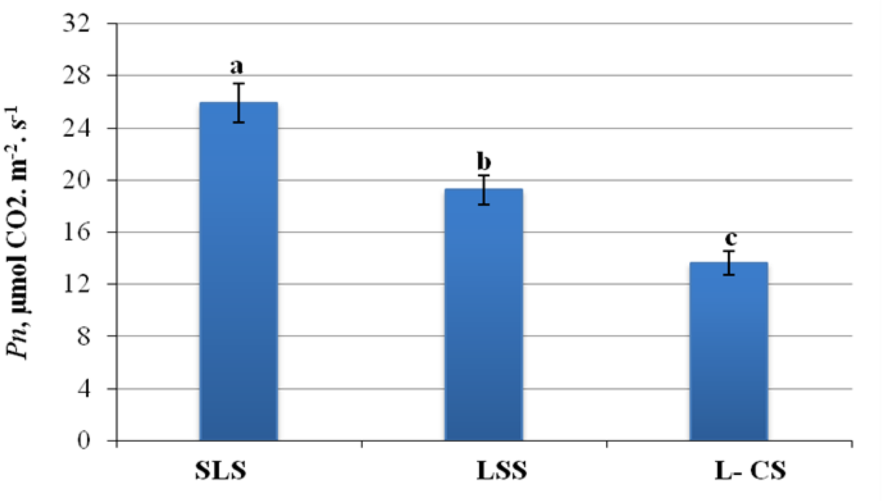

Figure 3. Stomatal conductance (SC, mmol H_2O m^{-2s-1}) in Tunisian wheat (cultivar karim) grown on different Fe- deficient soils. SLS: sandy loam soil, LSS: loamy sand soil, L-CS: loamy calcareous calcareous soil. Within columns, means with the same letter are not significantly different at α = .05 according to Fisher’s least significant difference. Bars on the columns represent the standard error of the mean (n = 10).

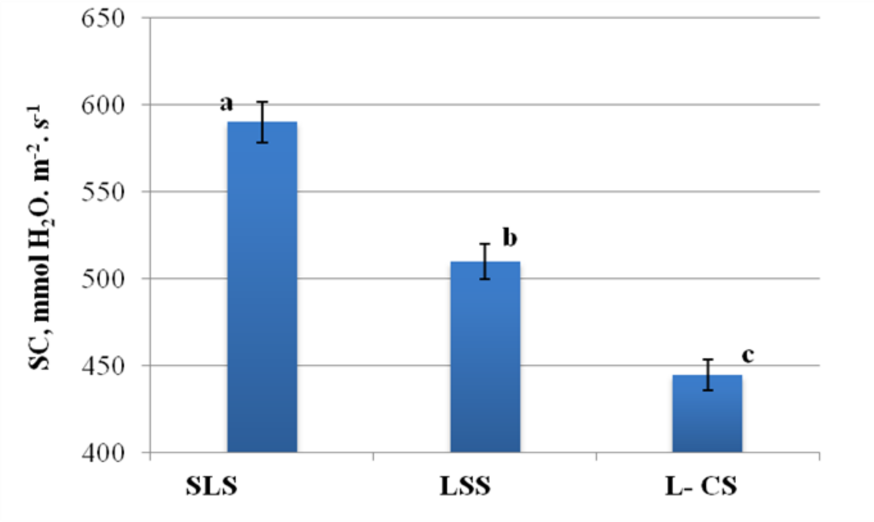

Figure 4. Active iron (Fe^{II}) concentration in the plant organs (µg g^{-1} DW) of Tunisian Durum wheat cultivated on sandy loam soil (SLS), loamy sand soil (LSS), and loamy calcareous soil (L-CS). Within columns, means with the same letter are not significantly different at α = .05 according to Fisher's least significant difference. Bars on the columns represent the standard error of the mean (n = 10).

