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Research Article

Contribution to the optimization of citrus (*Citrus clementina* Hort. Ex Tanaka) fruit fertilization using mobile lysimetry in orchards of the Souss-Massa region, Morocco

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Abstract
The growth and development of citrus trees and the quality of their fruits are significantly influenced by the essential role of mineral plant nutrition. This study aimed to improve the productivity of the citrus (*Citrus clementina* Hort. Ex Tanaka) orchards by optimizing mineral nutrition through well-monitored fertilization and fertigation aspects using lysimetry. The first phase consisted of studying the behavior of the nutrients in the soil solution at the high root concentration level, analysis of the nutritional status of five varieties of clementines (Sidi Aissa, Cadoux, Orogrande, Nules, and Nour), and the variation of leaf composition in major elements (Nitrogen, phosphorus, potassium, magnesium, and calcium) for the five varieties along phenological stages, through the exploitation of the results of analyses carried out for the management of mineral nutrition in 47 plots of citrus fruit in the Souss-Massa region with the use of lysimetry. The results obtained in this first part revealed an important variation of the nutrients in the soil solution (55.24%) in terms of water inputs, fertilizers, and edaphic conditions, as well as a large variation of foliar compositions (62.98%). The second phase, consisting of regular monitoring of the mineral nutrition dynamics targeting the "Nules" variety grafted on "*Citrus macrophylla*" affirmed the importance of the citrus fertilization approach for determining the availability, distribution, nutrient interactions in soil solution and plant response by regular leaf diagnostics. Thus, mobile lysimetry offered a powerful tool for achieving both productivity and sustainability in citrus fertilization programs.

Keywords: Citrus, Diagnostic, Fertilization, Foliar composition, Mobile lysimetry

INTRODUCTION

Citrus cultivation holds immense economic and agricultural significance in Morocco, contributing substantially to the country's agricultural sector (Klein, 2014). Over the years, the citrus industry in Morocco has evolved, adapting to changing market demands, climate conditions, and technological advancements (Raveh *et al*., 2020). In this context, the optimization of citrus fruit fertilization has emerged as a critical area of research and development to enhance crop yield, quality, and sustainability (Weisskopf and Fuller, 2014).

Morocco's citrus industry has a rich history, dating back to the early 20th century when citrus orchards were first established (Curk *et al*., 2022). This sector has witnessed remarkable growth, becoming one of the country's leading agricultural exports (Mohammed *et al*., 2015). Citrus fruits, primarily oranges, clementines, mandarins, lemons, and grapefruits, play a pivotal role in the Moroccan agricultural landscape (INRA, 2017). They have significantly contributed to the diversification of the agricultural sector and provided employment opportunities, especially in rural areas (ASPAM, 2018; INRA, 2017). Morocco is currently one of the largest citrus producers in the Mediterranean region, with citrus exports forming a substantial part of the country's agricultural exports, providing substantial revenue and foreign exchange earnings (Schimmenti *et al*., 2013). The evolution of the citrus sector in Morocco is characterized by increased cultivation, modernization, and efforts to enhance fruit quality and production efficiency (Smaili *et al*., 2020). The industry has expanded geographically, with citrus orchards now covering vast areas across the country. This expansion, however, comes with challenges related to sustainable resource management, particularly in the context of mineral nutrition and fertilization (Li *et al*., 2021).

Mineral nutrition plays a crucial role in the growth and development of citrus trees and the quality of their fruits (Bons *et al*., 2015). Citrus trees require a balanced supply of essential nutrients to produce high-quality fruit and maintain long-term tree health. Macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) are essential, as well as micronutrients like iron (Fe), zinc (Zn), and manganese (Mn) (Morgan and Kadyampakeni, 2020; Hazarika *et al*., 2023). Imbalances or deficiencies in these nutrients can result in reduced yield, poor fruit quality, and increased susceptibility to diseases and pests (Toselli *et al*., 2020).

Fertilization is fundamental in citrus cultivation to address nutrient deficiencies and maintain optimal tree health (Vashisth and Kadyampakeni, 2020). Traditionally, fertilization has been conducted through soil applications, but more recently, fertigation has gained prominence in the citrus industry (Srivastava et al., 2021). Fertigation involves the precise application of nutrients through irrigation systems, allowing for efficient nutrient uptake by the trees (Quiñones *et al*., 2012). This method has been shown to enhance nutrient use efficiency and reduce environmental impacts, making it particularly attractive in the context of sustainable agriculture (Lin *et al*., 2020). Efficient and precise fertilization is essential for maximizing yield, reducing nutrient wastage, and minimizing environmental consequences (Panhwar *et al*., 2019). The citrus industry in Morocco recognizes the need for sustainable technologies that ensure long-term productivity while minimizing ecological footprint.

