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# Integrated effect of saline water irrigation and phosphorus fertilization practices on wheat (*Triticum aestivum*) growth, productivity, nutrient content and soil proprieties under dryland farming

Hamza Bouras[a], Achraf Mamassi[b,c,*], Krishna Prasad Devkota[d], Redouane Choukr-Allah[c], Bassou Bouazzama[e]

[a] Department of Crop Production, Protection and Biotechnology, Hassan II Institute of Agronomy and Veterinary Medicine, Rabat 10101, Morocco
[b] Spheres Research Unit, University of Liege, Arlon B-6700, Belgium
[c] Agricultural Innovation and Technology Transfer Center (AITTC), Mohammed VI Polytechnic University (UM6P), Ben Guerir 43150, Morocco
[d] International Center for Agricultural Research in the Dry Areas (ICARDA), Rabat, Rabat, Morocco
[e] National Institute for Agricultural Research (INRA), Beni-Mellal 23020, Morocco

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ABSTRACT

Wheat (*Triticum aestivum*) is the most common and oldest crop in Morocco and MENA region countries, cultivated both for human and animal nutrition. In Morocco, the irrigated perimeter of Tadla is the major wheat growing area affected by soil and groundwater salinity problematic. Previous studies have shown that phosphorus (P) fertilization can mitigate the negative effects of salinity on different crops. Thus, field experiments from the combination of four levels of irrigation water salinity and three P-fertilization rates were conducted during two successive growing seasons (between 2019 and 2021) at the National Institute of Agronomic Research (INRA), Tadla, Morocco. Our main objective was evaluating the potential of P-fertilization to improve wheat growth, productivity and quality under saline water irrigation practices. The crop simulation model APSIM, was also tested to assess its performance in simulating wheat growth, productivity, phosphorus and nitrogen nutrient dynamics in soil-plant system under saline conditions. Results showed that appropriate P-fertilization under saline conditions contributed to minimize the effect of salinity and improved wheat growth and production. Also, it was found that increasing P-fertilization improved nutrient uptake, and consequently the plant nutrient content. A good agreement between the measured and APSIM model simulated growth and yield state variables, as well as the plant and soil-N content. However, a model uncertainty and relevant limitations in simulating plant- and soil-P content output were identified and discussed. Overall, our finding suggests that appropriate P-application minimizes the adverse effects of high soil salinity and can be adopted as a coping strategy in wheat cultivation under saline water irrigation practices.

## 1. Introduction

Globally, salinity affects more than 800 million hectares of land, accounting for 6% of the earth's total land area and 20% of the total cultivated land area (Munns and Tester, 2008). Soil salinity stress adversely affects plant growth and development and causes considerable losses in cereal crop production worldwide (Kumar et al., 2022). In future, saline region is anticipated to increase due to the adoption of excessive amounts of saline water irrigation practices, particularly in arid and semi-arid regions where the evapotranspiration rate is higher than precipitation (Jha et al., 2019; Wang et al., 2019; Zhang et al., 2021). Soil salinity is the high concentration of soluble salts in soils: more than 4 $dS.m^{-1}$ electric conductivity (Munns et al., 2006). Soil salinity affects productivity by affecting growth and development; physiological processes such as decline in photosynthetic capacity (El-Hendawy et al., 2009) and decline in nutritional values in wheat (Hussain et al., 2022): which causes yield reduction by more than 60% (El-Hendawy et al., 2017). Wheat is considered moderately tolerant to salinity (6 $dS.m^{-1}$), however, the threshold varies depending on the crop growth stage and crop management practices. The inhibition of plant growth under high salinity conditions is related not only to changes and imbalances of ions in the soil solution but also to poor water availability

* Corresponding author at: Spheres Research Unit, University of Liege, Arlon B-6700, Belgium.
*E-mail address:* achraf.mamassi@uliege.be (A. Mamassi).

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for uptake. High salt concentrations in the soil solution lower the soil water potential, which in turn leads to a higher leaf water potential (El-Hendawy et al., 2017).

Similarly, salinity affects soil nutrient dynamics and its availability and uptake to the plant. It reduces soil fertility and crop productivity by affecting several soil nutrients, such as inducing P deficiency (Ding et al., 2020); influencing N metabolism, including N uptake; reducing $NO_3^-$ and impacting $NH4^+$ assimilation (Ashraf et al., 2018), and declining soil osmotic potentials and lowering water absorption (Irshad et al., 2002). Excessive $Na^+$ ions and high pH induced swelling and dispersion of clays as well as slaking of soil aggregates decrease soil permeability, available water capacity, and infiltration rate (Lakhdar et al., 2009). The accumulation of salt in the root zone causes the development of osmotic stress and alters the homeostasis of cell ions by inducing both the inhibition of uptake of essential plant elements such as $K^+$, $Ca^{2+}$ and $NO_3^-$ and the accumulation of $Na^+$ and $Cl^-$ (Ahanger and Agarwal, 2017; Machado and Serralheiro, 2017). Depending on the severity of salt stress, addition of a limiting nutrient could improve salt tolerance and increase plant growth (Grattan and Grieve, 1998). Disparities in uptake and translocation of different ions vary with crops and fertilizer application rate and consequently with plant tolerance to salinity (Bouras et al., 2022b, 2021a; Wagdi et al., 2013).

Phosphorus (P) is one of the major plant nutrients, and its deficiency substantially reduces plant growth and production (von Tucher et al., 2018). P is involved in many plant physiological processes including photosynthesis, energy transfer, and synthesis of antioxidants (Tang et al., 2019). In most cases, salinity decreases P concentration in plant tissue. The salt stress intensifies the adverse effects on P uptake (Sahin et al., 2018). Also, under a high saline environment, the translocation of P from root to shoot is inhibited (Shahriaripour et al., 2011). The plants P-uptake under salt stress is influenced by many parameters like the plant species, growth stage, degree and extent of stress, temperature, moisture, soil pH, and the prevailing soil P level (Roy and Chowdhury, 2020). The increases in plant concentrations of $Na^+$ and $Cl^-$ reduce N and P concentrations due to the antagonistic relations of $Na^+$ and $Cl^-$ with plant-N and -P available forms (i.e., ammonium ($NH_4^+$), nitrate ($NO_3^-$), and phosphate ($H_2PO_4^-$) etc.) (Maksimovic and Ilin, 2012; Roy and Chowdhury, 2020; Sahin et al., 2018). Fertilization management is considered an effective strategy to alleviate the adverse effect of salt stress, mainly by improving nitrogen (N), phosphorus (P), and potassium (K) availability in soils (Colla et al., 2008; Wang et al., 2021). Also, the appropriate P supply is considered an effective way to alleviate the damage of salt stress (Bouras et al., 2021b), and increased biomass and P accumulation in plant organs (Wang et al., 2021).

The complex processes of crop-P nutrition depend on soil chemical and physical characteristics, soil management practices, crop root activities as well as climatic conditions (Raymond et al., 2021); and the crop recoveries of applied P vary from 10 to 80% (Wang et al., 2014). In the case of Morocco, P-use-efficiency (PUE) fractions were often very low primarily due to the dominance of alkaline soils (pH exceed 8 in most cases) (Iaaich et al., 2021; Ruellan, 1971), which intensify the sorption reactions of P with $Ca^{2+}$ and form less soluble or insoluble P. Consequently, a long-term experiments or monitoring farmers' fields is required to understand the P dynamics in soil-plant systems. Crop simulation models with capabilities to simulate soil-plant P dynamics can help to understand the crop response to P fertilization practices (Delve et al., 2009; Raymond et al., 2021; Wang et al., 2014). They offer an opportunity to understand the interactions among soils, management practices, and climatic conditions in crop response to P and assess P-use-efficiency using short or long-term experiments data (Wang et al., 2014). The Agricultural Production Systems Simulator (APSIM) (Keating et al., 2003) is among the most widely used models for increased understanding of cropping system functioning as affected by phosphorus fertilization. The Soil-P module is the specific APSIM component that allowed integrating P dynamic in soil and P fertilization practices and assessing their effect on crop growth, development and productivity (Keating et al., 2003).

This research study was conducted to better understand the wheat growth, productivity, and physiological development as affected by saline water irrigation practices under different P-fertilization rates in semi-arid regions. Our detailed objectives were: (i) evaluating the impacts of P supply on wheat growth and production under various levels of salinity conditions, (ii) examining the P application effect on plant tolerance to salinity (physiological traits), and (iii) testing the APSIM-wheat model in simulating wheat growth and productivity parameters as well as P and N dynamics in soil-plant system and under different P-fertilization rates.

## 2. Materials and methods

### 2.1. Experimental site

The experiment was conducted in a semi-arid region; the irrigated Tadla plain of Morocco, between November 2019 and July 2021. It was conducted in an experimental farm of the National Institute of Agronomic Research (INRA) (latitude = 32.2° N; longitude = 6.31° W; altitude = 450 m). The soil of the experimental site is classified as Chromic Luvisols (Debbarh and Badraoui, 2002) and the climate of the site is semi-arid with high rainfall variability. The average annual rainfall of 286 mm and the average temperature 18 °C with the highest recorded temperature in August, which often exceeds 45 °C, and the lowest in January which range up to -3 °C.