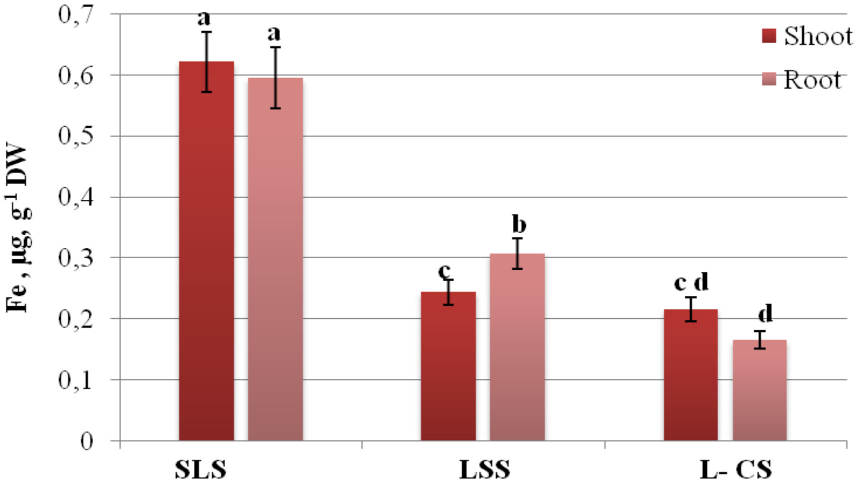

Figure 5. Relationship between plant growth and plant Fe content (A), net photosynthesis and shoot Fe (B), and between plant growth and net photosynthesis (C) in Durum wheat cultivated on different Tunisian soils. SLS: sandy loam soil, LSS: loamy sand soil, L-CS: loamy calcareous calcareous soil. Vertical and horizontal bars represent the standard errors of the mean (n= 10) at α = 0.05.

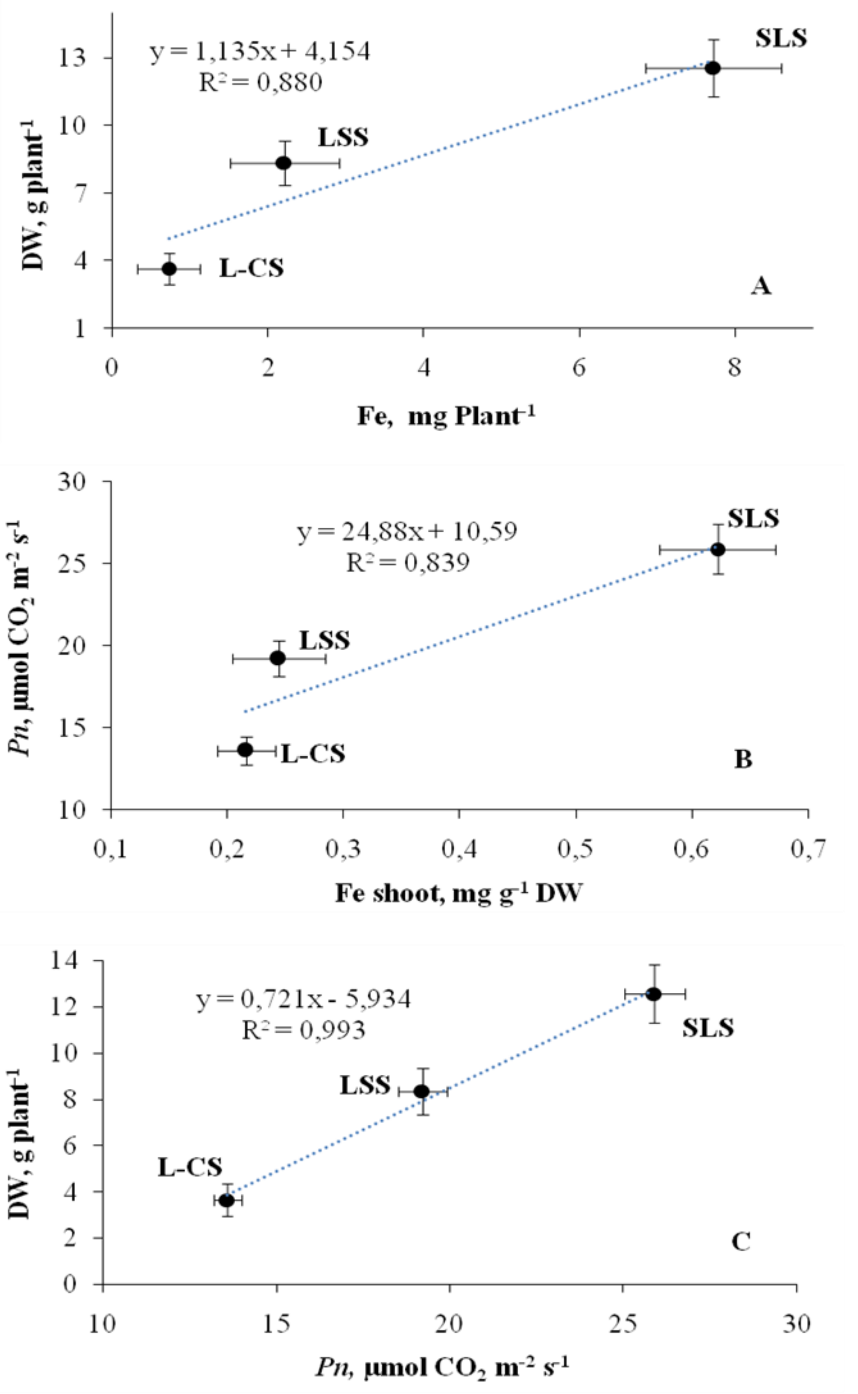

Figure 6. Relationship between grain yield and plant growth (A), grain yield and net photosynthesis (B), and grain yield and plant Fe content (C) in Durum wheat cultivated on different Tunisian soils. SLS: sandy loam soil, LSS: loamy sand soil, L-CS: loamy calcareous calcareous soil. Vertical and horizontal bars represent the standard errors of the mean (n= 10) at α = 0.05.