Mobile lysimetry, as a monitoring and measurement technique, has gained attention in optimizing agricultural nutrient management (Incrocci *et al*., 2017). In agronomy, lysimetry is one of the methods that makes it possible to refine the balance of inputs and outputs of mineral compounds on a vertical column of soil whose volume is perfectly known. For this reason, it fits naturally into studies relating to the prospecting of plant production systems (Sołtysiak and Rakoczy, 2019). These assessments are essential for understanding and managing agrosystems, not only with a view to productivity and sustainability but also with respect for the environment, especially in the context of good agricultural practice and environmental protection (Matusek *et al*., 2016). This technology involves the use of mobile lysimeters to collect soil and water samples, allowing for real-time monitoring of nutrient levels in the root zone (Sołtysiak and Rakoczy, 2019). There are three main types of lysimeters, closed lysimeters with modified soil, open lysimeters, and porous candle lysimeters (Schuhmann et al., 2016). Each lysimeter type enables farmers to make informed decisions regarding when and how much fertilizer to apply, tailoring nutrient management to the specific needs of trees (Yang et al., 2015). This technology offers a valuable tool for precision agriculture and efficient use of resources.

The present study aimed to contribute to the optimization of citrus fruit fertilization in Morocco through the innovative use of mobile lysimetry. The objectives included (*i*) Assessing the current nutritional status of citrus (*Citrus clementina* Hort. Ex Tanaka) orchards; (*ii*) Investigating the mineral profiles of citrus varieties; (*iii*) Evaluating the dynamics of nutrients of citrus varieties in terms of their phenological stage; (*iv*) Exploring the application of mobile lysimetry as a monitoring tool for precise nutrient management with different irrigation treatments.

MATERIALS AND METHODS

Survey phase

Study areas

The survey concerned 29 citrus (*C. clementina* Hort. Ex Tanaka) orchards with 47 plots located in the Souss region. These areas were located in the middle part of the Souss River, between the region of Ouled Teima and Aoulouz (Fig. 1). The orchards were categorized in each production zone, the number of plots per orchard and also the variety and rootstock. The clementine varieties, notably “Nules”, “Nour”, “Orogrande”, “Sidi Aissa” and “Cadoux” constituted more than 80% of the total orchard data, and more than 80% of the varieties were grafted on the sour orange (Table S1)

Lysimeter installation

In the orchards visited, the lysimeters used for fertilization management were of the "porous candle" type.

Each orchard had three porous candle lysimeters of different lengths (20, 40, and 60cm) (Fig. S1). The use of the three depths was very important to know the behavior of the mineral elements in different depths of the soil profile, thus having an idea of the accumulation and leaching of salts. Regarding location, the lysimeters were installed right next to the irrigation boom. The application of depression in the candles was carried out for approximately one hour after irrigation and extraction of the solution from the soil was done after 24 hours of the applied depression.

Measurements

In addition to soil and irrigation water analyses carried out annually to characterize edaphic conditions and irrigation water quality in orchards, other analyses were carried out periodically, targeting important phenological stages. and the most critical in the production cycle (the start of vegetative growth, flowering-fruit set, physiological drop, and fruit ripening). These were analyses of the soil solution extracted by the porous candles at three depths of the root profile alongside those of the actual fertilizer solution recovered directly from the drippers and foliar analyses.

Database establishment

The database represented soil analyses carried out during February 2022 at two different depths, notably at 20, 40, and 60cm depths. These analyses represented both the physical characteristics, particularly the particle size and type of soil, and the chemical constituents of the soil, namely acidity, salinity, nutritional fertility, and the presence of undesirable elements such as active limestone (Mwendwa, 2022). On the other hand, irrigation water analysis is concerned with the water's salinity, acidity, hardness, and the presence of undesirable elements (chloride and sodium) (Nishanthiny *et al*., 2010). In addition, for fertilization management, analyses of the soil solution, the fertilizer solution, and foliar analyses were carried out six times in 2022.

Soil solution and foliar analyses

The analyses of the soil and fertilizer solutions (Fig. S2) concerned several mineral elements: NH_4^+, NO_3^-, K^+, Ca^{++}, Cl^-, $H_2PO_4^-$, Mg^{++}, SO_4, and Na^+ in meq/l and Fe, Mn, Cu, B, and Zn in mg/l, as well as salinity and pH (Fig. S2A) (Kim *et al*., 2007). The foliar analyses were carried out in parallel with the analyses of the soil solution and those of the actual fertilizer solution (Fig. S2B). This involves the determination of the chemical composition of the leaves in the following elements: N, K, P, Ca, Mg, and S, expressed as a weight percentage or in g (element)/100 g (plant), and in B, Cl, Cu, Fe, Mn, Mo, Na and Zn expressed in ppm or mg (element)/kg (plant) (Sharma *et al*., 2021).

Experimental phase

Experimental site

The experimental study is located in the Experimental Station of the Agadir Horticultural Complex (CHA), on a plot of "Nules" clementine grafted on planted "*Citrus macrophylla*", over an area of 2,500 m^2 (50 m x 50 m). This plot has a latitude of 30.350699° North and a longitude of -9.477062° East (Fig. S1). Planting in the experimental plot was carried out on adulates 40 cm high and 1.5 m wide. This planting system has many advantages, and it makes it possible to resolve the constraint of the soil, which is not deep (around 40 cm); on the other hand, it allows for good aeration and better exposure of adolescents to the sun, as well as ease of drainage at the level of the rhizosphere. The plot comprised 14 planting lines; on each line, 33 plants, with 1.5 m spacing along the line and 4 m spacing between the lines, giving a density of 1666 plants per hectare (Fig. 2).