### 2.2. Initial soil and water characteristics

Before wheat sowing, the soil analyses at two soil depths were performed following the protocol described by Jackson (Jackson, 2005) (Table 1). The electrical conductivity (EC) of the soil as measured using the soil-saturated paste method with an EC meter (HI 9812. Hanna Instruments. Casablanca. Morocco) (Table 1) showed soil is non-saline as the initial EC values were relatively low (Shahid et al., 2018). Similarly, the initial analysis of the irrigation water value was below 1 $dS.m^{-1}$ and the water is categorized as fresh (non-saline) (Table 2).

### 2.3. Experimental design, treatments, and crop management

The field experiment was conducted using a split-plot design with three repeats, applying four salinity levels of irrigation water in the main-plot, and three P-fertilization rates in sub-plots (Fig. 1). The evaluated salinity levels were freshwater with an EC value of 0.7 $dSm^{-1}$ (the control) and three levels of saline water with an EC of 4, 8, and 12 $dS.m^{-1}$. Salinity levels were achieved by adding salt (NaCl) to freshwater (Table 2). The P-fertilization rate consisted of 85 kg $P_2O_5$ $ha^{-1}$ (the control and the recommended rate used by farmers), 102 (plus 20%), and 120 kg $P_2O_5.ha^{-1}$ (plus 40% of recommended rate) were used. The area of the individual plot was 20 $m^2$ (4 × 5 $m^2$), and soft wheat variety "Achtar" was used. For P fertilizer, triple superphosphate (45% of $P_2O_5$) was applied, which is commonly used in the region. P-fertilizer was incorporated into the soil before sowing during the soil preparation, which consisted of a deep ploughing using disc plough followed by a shallow ploughing (Fig. 1).

Other fertilizers (i.e., N and K) were applied equally for all treatments through fertigation with a drip irrigation system using integrated drippers with a discharge rate of 2 L $h^{-1}$ and a distance of 40 cm between drippers. Irrigation with saline water started 35 days after planting, and the crop was irrigated daily until harvest dates: 01 July 2020 for the first season and 20 June 2021 for the second season. The amount of irrigation water matched with the amount of potential evapotranspiration. Saline irrigation solutions were prepared in a separate tank of 1 $m^3$ before each irrigation and irrigation water EC was monitored using EC meter (Fig. 1). During the first season, wheat crop was sown on 25 November 2019 and harvested on 1 July 2020, while in the second season, the sown

**Table 1**
Initial soil characteristics in the experimental site Tadla.

| Soil Depth (cm) | Clay (%) | Silt (%) | Sand (%) | Soil pH | pH | | EC ($dS \cdot m^{-1}$) | Organic matter (%) | Total N (Kjeldahl) ($g.kg^{-1}$) | $P_2O_5$ (Olsen) ($mg.kg^{-1}$) | $K_2O$ (Acetate of Na) ($mg.kg^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Water | KCl | | | | | |
| 0–20 | 28.1 | 52.8 | 19.1 | 7.92 | 8.24 | 7.36 | 0.1 | 1.45 | 2.34 | 43 | 459 |
| 20–40 | 43.1 | 18.7 | 38.2 | 8.09 | 8.38 | 7.24 | 0.22 | 0.59 | 3.44 | 22 | 405 |

**Table 2**
Irrigation freshwater chemical analysis.

| EC ($dS.m^{-1}$) | pH | Cations ($meq.l^{-1}$) | | | | Anions ($meq.l^{-1}$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $Ca^{2+}$ | $Mg^{2+}$ | $Na^{+}$ | $K^{+}$ | $Cl^{-}$ | $SO_4^{2-}$ | $CO_3^{2-}$ | $HCO_3^{-}$ | $NO_3^{-}$ |
| 0.7 | 7.4 | 2.4 | 3.9 | 2.29 | 0.001 | 2.25 | 0.54 | 1.2 | 4.3 | 0.12 |

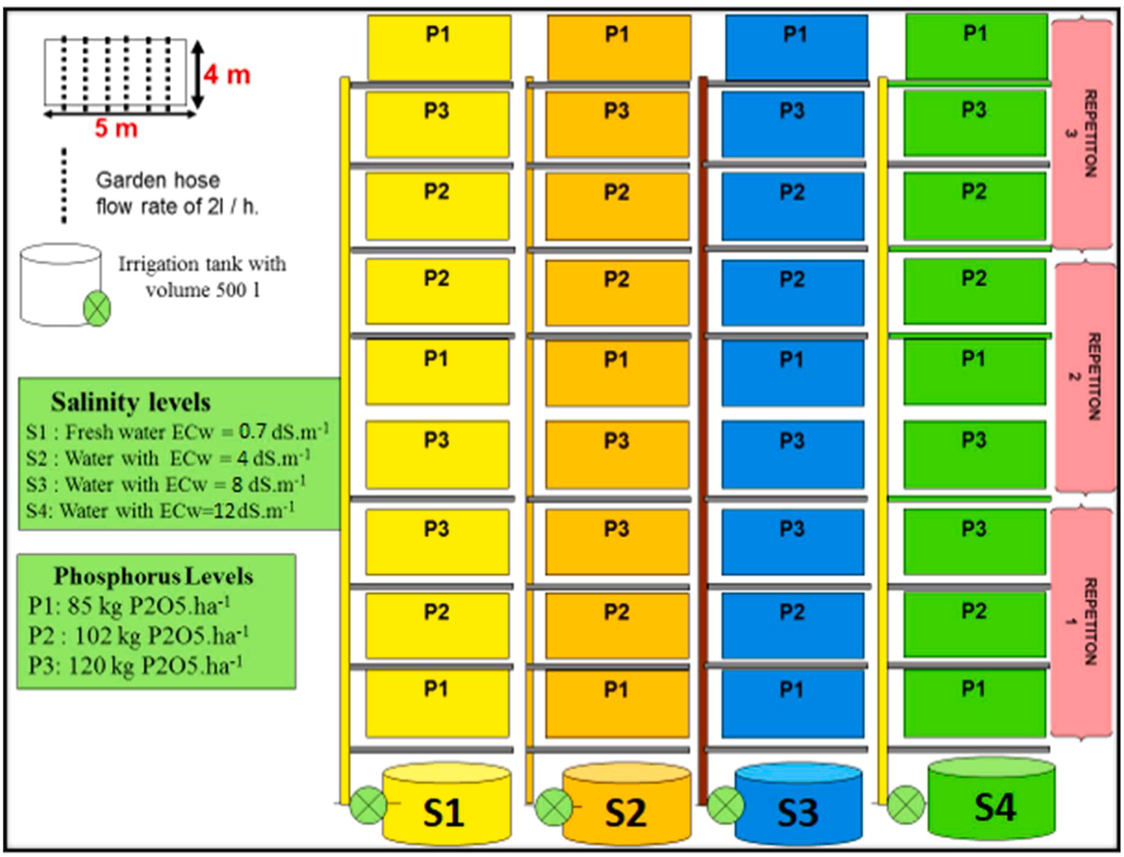


**Fig. 1.** Schematic view of the irrigation water tanks laid out for using irrigation in the experimental plots.

date was on 25 November 2020 and the harvesting date was on 20 June 2021. The soil was supplemented with a total quantity of 200 kg $N.ha^{-1}$. About 80 kg. N $ha^{-1}$ was applied at soil preparation using ammonium sulfate and 120 kg N. $ha^{-1}$ using ammonium nitrate through fertigation system during the growing period.

### *2.4. Observation collected*

#### *2.4.1. Stomatal conductance*

Stomatal conductance was measured using the SC-1 Leaf Porometer (Decagon Devices. Inc. Pullman. WA 99163. USA). It was determined between 10 am and 13 pm on the upper leaf surface well exposed to sunlight. Twice for each cropping season, one measurement per plant was carried out for four plants per plot.

#### *2.4.2. Wheat yield and growth attributes*

The dry matter yield at harvest was measured from the whole plot area (20 $m^2$) and then extrapolated to $t \cdot ha^{-1}$. Wheat growth and yield components, including root weight and length, plant height, shoot fresh weight and leaf number and area were determined from 1 $m^2$ area. The sun-dried grain yield was measured at harvest from 3 × 4 $m^2$ quadrant (12 $m^2$).

#### *2.4.3. Leaf mineral content*

Samples of fresh leaves were collected at the wheat anthesis stage, and the samples dried at 70 °C until they reached a constant weight before grinding into a fine powder for macro and micronutrient concentration analysis. Total nitrogen (N) was determined using the microKjeldahl method. Potassium ($K^{+}$) and sodium ($Na^{+}$) in leaves were determined in plant samples by a wet digestion procedure using a mixture of nitric acid and perchloric acid with a ratio of 2:1 using a flame photometer according to the method described by Chapman and Pratt (1961). P (%) was determined by colorimetry using the stannous chloride and ammonium molybdate reagent as described by Jackson (2005) after its extraction with sodium bicarbonate according to Olsen (1954). Calcium (Ca), Magnesium (Mg), Iron (Fe), and Zinc (Zn) were determined in plant and soil samples using methods described by Ryan et al. (2001). Finally, organic matter (OM) was measured following the dry combustion method using an elemental analyser.

#### 2.4.4. In situ measurement of soil salinity

In situ EC was measured using conductivity meter that allowed to measure soil EC in six different soil depths at the interval of 10 cm from 0 to 60 cm depth. It was measured at the end of experimentation after the crop harvest on July 2021.