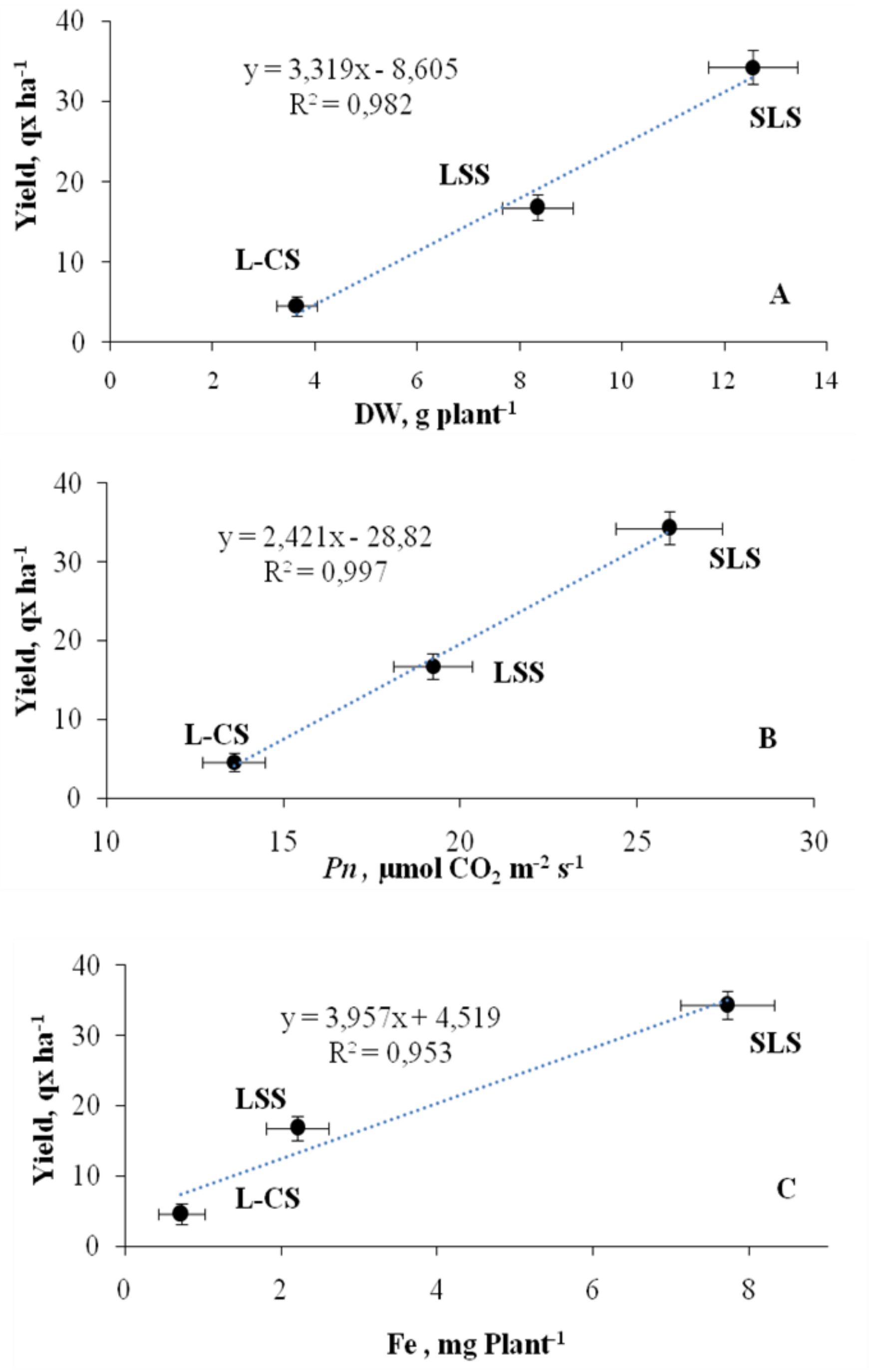

Figure 7. Relationship between grain qualities estimated by mean weight 100 grain (MW100) and shoot Fe (A) and between grain quality (MW100) and net photosynthesis (B) in Durum wheat cultivated on different Tunisian soils. SLS: sandy loam soil, LSS: loamy sand soil, L-CS: loamy calcareous calcareous soil. Vertical and horizontal bars represent the standard errors of the mean (n= 10) at α = 0.05.