Fertilization management

The fertilization program adopted for the experimental plot was recommended during previous work carried out by Mohammed *et al*. (2015), which made it possible to determine the most appropriate nutritional program for the three varieties: "Nour", "Orogrande", and

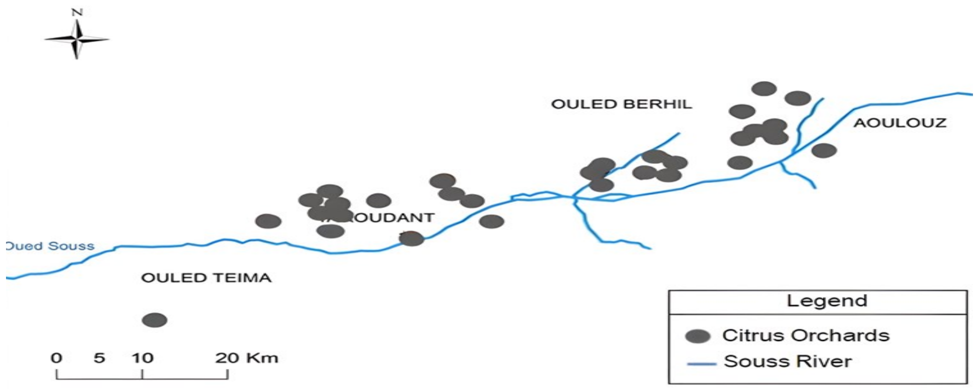

Fig. 1. *Geographical map of surveyed citrus (Citrus clementina* Hort. Ex Tanaka*) orchards in the Souss-Massa region (Morocco)*

"Nules". This work considered the edapho-climatic conditions of the Souss Massa region and tested the impact of several fertilization programs on fruit yield and quality. Thus, the fertilization program adopted was based on annual inputs characterized by an additional supply of nitrogen and potassium compared to the programs commonly used by local farmers. In addition, the monthly foliar diagnostics carried out during this work revealed a poor distribution of the nitrogen and potassium supply. It is also important to meet the high potassium requirements with additional supplies of this element before the start and during the fruit growth and ripening phase. The fertilizers used were ammonium nitrate, potassium sulfate, monoammonium phosphate (MAP), and phosphoric acid. The nutrient solution obtained had an average electrical conductivity of 1.5 dS/m (Table 1). Furthermore, the fertilization process was actively monitored by conducting regular soil and foliar analyses.

Irrigation management

Three irrigation regimes were established with constant dose and variable frequencies: T_1 (2.3 l/h/dripper), T_2 (4 l/h/dripper), and T_3 (8 l/h/dripper). In addition, a Control T_0 treatment (2.3 l/h/dripper) was considered. Despite the use of drippers with different flow rates, the volume

Table S1. List of surveyed citrus orchards in the Souss-Massa region (Morocco)

Region	Orchard	Plots	Variety	Rootstock
HMER (H)	X1	1	SIDI AISSA	Bigaradier
		2	NULES	Bigaradier
	X2	1	NULES	Bigaradier
		2	NULES	Bigaradier
	X3	1	NOUR	Bigaradier
	X4	1	NOUR	Bigaradier
	X5	1	OROGRANDE	Bigaradier
	X6	1	NULES	Bigaradier
		2	OROGRANDE	Bigaradier
	X7	1	CADOUX	Bigaradier
		2	SALUSTUANA	Bigaradier
OULED BERHIL (OB)	X8	1	W NAVEL	Bigaradier
		2	NULES	Bigaradier
	X9	1	NULES	Bigaradier
	X10	1	OROGRANDE	Bigaradier
	X11	1	SIDI AISSA	Bigaradier
		2	NULES	Bigaradier
	X12	1	ESBAL	Carrizo
		2	OROGRANDE	Bigaradier
		3	SIDI AISSA	Carrizo
		4	NOUR	Bigaradier
IGLI RZAGNA (IR)	X13	1	NOUR	Bigaradier
		2	MAROC LATE	Bigaradier
	X14	1	MAROC LATE	Bigaradier
		2	CADOUX	Bigaradier
	X15	1	CADOUX	Bigaradier
	X16	1	CADOUX	Bigaradier
	X17	1	OROGRANDE	Carrizo
		2	NULES	Bigaradier
		3	NULES	C. Troyer
	X18	1	CADOUX	Bigaradier
AIT IAZZA (AI)	X19	1	MAROC LATE	Bigaradier
		2	CADOUX	Bigaradier
	X20	1	NULES	Bigaradier
		2	LARACHE	Bigaradier
	X21	1	NULES	Marophylla
	X22	1	LANE LATE	Bigaradier
	X23	1	NULES	Bigaradier
	X24	1	NOUR	Bigaradier
OULED TAIMA (OT)	X25	1	NULES	Carrizo
		2	NOUR	Carrizo
	X26	1	CADOUX	Bigaradier
	X27	1	NULES	Marophylla
	X28	1	LANE LATE	Bigaradier
		2	NOUR	Bigaradier
	X29	1	NULES	Marophylla
		2	NOUR	Bigaradier