### 2.5. Statistical analysis

Statistical analysis was carried out using SPSS software version 17.0. A two-way analysis of variance (ANOVA) was conducted to assess the effects of both salinity and P-fertilization on measured parameters. Before conducting the ANOVA, the normality of the data distribution was examined for dry matter and grain yield using the Shapiro–Wilk test. ANOVA combined over the season was performed as the season x treatment effect was no-significant: the level of significance was set to $p < 0,05$. The treatment mean differences were analyzed using Tukey's test ($p \leq 0.05$). Also, correlation and multivariate analysis were performed using the statistical programming language R version 4.0.5. The "corrplot" package was used to display the Pearson correlation matrix values among variables, and the level of significance was set to $p < 0.05$.

### 2.6. Simulation modelling using APSIM-wheat model

#### 2.6.1. APSIM crop simulation model

APSIM is a process-based model capable of simulating crop growth and development, nutrient dynamics and water balance considering climate, soil, crop, and crop management processes, which can be used to generate different scenarios of outputs under Genotype x Environment x Management interactions (Holzworth et al., 2014; Keating et al., 2003). APSIM is one of the highly applied cropping system models to carry-out studies related to the evaluation and improvement of crop management strategies such as fertilization (Ahmed et al., 2016; Takahashi et al., 2021), irrigation (Balwinder-Singh et al., 2011), pest management (Castaldi and Casa, 2016), crop rotation (Chen et al., 2008) etc. The detailed development history of APSIM is reported in Halzworth (2014). APSIM-wheat, the wheat version of APSIM model, was used in the present study. "Achtar" wheat cultivar coefficients values from APSIM-wheat calibration study as derived by Mamassi et al. (2022), were directly used in the current study to testing the robustness of APSIM-wheat in simulating the crop productivity, as well as the P and N dynamics' output parameters in soil-plant system under different P-fertilization rates during two crop seasons (2019/2020 and 2020/2021) experiment.

To evaluate the performance of APSIM model simulations, we have computed and interpreted different performance metric indices: the coefficient of determination ($R^2$), the root mean square error (RMSE), and the normalized root mean square error (NRMSE). (RMSE) and (NRMSE) were calculated using Eq. (1) and Eq. (2), respectively.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[x_{s_i} - x_{m_i}\right]^2} \tag{1}$$

$$\mathrm{NRMSE} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[x_{s_i} - x_{m_i}\right]2}}{\overline{x}_m} \times 100 \tag{2}$$

where $x_{m_i}$ are the measured values, $x_{s_i}$ are the simulated values, $x_m$ is the mean of the observed values, and n is the number of observations.

#### 2.6.2. APSIM soil-P module

The APSIM Soil-P module define the plant-available P by the P-sorption characteristics of a soil and based on the Freundlich sorption equation, which indirectly relate the labile-P pool to the soil solution P (secondary pool of labile-P) using two sorption coefficients (a and b). In other words, the P supply available for plant uptake is a function of soil solution P that is directly linked to the labile-P pool and defined by the sorption process. Then, the plant module calculates the crop P demand (crop P-uptake) that will be provided from the soil P supply (calculated by Soil-P module in each layer). Two other pools interfere with labile-P pool in the APSIM Soil-P module: unavailable organic-P and unavailable inorganic-P. The labile-P and unavailable organic P pools are connected by mineralization and immobilization movements influenced by water and temperature. The unavailable organic-P pool is estimated from the soil organic matter (SOM) pool and the C:P ratio. Labile-P pool and unavailable inorganic P pool are linked by slow exchange rate called loss or gain of availability; it is an analogous of P precipitation and dissolution processes. A relative "rate loss available" coefficient (r) used to both calculate the loss and the gain of available P, respectively, from the labile-P pool to the unavailable inorganic P pool and the reverse. Finally, the P fertilizer input rate is connected directly to the labile-P taking into account differentiation in the placement method (banded or broadcasted) and the type of fertilizer used (water-soluble or P-rock). More details about APSIM Soil-P structure is reported in Kinyangi et al. (2004) and Wang et al. (2014).

In the present work, wheat P demand represented by the P concentration limits of plant organs at different stages (i.e., minimum and maximum P concentrations in plant dry matter) were required as parameters to activate the phosphorus component for APSIM-wheat model. The values of wheat P concentration limits were derived from the database of Wang et al. (2014), which was created using experimental measurements on wheat crop (from Elliott et al. 1997; Rose et al. 2007; Bolland and Brennan 2008). Labile-*P* value was initialized from the pre-season measured soil Olsen-P (available-phosphorus) values, using linear factor reported in (Micheni et al., 2004) that relate the Labile-P pool with Olsen-P soil test. Raymond et al. (2021) and Wang et al. (2014) have adjusted the sorption coefficients (a and b) and rate loss available (r) coefficient, for Australian Vertisols and Red Ferrosols characterized by neuter to high alkalinity, to match the high simulation efficiency not only for wheat yield and biomass estimation, but also soil P dynamic simulation. Actually, these soil types are common in Morocco, and known by other names as "Tirs" for Vertisols (Moussadek et al., 2017) and "Hamri" for Ferrosols. Thus, we have directly adopted those Australian extracted coefficients, and based on each site-specific soil proprieties, we have parametrized the Soil-P module for the Moroccan fields.

## 3. Results

### 3.1. Analysis of variance of growth and physiological parameters

Table 3 summarizes the results of the analysis of variance (ANOVA) of measured growth and physiological parameters as affected by saline water irrigation and P-fertilization rates during the two growing seasons. Salinity has affected ($p < 0.05$) all parameters in both years. P-fertilization also has influenced ($p < 0.05$) most of the parameters except stomatal conductance, straw yield and harvest index during the first growing season 2019/2020. During the second growing season, P-fertilization has an effect on the most parameters except, stomatal conductance, total dry matter, yield, tillers, and straw yield. The interaction (salinity × P fertilization) effect was significant for 1000-grain weight, grain yield parameters and harvest index during the first growing season. However, the interaction effect was no-significant

**Table 3**
Results of ANOVA (analysis of variance) for all investigated parameters during 2019–2020.

| Season | Salinity and P rates | Stomatal Conductance | Dry matter yield | Leaf area | Root length | Tillers | 1000 grain weight | Grain yield | Straw yield | HI |
|---|---|---|---|---|---|---|---|---|---|---|
| 2019-2020 | Salinity | 0.042** | 0.023* | – | – | – | 0.001** | 0.001** | 0.002** | 0.001** |
| | Phosphorus | 0.06 | 0.001** | – | – | – | 0.002** | 0.001** | 0.504 | 0.341 |
| | Interaction | 0.67 | 0.299 | – | – | – | 0.002** | 0.002** | 0.67 | 0.006** |
| 2020-2021 | Salinity | 0.001*** | 0.038* | 0.001** | 0.027* | 0.001** | 0.001** | 0.001** | 0.029* | – |
| | Phosphorus | 0.612 | 0.136 | 0.001** | 0.001** | 0.878 | 0.001** | 0.001** | 0.12 | – |
| | Interaction | 0.99 | 0.32 | 0.13 | 0.697 | 0.999 | 0.1 | 0.44 | 0.41 | – |

Significance levels are as follows: *$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$

during 2020/2021.

Monitored plant growth parameters for both seasons are presented in Table 4. Under irrigation with saline water, stomatal conductance, root length, leaf area, straw, number of spike, shoot water content, and leaf area showed an average reduction by 3 to 26%. Conversely, root length increased by 16, 14 and 10% under moderate (4 dS·m$^{-1}$) and high salinity (8 and 12 dS·m$^{-1}$), respectively as compared to the fresh water. The salinity has contributed to reduce grain weight by 3, 6 and 8 %, respectively, under 4, 8 and 12 dS.m$^{-1}$ as compared to the control. Irrigation water salinity has also diminished the leaf area by 4, 23 and 23 % under 4, 8 and 12 dS.m$^{-1}$, respectively. Increasing P fertilization under salinity conditions has improved all growth parameters ($p \leq 0.05$), in which the highest values of most parameters were obtained when the plant was supplied with 120 kg $P_2O_5$·ha$^{-1}$ of P fertilization. For example, an application of 120 kg $P_2O_5$·ha$^{-1}$ resulted in an average increase in weight of grain by 12, 2, 5 and 3 % under 0.7, 4, 8 and 12 dS·m$^{-1}$, respectively, compared to control (85 kg $P_2O_5$·ha$^{-1}$). The P supply with rate of 120 kg $P_2O_5$·ha$^{-1}$ was significantly improved leaf area and root length. This increment was by 13, 26, 16 and 63 % for leaf area, and by 9, 13, 24 and 21 % for root length, respectively at 0.7, 4, 8 and 12 dS.m$^{-1}$.

### 3.2. Stomatal conductance

The combined data over two years showed that salinity has reduced the stomatal conductance by 35, 27 and 39% under saline irrigation with EC values 4, 8 and 12 dS·m$^{-1}$, respectively compared to control (0.7 dS·m$^{-1}$) (Table 4, Fig. 3). It is obvious from the obtained results that increased P fertilization significantly improved stomatal conductance under saline conditions for both seasons 2020 and 2021. For example, an application of 120 kg $P_2O_5$·ha$^{-1}$ resulted in an average increase in stomatal conductance by 5, 8, 12 and 18 % under 0.7, 4, 8 and 12 dS·m$^{-1}$, respectively compared to control (85 kg $P_2O_5$·ha$^{-1}$).