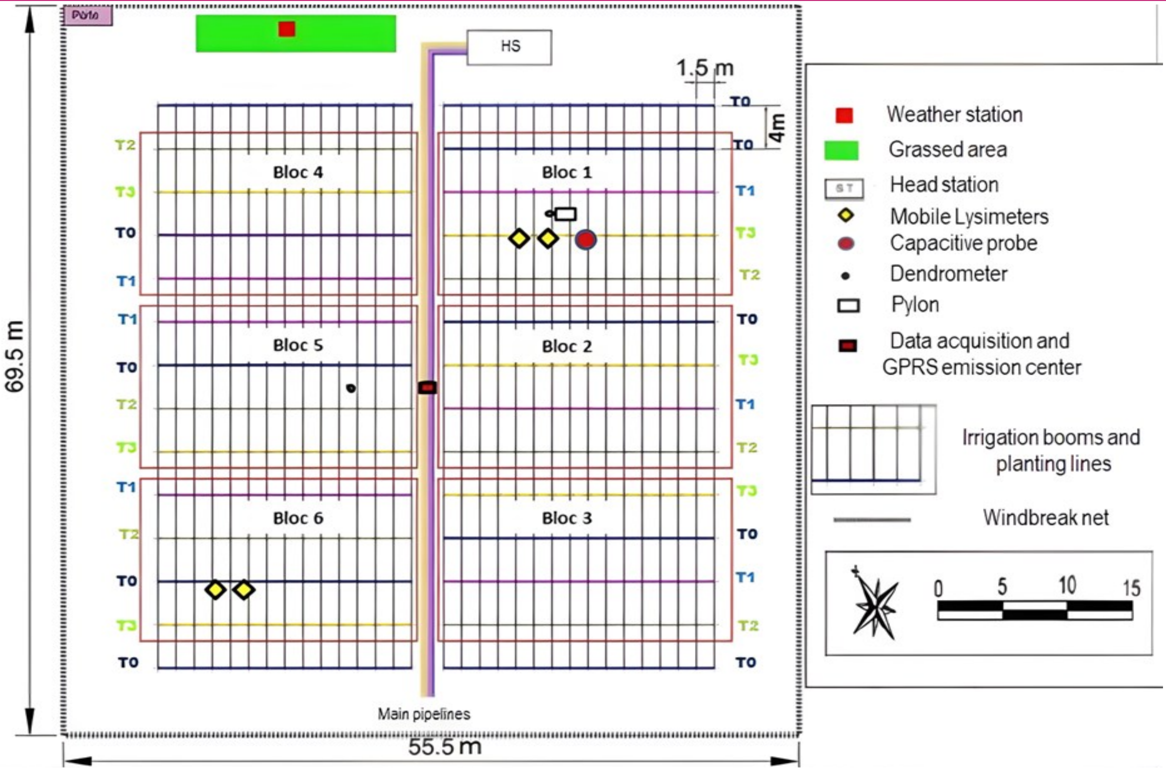

Fig. 2. *Scheme of the experimental plot planted with "Nules" clementine tree grafted on "Citrus macrophylla"*

Table 1. Composition of the nutrient solution in fertilizers sources of nitrogen, phosphorus, and potassium in g/1000

Fertilizers	Before BI	BD-FF	FF-PF	PF-CC	CC-HE
Ammonium nitrate	2680	3000	1250	700	0
mono ammonium phosphate (MAP)	0	282	80	50	70
potassium sulfate	1200	1080	280	450	1000
phosphoric acid	100	100	30	20	20

BI = Bourgeon Initiation; FF = Full Flowering; PF: Fruit Fall; Fruit Color Change; HE: Harvest End

of water supplied over the entire season was approximately identical between the three treatments, since the duration of each water supply is adapted to each type of dripper: 150 min for T_1 and T_0, 100 min for T_2 and 50 min for T_3.

Statistical data processing

Statistical analyses were conducted using XLSTAT (version 2023, Lumivero, USA) statistical software and Python (version 3.11) programming language. Before each analysis, datasets were assessed for normality using the Anderson-Darling test and subjected to logarithmic transformation ($Log_{10}(x+1)$) if normality conditions were not met. Correlation analyses (Pearson type) revealed potential relationships between salinity proprieties and mineral content embedded in soil solution and foliar parts. Principal Component Analysis (PCA) and Redundancy Analysis (RDA) were conducted using *sklearn. decomposition. PCA* and *skbio. stats. ordination. rda* modules in Python to visualize nutrient and mineral profiles alongside their spatial distribution in terms of surveyed citrus orchards. All Statistical tests were established based on replicated treatments (n = 6) at a significance level of 5% ($P < 0.05$).

RESULTS AND DISCUSSION

Nutrient distribution of soil and foliar matrices in citrus orchards

Soil solution profile

The principal component analysis (PCA) was employed to investigate the soil solution profile characteristics of the surveyed citrus orchards. The first two principal components, PC1 and PC2, collectively explained 86.86% of the variance. PC1 accounted for the majority of the variance at 55.24%, while PC2 contributed 31.62%. This distribution of variance highlights the substantial influence of these axes in characterizing the soil solution properties (Fig. 3A)

The distribution of nutrient content in the soil exhibited a notable level of variability, indicative of a significant trend in nutrient composition across the orchards. Notably, salt elements such as electrical conductivity (EC), sodium (Na^+), calcium (Ca^{2+}), chloride (Cl-), magnesium (Mg^{2+}), and sulfate (SO4) were prominently present throughout the citrus soils. Furthermore, a positive correlation was observed between magnesium (Mg^{2+}) and sulfate (SO4), suggesting a potential interaction or shared source for these elements. Beyond the salt elements, other mineral contents, both macro and oligo-elements, were also highly prevalent in the soil profile, adding to the complexity of the nutrient composition (Fig. 3A).

Redundancy analysis (RDA) was applied to explore surveyed citrus orchards' spatial tendencies concerning the soil profile's analyzed nutrients. The RDA results revealed that the variance in soil composition could be largely explained by both axes, with 58.11% of the variance explained by PC1 and 40.89% by PC2. The surveyed citrus orchards displayed a structured distribution across different regions, corresponding to the soil's nutrient contents. For instance, orchards in Ouled Taima (OT), Ouled Berhil (OB), and Hmer (H) exhibited high tendencies towards calcium (Ca), copper (Cu), chloride (Cl), and sulfate (SO4). In contrast, orchards in Igli Rzagna (IR) and Ait Iazza (AI) were more oriented towards iron (Fe), zinc (Zn), sodium (Na), and potassium (K) (Fig. 3B). This regional differentiation suggests that soil nutrient profiles play a crucial role in shaping the characteristics of citrus orchards, with specific nutrients favoring distinct regions.

Foliar profile

In a parallel analysis, the foliar profile of the surveyed citrus orchards was examined using PCA. The first two principal components, PC1 and PC2, collectively explained 98.02% of the variance. PC1 contributed significantly, explaining 62.98% of the variance, while PC2 accounted for 35.04%. Similar to the soil profile, the distribution of foliar nutrient content displayed substantial variability with a significant overall trend. Macroelements, such as potassium (K), phosphorus (P), magnesium (Mg), and calcium (Ca), were highly represented in the foliar composition. In contrast, oligoelements, including chloride (Cl), iron (Fe), and boron (B), were prominent in the foliar setting. This distinction highlights the importance of both macro and oligoelements in the nutritional makeup of citrus orchards (Fig. 3A).