Fig. 2 shows the correlation between several measured parameters. There was a significant correlation between salinity and several measured parameters such as OM, N, P, K, Ca, Na and Cl. The correlations of those parameters with Ca, Na and Cl were positive, while the correlations were negative with OM, N and P. Accordingly, the leaf-$Na^+$ content had a significant positive correlation with K, Mg, Ca and Zn, whereas, it had a negative effects on N, P and Ca.

### 3.3. Total dry matter yield

Fig. 4 illustrates the variation of dry matter yield influenced by both salinity and P fertilization rates. It is clear that the salinity has decreased dry matter yield, and the average reduction rate over the two seasons were 6, 8 and 18% for first growing season and by 7, 9 and 21% for the second season compared to control under irrigation water salinity equal, respectively, to 4, 8 and 12 dS·m$^{-1}$. However, the dry matter yield has responded positively to the increased P rate, and this improvement was more pronounced under salinity conditions compared to freshwater irrigation. For example, under fresh water (0.7 dS.m$^{-1}$), the phosphorus rate of 102 $P_2O_5$·ha$^{-1}$ significantly increased the yield (by 32%) during first season. For the second season (2020-2021), 102 and 120 kg $P_2O_5$·ha$^{-1}$ significantly increased dry biomass yield by 8%. Under low salinity level (4 dS·m$^{-1}$) the application of 102 and 120kg $P_2O_5$·ha$^{-1}$ significantly increased dry matter yield (by 4 and 22% in 2019/2020 and by 20 and 22% in 2020/2021) as compared to control. While under moderate salinity (8 dS·m$^{-1}$), the increment rate of 120 kg $P_2O_5$·ha$^{-1}$ significantly increased the total dry matter yield by 36 and 19%, respectively, for 2019/2020 and 2020/2021 growing seasons as compared to control (85 kg $P_2O_5$·ha$^{-1}$). Conversely, the application of 102 and 120 kg $P_2O_5$·ha$^{-1}$ under the high level of salinity (EC 12 dS·m$^{-1}$), was significantly increased dry matter yield only in 2020/2021 by 14 and 13%, respectively, as compared to the control. The interaction between irrigation water salinity and P rate was significant only for 2019/2020, which indicates that dry matter yield responded differently to phosphorus application under high salinity irrigation water. In fact, dry matter yield was not affected by phosphorus application under freshwater irrigation (0.7 dS·m$^{-1}$), in contrast, it increased ($p < 0.05$) in high salinity level with increasing P rates.

### 3.4. Grain yield

Similar to dry matter yield, grain yield of wheat was significantly affected by salinity level and P rates (Fig. 5). In the first growing season, the salinity significantly decreased the grain yield by 11 and 8% under 8 and 12 dS.m$^{-1}$, respectively, in comparison with the control, whereas, no significant difference was founded for 0.7 and 4 dS.m$^{-1}$. In the second growing season, irrigation water salinity significantly reduced the grain yield by 13 and 21%, respectively, under salinity levels of 8 and 12 dS.m$^{-1}$. However, no significant difference revealed under salinity levels of 0.7 and 4 dS.m$^{-1}$. The interaction between salinity and P rate on grain yield was significant for both growing seasons. The phosphorus effect was significant for all treatments and for both seasons. The results showed that grain yield responded differently to phosphorus application. Under low salinity level (0.7 dS·m$^{-1}$), applying supplementary phosphorus ensures to increase the grain yield by 9 and 12%, respectively under 102 and 120 kg $P_2O_5$·ha$^{-1}$ during the first season; and by 1 and 6% the second growing season. Under 4 dS.m$^{-1}$, P fertilization helped the plant to tolerate salinity and improved grain yield ($p < 0.05$), especially with the dose of 120 kg $P_2O_5$·ha$^{-1}$. Which it increased the grain yield by 16 and 9 %, respectively, during 2019/2020 and 2020/2021. However, no significant effect was observed with the rate of phosphorus equal 102 kg $P_2O_5$·ha$^{-1}$. Under moderate salinity (8 dS·m$^{-1}$), grain yield was not affected ($p > 0.05$) by the P rate of 102 kg $P_2O_5$·ha$^{-1}$, while the rate of 120 kg $P_2O_5$·ha$^{-1}$ significantly increased the grain yield by 24 and 11 %, respectively, during 2019/2020 and 2020/2021. Under high salinity (12 dS.m$^{-1}$), the rate of 102 Kg $P_2O_5$·ha$^{-1}$ significantly increased grain yield by 31% during the first growing season (2019/2020). In addition, under the P rate of 120 kg $P_2O_5$·ha$^{-1}$, the grain yield was increased by 7% compared to the control during the second growing season (2020/2021).

### 3.5. Leaf mineral content

The leaf mineral nutrient content was affected by both irrigation water salinity and P application (Table 5) (Fig. 2). Irrigating with saline

**Table 4**
Plant growth and physiological parameters under different irrigation water salinity and P rate. Values with the same letters under the same salinity level are statistically equal. TGW: Thousand grain weight; TDM: Total Dry Matter.

| Crop season | Salinity ($dS.m^{-1}$) | P-rates ($kg.ha^{-1}$) | Stomatal conductance ($mmol.m^{-2}.s^{-1}$) | Root length (cm) | Leaf area (plant. $cm^2$) | Straw ($t.ha^{-1}$) | Number of spikes ($No/m^2$) | Shoot water content (%) | TGW (g) | Total dry matter ($t.ha^{-1}$) | Grain yield ($t.ha^{-1}$) | Grain/TDM (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2019/2020 | 0.7 | P1 | 64±9 a | – – | – – | 9±0.5 a | 371±31 a | – – | 34±0 b | 18±0.7 b | 5±0.1 b | 25±0 b |
| | | P2 | 46±7 a | – | – | 11 ±1.6 a | 425±37 a | – | 37±0 a | 24±0.9 a | 6±0.2 a | 25±1 ab |
| | | P3 | 41±5 a | | | 10 ±0.5 a | 350±13 a | | 38±0 a | 19±0.5 b | 5±0.3 a | 28±2 a |
| | | Average | 50±7 A | – | – | 10 ±0.9 A | 382±37 A | – | 36±2 A | 20±2.3 A | 5±1.6 B | 26±2 BC |
| | 4 | P1 | 35±4 a | – – | – – | 9±1.3 a | 338±10 a | – – | 37±0 ab | 18±1 b | 6±0.4 b | 35±2 a |
| | | P2 | 29±6 b | – | – | 9±0.2 a | 374±11 a | – | 36±1 b | 18±0.3 b | 6±0.4 b | 31±1 a |
| | | P3 | 29±5 a | | | 10 ±0.3 a | 379±21 a | | 38±0 a | 21±0.6 a | 7±0.3 a | 33±1 a |
| | | Average | 31±5 AB | – | – | 9±0.7 A | 363±20 AB | – | 37±1 A | 19±1.6 AB | 6±0.5 A | 33±2 A |
| | 8 | P1 | 33±6 a | – – | – – | 8±0.4 b | 337±33 b | – – | 34±1 b | 17±0.8 b | 4±0.1 b | 27±1 a |
| | | P2 | 19±6 a | – | – | 9±0.3 a | 386±36 a | – | 34±1 b | 17±0.8 b | 5±0.2 ab | 26±1 a |
| | | P3 | 37±4 a | | | 10 ±0.3 a | 387±35 a | | 35±0 a | 23±0.4 a | 5±0.5 a | 24±2 a |
| | | Average | 30±5 B | – | – | 9±0.8 AB | 370±42 B | – | 34±1 B | 19±2.5 AB | 5±0.4 B | 26±2 C |
| | 12 | P1 | 18±4 b | – – | – – | 8±0.7 a | 348±19 a | – – | 36±0 b | 17±0.5 b | 4±0.2 b | 25±1 b |
| | | P2 | 32±7 a | – | – | 8±0.3 a | 363±14 a | – | 37±1 a | 17±0.8 a | 6±0.2 a | 32±2 a |
| | | P3 | 31±8 a | | | 7±0.6 a | 366±26 a | | 36±1 ab | 16±0.2 a | 5±0.4 ab | 31±2 ab |
| | | Average | 27±6 B | – | – | 8±0.8 B | 359±21 B | – | 36±1 A | 17±0.7 B | 5±0.6 BC | 29±3 B |
| 2020/2021 | 0.7 | P1 | 43±14 a | 14±1 a | 505±32 a | 15±4 a | 507±60 a | 77±1 a | 44 ±0.9 b | 25±4 a | 8±0.1 b | 34±5 a |
| | | P2 | 44±2 a | 14±1 a | 517±53 a | 16±4 a | 522±144 a | 77±1 a | 43 ±0.2 b | 27±4 a | 9±0.1 a | 34±5 a |
| | | P3 | 45±2 a | 15±1 a | 569±23 a | 18±7 a | 529±63 a | 78±1 a | 46 ±0.4 a | 27±8 a | 9±0.2 a | 36±8 a |
| | | Average | 44±6 A | 15±1 B | 530±42 A | 16±5 A | 519±92 A | 77±1 A | 44 ±1.3 A | 26±5 A | 9±0.3 A | 34±6 A |
| | 4 | P1 | 32±4 a | 15±1 b | 453±11 b | 15±1 a | 471±76 a | 74±2 a | 42 ±0.3 a | 22±2 b | 8±0.4 b | 39±7 a |
| | | P2 | 33±6 a | 17±0 a | 504±25 b | 15±2 a | 476±71 a | 74±0 a | 43 ±1.6 a | 26±0 a | 8±0 b | 32±0 a |
| | | P3 | 34±4 a | 18±1 a | 573±8 a | 15±0 a | 501±20 a | 75±1 a | 44 ±1.1 a | 26±0 a | 9±0.1 a | 34±1 a |
| | | Average | 33±5 B | 17±1 A | 510±49 A | 15±1 AB | 483±60 AB | 74±1 AB | 43 ±1.4 A | 24±2 AB | 8±0.4 A | 35±3 A |
| | 8 | P1 | 29±0 a | 15±1 b | 377±42 a | 13±1 a | 459±46 a | 68±6 a | 38 ±0.9 b | 22±2 b | 7±0 b | 32±3 a |
| | | P2 | 32±6 a | 17±1 ab | 406±4 a | 14±2 a | 471±44 a | 70±5 a | 41 ±0.4 a | 23±1 b | 8±0.1 ab | 33±1 a |
| | | P3 | 33±2 a | 18±1 a | 437±28 a | 14±3 a | 491±20 a | 73±6 a | 42±0 a | 27±1 a | 8±0.3 a | 30±2 a |
| | | Average | 31±3 B | 17±1 AB | 406±23 B | 14±2 AB | 474±37 AB | 70±6 B | 40 ±1.3 B | 24±2 AB | 8±0.3 B | 32±2 A |
| | 12 | P1 | 27±8 a | 15±0 b | 327±26 b | 10±1 a | 371±2 a | 68±2 a | 39 ±0.2 b | 19±3 a | 7±0.1 b | 36±5 a |
| | | P2 | 28±1 a | 16±0 ab | 384±9 b | 11±1 a | 421±7 a | 69±1 a | 40 ±0.5 a | 22±1 a | 7±0.1 b | 30±1 a |
| | | P3 | 31±1 a | 18±1 a | 532±71 a | 12±1 a | 443±36 a | 72±2 a | 41 ±0.7 a | 22±1 a | 7±0.1 a | 33±2 a |
| | | Average | 29±4 B | 16±1 AB | 414±78 B | 11±1 B | 411±33 B | 70±2 B | 40 ±0.8 B | 21±1 B | 7±0.3 C | 33±3 A |

Any two values within a column are significantly different ($p < 0.05$) if they have no letter in common. Small and same letters (a, ab, b) indicate the statistically homogeneous groups within phosphorus fertilization treatments, and capital and same letters (A, AB, B) indicate the statistically homogeneous groups within salinity treatments.

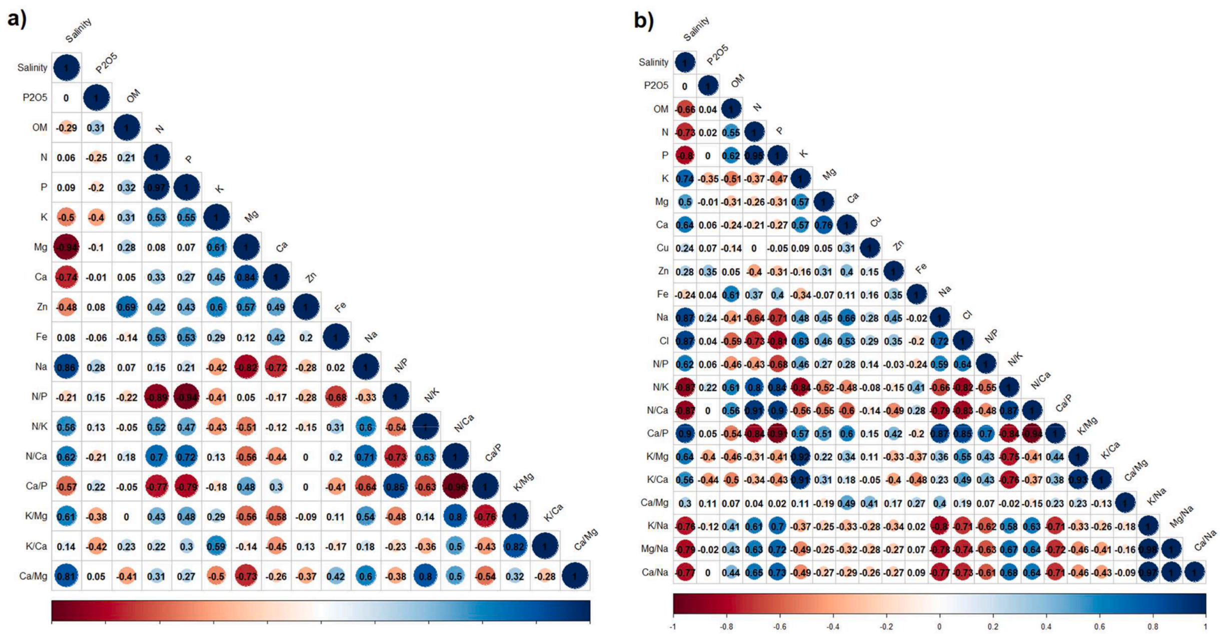


**Fig. 2.** Pearson's correlation matrix for all the investigated chemical foliar parameters during (a) 2020 and (b) 2021. Color gradient corresponds to the Pearson coefficient of correlation.

**Table 5**
Analysis of variance (ANOVA) showing *p*-value of different leaf nutrient contents as affected by different irrigation water salinities and phosphorus rates and their interaction.

| Crop season | Factor | Organic matter | N | P | K | Mg | Ca | Cu | Zn | Fe | Na | Cl |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2020 | Salinity (S) | 0.699 | 0.136 | 0.270 | 0.168 | 0.0001*** | 0.013 | - | 0.129 | 0.202 | 0.007*** | - |
| | Phosphorus (P) | 0.070 | 0.639 | 0.513 | 0.374 | 0.940 | 0.681 | - | 0.681 | 0.963 | 0.569 | - |
| 2021 | Salinity (S) | 0.0001*** | 0.0001*** | 0.0001*** | 0.0001*** | 0.018* | 0.0001*** | 0.454 | 0.026* | 0.022* | 0.0001*** | 0.0001*** |
| | Phosphorus (P) | 0.957 | 0.904 | 0.965 | 0.075 | 0.824 | 0.547 | 0.926 | 0.057 | 0.899 | 0.321 | 0.661 |
| | P in S1 | 0.022* | 0.061 | 0.026* | 0.026* | 0.301 | 0.603 | 0.154 | 0.420 | 0.119 | 0.399 | 0.143 |
| | P in S2 | 0.408 | 0.396 | 0.478 | 0.097 | 0.571 | 0.726 | 0.0001 | 0.298 | 0.003** | 0.090 | 0.100 |
| | P in S3 | 0.739 | 0.019 | 0.077 | 0.019 | 0.246 | 0.112 | 0.189 | 0.011* | 0.524 | 0.096 | 0.032* |
| | P in S4 | 0.108 | 0.052 | 0.242 | 0.004** | 0.288 | 0.153 | 0.469 | 0.013* | 0.007** | 0.0001*** | 0.216 |
| | P*S | 0.020* | 0.003** | 0.019* | 0.002** | 0.257 | 0.699 | 0.005* | 0.035* | 0.001*** | 0.0001*** | 0.031 |

water significantly decreased the N, P and Fe content in soft wheat leaf, whereas, K, Mg, Ca, Zn, Na and Cl content in leaf increased significantly ($p < 0.05$). Salinity significantly reduced N content by 20, 15 and 25 %, respectively under salinity levels of 4, 8 and 12 $dS.m^{-1}$ as compared with the control. Also, leaf-P content decreased significantly ($p < 0.05$) due to salinity by 21, 24 and 31 %, respectively under 4, 8 and 12 $dS.m^{-1}$. Whilst, leaf-K increased significantly by 3, 22 and 30 %, respectively under 4, 8 and 12 $dS.m^{-1}$. In addition, saline water was also increased Na and Cl content in wheat leaf by 54, 196 and 374 % for Na, and by 45, 79 and 99 % for Cl, respectively under salinity levels of 4, 8 and 12 $dS.m^{-1}$.

Under fresh water irrigation (0.7 $dS{\cdot}m^{-1}$), P supply significantly decreased OM, P and K contents in the wheat leaf. Also, leaf-Cu, Fe and Cl content were decreased due to P-fertilization. It was observed that P-fertilization had no significant effect on leaf N, Mg, Ca, Zn and Na when irrigating with fresh water (0.7 $dS.m^{-1}$). The effect of P-fertilizer rate varied according to salinity level. For example, under low salinity (4 $dS{\cdot}m^{-1}$), P application significantly increased P, Mg, Cu and Fe contents in the leaf. However, it significantly reduced leaf-K content. On other hand, leaf-OC, N, Ca, Zn, Na and Cl content did not respond to increasing P rates. Under medium salinity, the response of leaf nutrient content to rising P rate is different, in which an increase in P application led to rise significantly leaf-N, P, Mg, Zn and Na content, and a decrease in leaf-K content. Under a high salinity level (12 $dS.m^{-1}$), the application of 120 kg $P_2O_5{\cdot}ha^{-1}$ contributed to increase significantly the leaf-Zn, Fe, Na, and Cl content, whereas, leaf-K content reduced after P application at the rate of 120 kg $P_2O_5{\cdot}ha^{-1}$. Under high salinity conditions, the highest P rate led to the accumulation of the highest amount of Na. It was also observed that P fertilization had no significant effect on leaf-OM, Mg and Ca content under all tested levels of salinity.