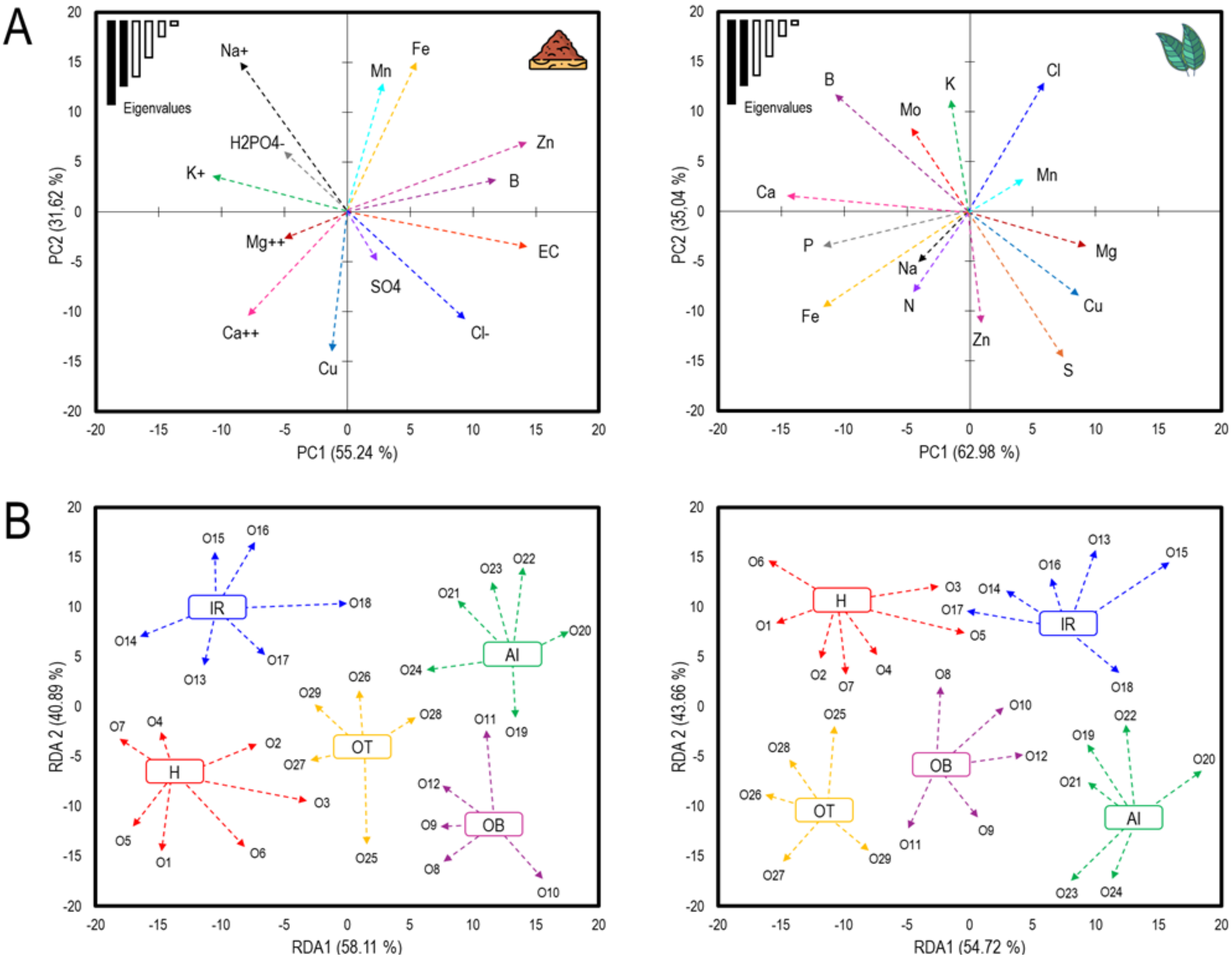

Fig. 3. *Soil solution and foliar nutritional profiles showing the distribution of mineral contents monitored by mobile lysimeters in Moroccan citrus orchards; A) Principal Component Analysis (PCA) showcasing the distribution of minerals in soil solution (left) and citrus leaves (right) B) Redundancy Analysis (RDA) showcasing spatial distribution of surveyed citrus orchards in terms of monitored mineral content*

The results of the RDA revealed that both axes played a significant role in explaining the variance, with 54.72% of the variance explained by PC1 and 43.66% by PC2. The spatial distribution of citrus orchards following the composition of their leaves exhibited positive affiliations with the surveyed orchards. For instance, orchards in Ouled Berhil (OB) and Hmer (H) demonstrated high tendencies towards zinc (Zn), calcium (Ca), and nitrogen (N) in their foliar composition, suggesting a distinct nutrient profile in these regions. In contrast, Igli Rzagna (IR) and Ait Iazza (AI) displayed a preference for sulfur (S), copper (Cu), chloride (Cl), and magnesium (Mg) (Fig. 3B).

Soil depth effect

The behavior of soil nutrients was thoroughly monitored by mobile lysimeters in surveyed citrus orchards in three soil depths (Fig. 4). In terms of Macroelements (e.g., NPK), the highest concentrations were detected in topsoil layers (20 cm) while decreasing in high depths (Fig. 4A). The same trend was observed with Oligoelements (e.g., Cu, Fe, and Zn) as they were reaching the highest concentrations in low soil depths (Fig. 4B).

The study of nutrient distribution in soil and foliar matrices in citrus orchards is vital for optimizing citrus fruit production. Soil and foliar nutrient analysis helps to understand the nutrient availability, uptake, and transport within citrus trees (Srivastava and Singh, 2009). The distribution of nutrients in citrus orchards can significantly affect fruit quality and yield (Fan *et al*., 2020). Several studies have examined the nutrient distribution of soil and foliar matrices in citrus orchards. For instance, Meena *et al*. (2020) found that the concentration of nitrogen (N), phosphorus (P), and potassium (K) was highest in the topsoil layer (0-20 cm) and decreased with depth. The concentration of oligoelements, such as iron (Fe), manganese (Mn), and zinc (Zn), was also highest in the topsoil layer (Zhang *et al*., 2013). Furthermore, Quiñones *et al*. (2007) found that the concentration of N, P, and K in citrus leaves was highest in the spring and decreased during the summer and fall. The concentration of micronutrients in citrus leaves was also highest in the spring and decreased during the summer and fall.

Correlation trends

The electrical conductivity showed strong correlations only with the salts (Ca^{2+}, Cl^{-}, Mg^{2+}, SO_4^{2-} and Na^{+}) in the soil solution (Fig. 5A). The strongest correlation between EC and mineral element in soil solution was found with SO_4^{2-} with the coefficient of 0.82 (Fig. 5B). Nevertheless, the combination Mg^{2+}/Ca^{2+} gave a higher correlation of 0.91 with conductivity. There was no correlation between other mineral elements and EC (Fig. 5C).