### 3.6. Evolution of soil salinity

The obtained results were represented in the Fig. 6. Soil salinity varies with salinity of applied irrigation water, and with soil depth. For the control (EC=0.7 $dS.m^{-1}$) the variation in soil salinity does not exceed 1 $dS.m^{-1}$, and higher in the 50-60 cm layer. For EC=4 $dS.m^{-1}$, this variation is between 1.8 and 2.9 $dS.m^{-1}$, respectively, in depth of 20 and 40 cm. with regard to the application of a salinity of 8 $dS.m^{-1}$. The influence is very clear; it varies between 1.6 $dS.m^{-1}$ for the 20 cm layer to 3.6 for the 50-60 cm layer. Finally, in the case of irrigation with an EC of 12 $dS.m^{-1}$, this variation is 1.6 and 5.7 $dS.m^{-1}$, respectively for layers 30 and 10.

Table 6 illustrates the impact of soil salinity and P-fertilization on soil nutrient content. Results show the significant impact of saline water irrigation on rising the availability of $Na^+$ and $Cl^-$ ions in soil at the end

**Table 6**
Analysis of variance (ANOVA) showing *p*-value of different soil nutrient contents as affected by different irrigation water salinities and phosphorus rates.

| Crop season | Factor | pH | WC | EC | Cl | Na | OM | N | P | K | Mg | Ca | Zn | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2020 | Salinity (S) | 0.001*** | 0.017* | 0.001 ** | 0.001 *** | 0.001 *** | 0.030* | 0.022* | 0.383 | 0.002 *** | 0.001 ** | 0.006 ** | 0.001 ** | 0.232 |
| | Phosphorus (P) | 0.840 | 0.776 | 0.917 | 0.834 | 0.925 | 0.729 | 1 | 0.236 | 0.740 | 0.749 | 0.625 | 0.932 | 0.810 |

Significance levels are as follows: *$p<0.05$, **$p<0.01$, and ***$p<0.001$

of the two growing season. Moreover, the results reported a significant impact of saline water application by decreasing the $K^+$, $Ca^{2+}$, $Mg^{2+}$ and $Zn^{2+}$ ions concentrations in soil after the experiment. On the other hand, P-fertilization practices during the two growing seasons has not significantly affected the availability of other elements in the soil.

### *3.7. Assessment of APSIM-wheat performances in monitoring wheat productivity, P and N nutrient dynamics in soil-plant system*

Results of assessment of APSIM-wheat model for simulating wheat productivity showed a good agreement between observed and simulated data, with a very low NRMSE of yield (Table 7). Moreover, the simulated results showed a slight difference in the simulated values of all output parameters when applying P-fertilizer (i.e., 85, 102 and 120 kg. $P_2O_5{\cdot}ha^{-1}$). Also, the model has satisfactorily simulated the N nutrient dynamic in both, plant-N concentration within growing season and soil available-P after harvest during 2019/2020 crop season. In other hand, a clear limitation of model was observed in simulating P nutrient dynamic with a medium performance to simulate plant-P concentrations within crop season, and in soil after the crop season.

## 4. Discussion

### *4.1. Effect of salinity and P-fertilization on plant growth and yield*

Overall, wheat growth and yield parameters were affected in varying degrees depending on salinity level and applied P-rates. The decrease of wheat biomass and grain yield under salinity is mainly explained by the reduction in photosynthetic activity. (Alasvandyari et al., 2017) have reported that salinity influences seed germination, decreases node formation, retards plant development and decreases crop yield, and the reduction in yield and biomass is related to altering physiological function of the plant. This decrease is mainly due to the osmotic pressure generated by NaCl element on the plants. The $Na^+$ and $Cl^-$ ions accumulated in the leaves disturb the metabolic processes and the production of substances stored in the seeds as reserves. High salt concentration in the soil solution reduces the ability of plants to uptake water, known as the osmotic or drought effect of salinity. Damage occurs when the concentration is high enough to reduce plant growth (Machado and Serralheiro, 2017). The decrease in yield may also be attributed to interference within the absorption of plant nutrients and physiological water stress created by high salt concentration (Wagdi et al., 2013). Likewise, our results demonstrate that stomatal conductance normally decreased when wheat plants were exposed to high level of saline water irrigation (Fig. 3). In previous studies, they have affirmed that soil salinity affects photosynthesis, and hence grain yield by reducing stomatal conductance (Betzen et al., 2019; Brugnoli and Lauteri, 1991). Salinity reduces photosynthetic activities in several ways: by inhibiting photosystem II (Zarco-Tejada et al., 2003), downregulating photosynthesis by stomatal closure and reducing photochemical and carbon metabolism (Maia et al., 2016; Wani et al., 2019; Yuan et al., 2018). Our finding is consistent with previous findings in corn silage (Bouras et al., 2021b), and wheat (Zhu et al., 2018), in which soil salinity decreased photosynthetic rate, and consequently crop growth, and yield parameters.

The lower yield under saline conditions can be physiologically explained by the reduction of tillers per meter, leaf area, number of spike per area, number of kernel per spike and weight of grain (Table 4). Likewise, as the EC of the irrigation water increases, the length of the root system (LRS) decreased during the first sampling (after 3 months) (Table 4). In previous study, they have demonstrated that salinity has a depressive effect on the development of the root system of plants and a disturbance in physiological and metabolic processes due to reducing nutrient and water uptake through increasing the potential osmotic of soil (Abd El-Hamed et al., 2012). Overall, growth characters as well as stem and root length, leaf number and leaf area per plant, shoot and root dry weights and flowering branches per plant were all considerably reduced with increasing on salinity stress levels (Sakr et al., 2012). Result of this study is in line with the previous finding by Ouhaddach et al. (2016), in which they have stated that the increase in the NaCl content in the irrigation water causes the reduction of the height and the mass of the wheat dry matter of both the aerial and root organs.

Under saline conditions, P application significantly increased the wheat biomass and yield, and reduced the negative effect of salinity. This result is in agreement with the findings of Wagdi et al. (2013), which have indicated that P-fertilization ameliorates wheat dry matter yield and grain yield under saline soil conditions. In other study, P-supply caused an increase in biomass and P accumulation (Wang et al., 2021). The yield increase from P application under saline soil conditions may associated to a rise of essential plant nutrients uptake and concentrations, decrease on concentrations of toxic ions (i.e., sodium ($Na^+$) and chloride ($Cl^-$)), and thus expansion of $Ca^{2+}/Na^+$ and $K^+/Na^+$ ratios (Bouras et al., 2021b; Wagdi et al., 2013). The P applied rates through the rooting medium inhibits accumulation of $Na^+$ and $Cl^-$ in leaves and roots, while increasing leaf and root $K^+$, P with $Ca^{2+}$ (Naheed et al., 2008). The P-fertilization was shown to have more improving role in enhancing N contents and its uptake in wheat plant (Wagdi et al., 2013). Ability of P to enhance rooting would be of significant role to avoid salinity adverse effects through reducing $Na^+$ uptake, which could be a specific mechanism of P in the nutrient balance (Kaya et al., 2001; Shibli et al., 2001). While an increase in salt level caused a significant decrease on wheat growth and yield parameters, it is also adding P increased leaves area, the root length, the thousand grain weight and the plant dry weight and subsequently resulted in more resistance to salinity stress. This result is also consistent with the previous findings in Ghazi and Al-Karaki (1997), in which they have affirmed that phosphorus application caused a significant increase in the shoot and the root dry weights of barley.

**Table 7**
Assessment of APISM-wheat model performance. Calculation of prediction performance metrics: $R^2$, RMSE and NRMSE.

| Type | Output parameters | Units | RMSE | NRMSE | $R^2$ |
|---|---|---|---|---|---|
| Productivity related output | Pods | No. $m^{-1}$ | 55.84 | 13.33 | 0.37 |
| | Grains weight | $g.m^{-2}$ | 210.25 | 24.94 | 0.95 |
| | Yield | kg. $ha^{-1}$ | 7.43 | 11.14 | 0.95 |
| N and P related output | Plant-N | % | 0.42 | 23.94 | 0.98 |
| | Soil N (after harvest) | % | 0.011 | 8.55 | 0.99 |
| | Plant-P | % | 0.045 | 40.66 | 0.11 |
| | Soil P (after harvest) | ppm | 10.82 | 45.83 | 0.25 |

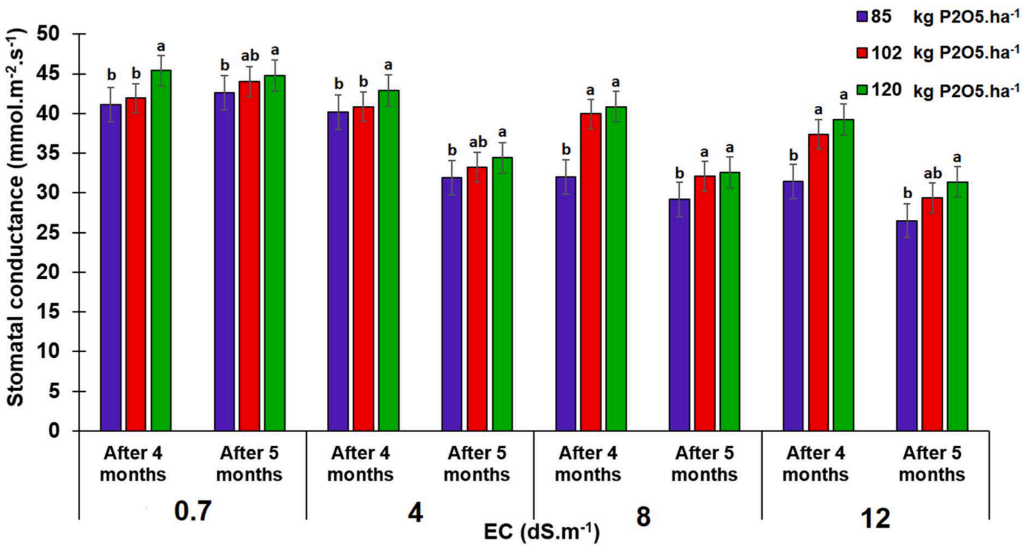


**Fig. 3.** Variation in stomatal conductance for 2019 and 2020 seasons under different salinity levels and P rates. Error bars indicate the standard deviation. Phosphorus treatments under the same salinity level and for the same season without a common letter are significantly different at $p < 0.05$.

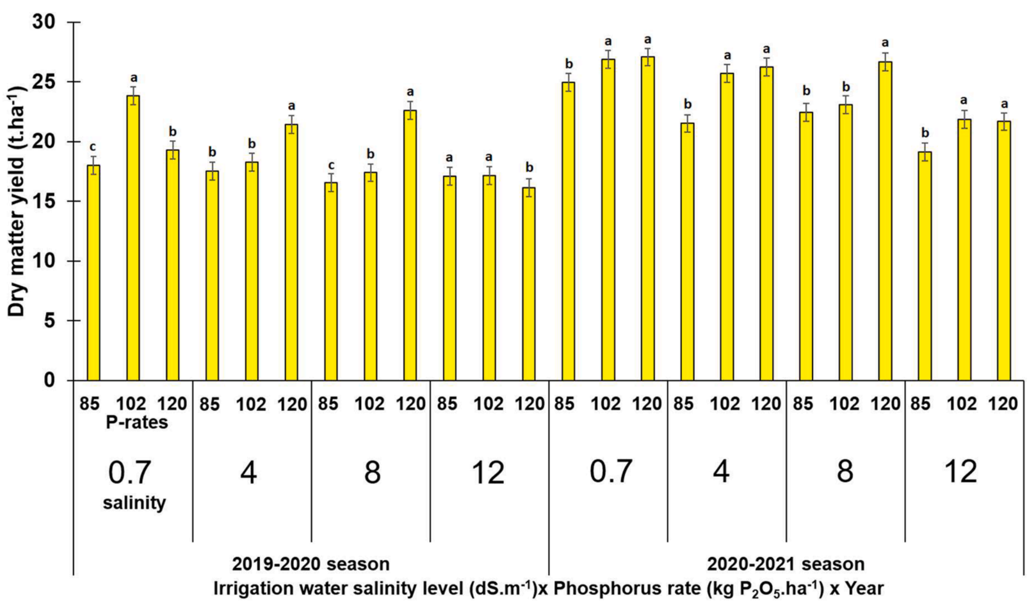


**Fig. 4.** Variation in dry matter yield for both 2019/2020 and 2020/2021 seasons under different salinity levels and P rates. Error bars indicate the standard deviation. Phosphorus treatments under the same salinity level and for the same season without a common letter are significantly different at $p < 0.05$.

A number of studies have addressed issues related to improvement in crop yield through P-fertilization supply. Similar results were found in other crops such as forage silage, green bean, mungbean, chickpea, wheat, sugar beet, and barley (Bargaz et al., 2016; Bouras et al., 2022a, 2022b, 2021b; Gulmezoglu, 2017; Jahan et al., 2020; Kaya et al., 2001; Sadji-Ait Kaci et al., 2017; Wagdi et al., 2013). Other Studies reported that there are positive effects between soil salinity and P-fertilization in improving plant function (Naheed et al., 2008). Moreover, Grattan and Grieve (1998) have stated that the interaction behavior between salinity and phosphorus (P) depends largely on the plant species (or cultivar), plant developmental age, composition and salinity level, and the concentration of P in the substrate.

### 4.2. Effect of salinity and P-fertilization on wheat nutrition

The interactions between salinity and mineral nutrition are very complex processes due to the external influence of different factors: plant species, genotypes within species, plant age, the composition and level of salinity, concentration of nutrients in the substrate and climatic conditions (Fageria et al., 2011). Imbalances can result from the effect of salinity on nutrient availability, competitive uptake, transport, or distribution within the plant, or can be caused by the physiological inactivation of a particular nutrient, resulting in an increase in the plants internal need for this essential item (Grattan and Grieve, 1998). In our study, the $Na^+$ content in the plants increased significantly with the level of salinity of irrigation water (NaCl treated treatments). In these treatments, $Na^+$ disrupted the influx of other ions, particularly N, P, and Fe. Nevertheless, application of P tends to reduce the negative effects of $Na^+$ and $Cl^-$ accumulation and increase plant capacity to counteract the effect of salinity stress. Our results are in agreement with those recorded by Alasvandyari et al. (2017), in which the ions toxicity and ionic imbalance due to the accumulation of $Na^+$ and $Cl^-$ are considered as results of salinity stress. Salinity provides an imbalance of mineral uptake, and high osmotic pressures generated by $Na^+$ and $Cl^-$ ions that

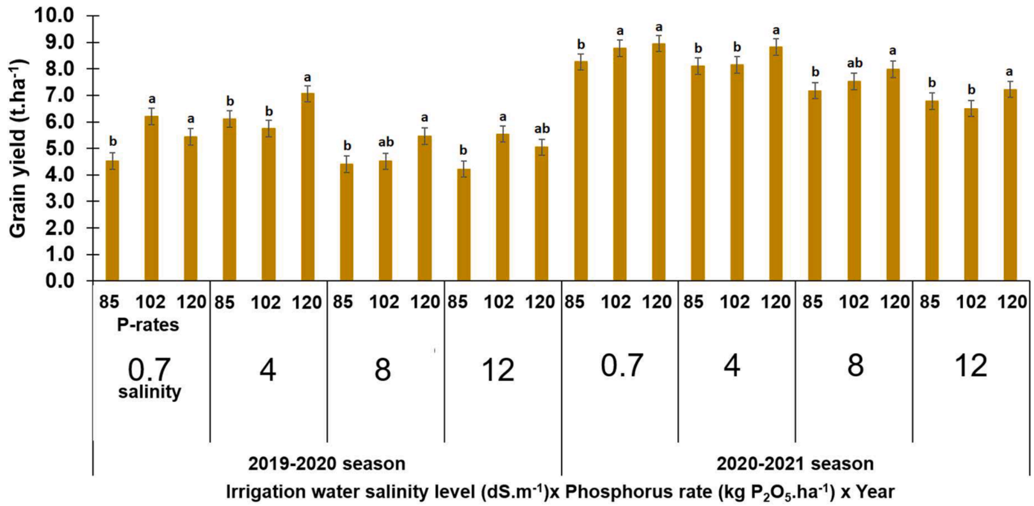


**Fig. 5.** Variation in grain yield for both 2019/2020 and 2020/2021 seasons under different salinity levels and P rates. Error bars indicate the standard deviation. Phosphorus treatments under the same salinity level and for the same season without a common letter are significantly different at $p < 0.05$.

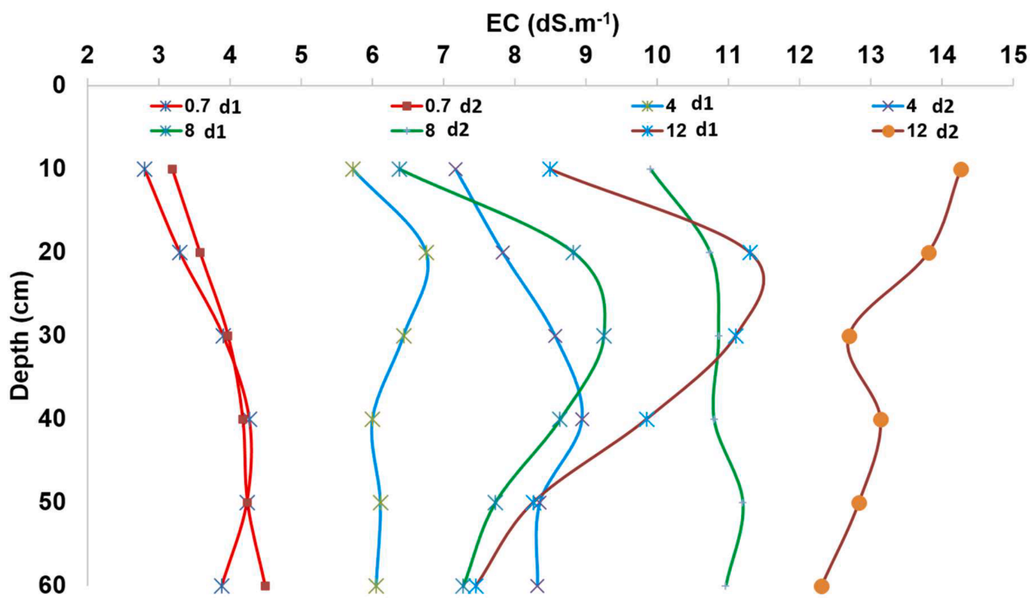


**Fig. 6.** Evolution of soil salinity between 3 months (February and May 2021) after applying saline water irrigation. d1: Date of the first sampling (25/02/2021), d2: Date of second sampling (28/04/2021).