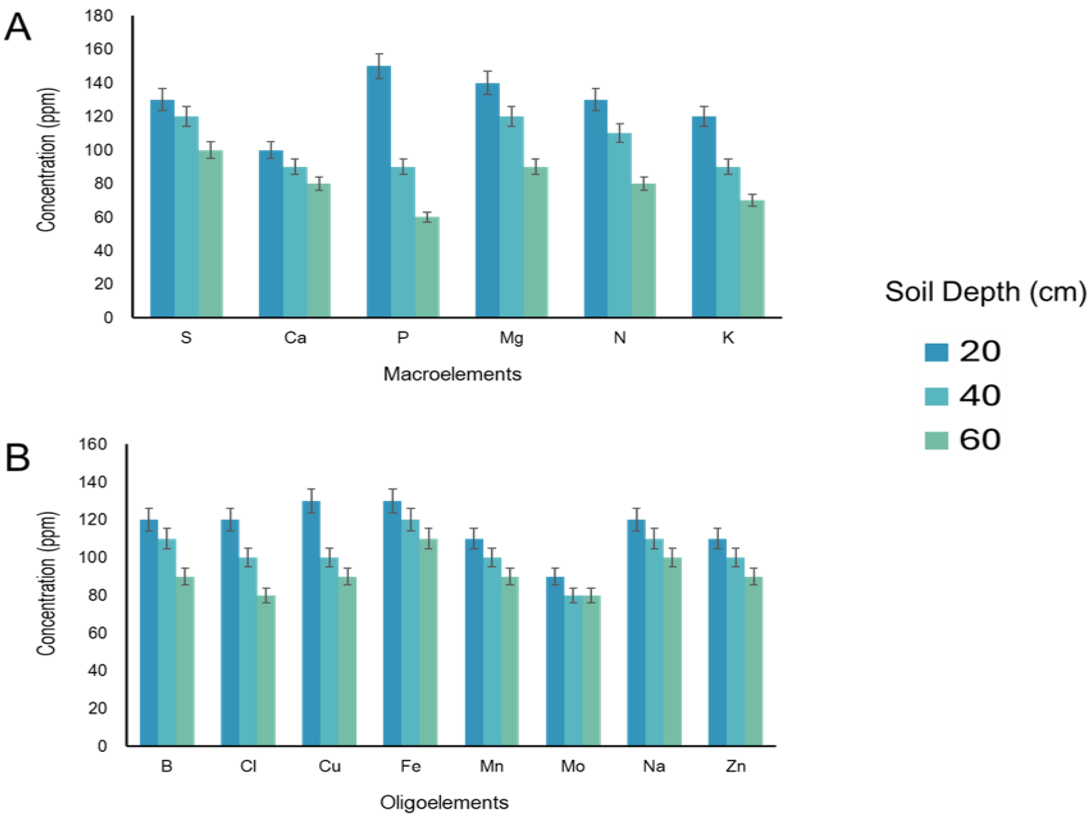

Fig. 4. *Concentrations of nutrients monitored by mobile lysimeters in different soil depths of citrus orchards- (A) Macroelements; (B) Oligoelements*

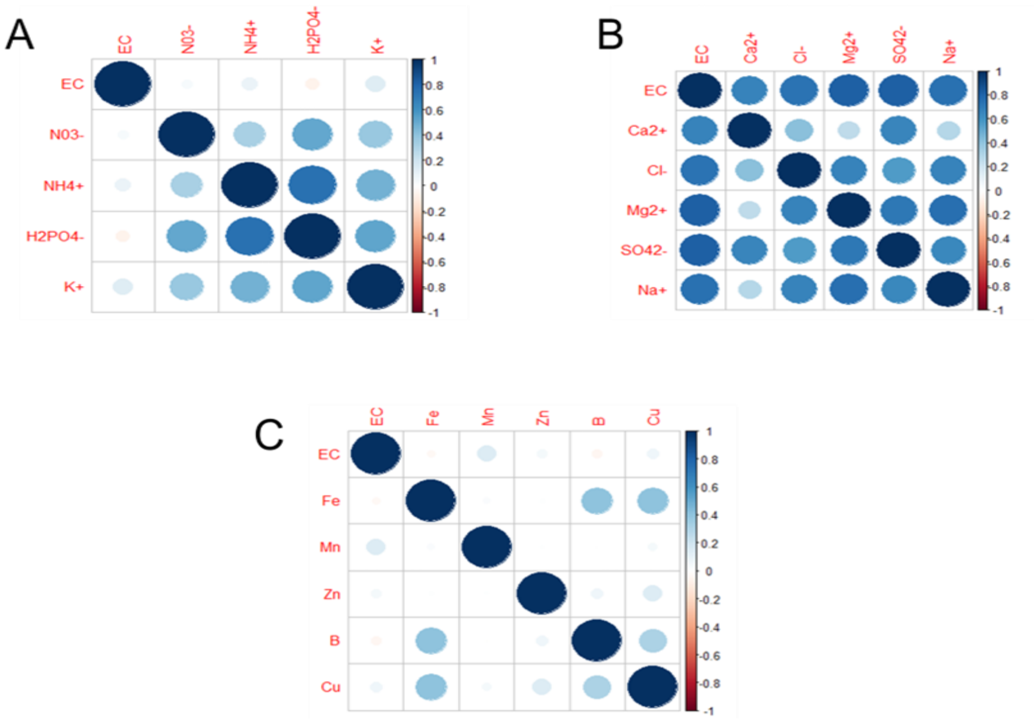

Fig 5. *Correlation maps (Pearson type) showcasing the relationships between (A) NPK elements; (B) soil solution salt elements; and (C) other mineral elements*