make water unavailable to the plants cause a depressive effect on the development of the root system of plants (Fageria et al., 2011). It can directly affect nutrient uptake, such as $Na^+$ reducing $K^+$ uptake or by $Cl^-$ reducing $NO_3^-$ uptake (Grattan and Grieve, 1998). $Na^+$ ions frequently replaces $K^+$ as cell channels cannot distinguish between these elements and the antagonism between $K^+$ and $Na^+$ cations increases considerably as salinity increases (Sairam et al., 2002). The reduction of $K^+$ uptake by plants was caused by the high concentration of $Na^+$ in the soil. Which can be explained by a competitive process and occurs regardless of whether the dissolution of $Na^+$ salts is dominated by $Cl^-$ or $SO_4^{-2}$. Various results recorded that under saline-sodic or sodic conditions, high levels of external $Na^+$ not only interfere with $K^+$ uptake, but also may disrupt the integrity of root membranes and alter their selectivity (Grattan and Grieve, 1998). Indeed, high levels of $Na^+$ can displace $Ca^{2+}$ from root membranes, altering their integrity and thus impairing $K^+$ selectivity (Cramer et al., 1987).

Our finding demonstrates the effect of salinity in the accumulation of $Cl^-$ in the leaf (Table 5). These results confirmed the previous results by Sakr et al. (2012), in which $Cl^-$ is a more sensitive indicator of salt damage than $Na^+$ because it is stored by the plant. $Cl^-$ accumulation can cause leaf damage and reduce photosynthesis and productivity. Similarly, other results as found by Özdemir et al. (2004) have suggested that the relatively higher uptake of $Cl^-$ compared to $Na^+$ in salt-stressed plants might be responsible for the reduced growth by suppressing the uptake of other anions.

### 4.3. APSIM-wheat simulations

As concluded from ANOVA tests (Table 5), the impact of varying P-rates on yield and plant-N and P concentration was no-significant due to the high level of applied P fertilizer rates (i.e., start from 85 kg $P_2O_5{\cdot}ha^{-1}$) as well as the response of wheat that has been always considered as low demanded crop for phosphorus (Olsen, 1982; Tsadila et al., 2012). APSIM-wheat model has highly succeeded to reflect this phenomenon, in which the simulation results of all output parameters show a slight variation of values when changing the P fertilizer rates (i.

e., 85, 102 and 120 kg $P_2O_5 \cdot ha^{-1}$). Same results were reported by Mamassi et al. (2022, 2023b), during conducting APSIM-wheat simulations in a field highly fertilized (i.e., P fertilizer exceed 60 kg $P_2O_5 \cdot ha^{-1}$), in which the assessment of the effect of changing soil available-P level on yield has shown no-significant impact.

The goodness of fit results of APSIM-wheat model showed the model is suitable to simulate wheat growth and yield in Moroccan arid and semi-arid conditions, as previously reported in Mamassi et al. (2023a). In the other hand, obvious limitations were noted in the model's ability to simulate phosphorus dynamics. Medium to limited abilities were observed when APSIM-wheat estimated plant-P concentrations within a growing season, as well as available-P amounts in soil after the crop season.

The APSIM-Soil-P module defines the plant-available P by the P-sorption characteristics of a soil and based on the Freundlich sorption equation, which indirectly relates the labile-P pool to the soil solution P (secondary pool of labile-P) using two sorption coefficients (a and b). In other words, the P supply available for plant uptake is a function of soil solution P that is directly linked to the labile-P pool and defined by the sorption equation. Then, the plant module calculates the P demand (crop P-uptake), that will be provided from the soil P supply (calculated by Soil-P module in each layer). The weakness in APSIM-wheat's ability to simulate P dynamics in soil may begin from the Soil-P module structure that describes the major P availability by the dominance of the P sorption process. The marginalization of P precipitation/dissolution processes results in the absence of any reference equations to replicate the two processes in the model structure. These processes are considered only as empirical rates (i.e., rate loss available (r)) in the slow exchange between labile-P pool and unavailable inorganic P pool (see Section 2.6.2). However, in alkaline soil types, both sorption/desorption and precipitation/dissolution reactions (e.g., Ca-P minerals) occur simultaneously with the same significance. Therefore, the sensitivity of (r) coefficient variation is highly significant in simulations of soil P dynamics in such soils (Raymond et al., 2021), as found in the Moroccan case.

Uncertainty in soil- and plant-P dynamic simulations may surpass the impact of APSIM-Soil-P structure to the module parameterization. Studies that attempt to parameterize APSIM-Soil-P using measured P-transfer coefficients for specific soil properties (i.e., soil texture and pH) are very rare. Most parameterizing works are focused on adjusting P-transfer coefficients to match the most accurate simulations of crop growth and yield response (i.e., crop P demand) toward the P-fertilizer and bioavailable P, without taking into account the functionality of the model in replicating P dynamics in soil and plants. Using results from Wang et al. (2014) and Raymond et al. (2021) – previous studies conducted in Australia – we implemented a P component in APSIM-wheat through integrating wheat P-demand parameters in the wheat.xml file, then we set up the labile-P coefficients (a and b) and rate loss available coefficient (r). In the Australian studies, the values were adjusted to achieve a high performance of APSIM-wheat in simulating not only biomass and yield, but also the P dynamic in soil. Thus, we considered the similarities in the soil characteristics (i.e., soil type and pH) as well as the crop species (i.e., wheat) when adopting the Australian values for parameterizing the APSIM-Soil-P module for Moroccan fields. Nevertheless, our operational processes during this parameterization were surrounded by other potential uncertainties that could result in moderate to low accuracy of soil- and plant-P dynamic simulations, for example:

- The simple linear relation (Micheni et al., 2004) used to set the labile-P values based on soil Olsen-P test values may not represent the real soil situation, especially for different soil types. For example, Wang et al. (2014) recently found a curvilinear relation between labile-*P* values and soil Colwell-P test values. Until now, no similar study has been undertaken for the Olsen-P test.
- Not all Moroccan fields have Vertisols and Ferrosols, the Australian soil types considered when parameterizing APSIM-Soil-P.
- Wheat P-demand values, extracted from Wang et al. (2014), could be slightly influenced by doubt related to differences between wheat genotypes as P-demand could vary between cultivars. However, this hypothesis was excluded because, originally, wheat is a low P-demand crop.

There is a need to conduct experimental works with different soil properties after parameterizing the APSIM-Soil-P module to better understand the P dynamics in soil-plant systems. Researchers and experts are attempting to directly link crop growth and productivity responses to P-fertilization rates, as in the present study. Consequently, we recommend extending APSIM model functionality to perform more accurate monitoring of P dynamics and status in plant and soil. We suggest that future experiments should parameterize the APSIM-Soil-P module based on measured values, or at least site-specific adjustments of values, of P-transfer coefficients, considering different soil properties, specifically site-specific pH and soil texture.

## 5. Conclusions

Salinity is a major abiotic stress that adversely affects crop growth and development, resulting in yield losses. Our results revealed that an increase in irrigation water salinity led to a substantial reduction in the growth and physiological parameter (stomatal conductance) of soft wheat. This, in turn, resulted in decreased grain yield, total biomass, and altered the nutrient balance in the leaf content. It was caused due to an accumulation of $Na^+$ and $Cl^-$ in the leaf and in soil. Contrariwise, application of P-fertilization has resulted in enhanced the plant mineral content, as well as improved the stomatal conductance under the water salinity stress conditions. Also, P-fertilization has significantly improved the wheat growth parameters, including biomass and grain yield, and while also augmenting the plant mineral nutrient content. The results obtained strongly support the use of P-fertilization as one of the most highly recommended practices for alleviating the adverse impacts of salinity stress, especially in the context of saline water irrigation practices. Therefore, within the scope of this study, we suggest applying P-fertilization at a rate of 120 kg $P_2O_5 \cdot ha^{-1}$ for achieving the highest grain yield and biomass harvest in salinity conditions up to 4 $dS.m^{-1}$. Meanwhile, using a rate of 102 kg of $P_2O_5 \cdot ha^{-1}$ in fresh water situations is the most favorable option. Overall, in light of the results obtained, we recommend applying P supply under similar condition of saline water irrigation practices. The good agreement between the measured and APSIM model simulated growth and yield parameters as well as plant and soil-N content. However, the limitations in model accuracy during simulating plant- and soil-P dynamic output was due principally to two factors of uncertainty: (i) model structure that neglect some important physicochemical processes of P element in soil (i.e., describes the major P availability by the dominance of the P sorption process, even in alkaline soils)., and (ii) parametrizing (or calibration) work of soil-P module confined only to set P crop demand to match the crop response to P-management decisions (i.e., P-fertilization), without taking into account the need to assess the model accuracy for simulating P-dynamic under changing characteristics of soil and plants.

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## Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Code availability

The codes of APSIM-wheat model generated during the current study are available from the corresponding author on reasonable request.

## Ethics approval

Not applicable

## Consent to participate

Not applicable

## Consent for publication

Not applicable

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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