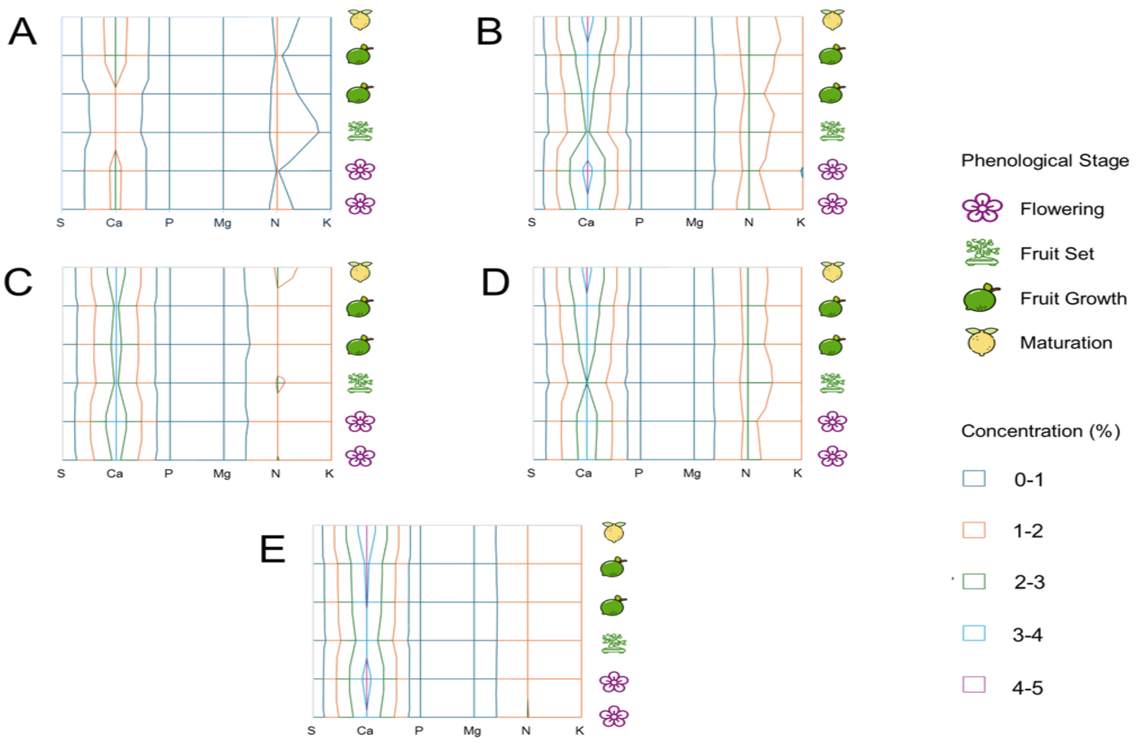

Fig 6. *Wireframe contour plots depicting the nutrient dynamics Macroelements monitored by mobile lysimeters in five clementine varieties in the function of their phenological stage. (A) Sidi Aissa; (B) Cadoux; (C) Nour; (D) Nules; (E) Orogrande.*

Electrical conductivity (EC) is a valuable indicator of soil salinity and can offer insights into nutrient availability in citrus orchards (Sefiani *et al*., 2017). Ozi *et al*. (2023) demonstrated a strong correlation between EC and the presence of macro and oligo-elements. Furthermore, a study by Werban *et al*. (2009) found that there was a significant positive correlation between EC and the concentration of N, P, and K in soil. Another study by Schumann (2006) found that there was a significant positive correlation between EC and the concentration of Fe, Mn, and Zn in citrus soils.

Nutritional status of clementine varieties in the Souss-Massa Region

Macroelements

Comparing the five varieties, nitrogen deficiencies were more widespread in the two varieties “Nour” and “Orogrande” with 92.98% and 88.66% of the nitrogen contents classified as low to very low (Fig. S3). In terms of dates for collecting foliar samples, nitrogen deficiencies were common during the growth stages, which coincided with June and July, with 74% of levels below 2.2% of foliar nitrogen during this period (Fig. S3A). Unlike nitrogen, phosphorus deficiencies were very rare in the Souss region. Furthermore, in all the foliar analyses in 47 citrus plots, only 3% of cases were detected with very low foliar phosphorus contents below 0.09%, and only 16% with low levels between 0.09 and 0.11% (Fig. S3B). The same applies to potassium deficiencies, as only 2% of cases are classified as low and very low according to the reference levels. However, 85% of cases present potassium levels greater than 1.01%; therefore, they were classified as high and very high (Fig. S3C).

The foliar calcium contents for the five varieties studied in the Souss region were generally normal to low. More than 66% of the measured contents are 3 to 5%. Percentages of 33% and 44% of foliar calcium levels, respectively, in the two varieties “Nules” and “Nour” were less than 2.9%. Regarding the collection date of foliar samples, 36% of low calcium levels were recorded in May (Fig. S3D). Similarly, magnesium in the leaves of the five varieties in the Souss region was normal to low. More than 70% of the contents were classified as Normal (0.25-0.45%) and almost 28% were less than 0.24%. The distribution showed that magnesium deficiencies were rare (less than 2%) during September (Fig. S3E). The distribution of foliar sulfur contents showed that sulfur deficiencies are very common in the Souss-Massa region. More than 66% of the measured contents were less than 0.19%, of which 40% were recorded between May and June (Fig. S3F).

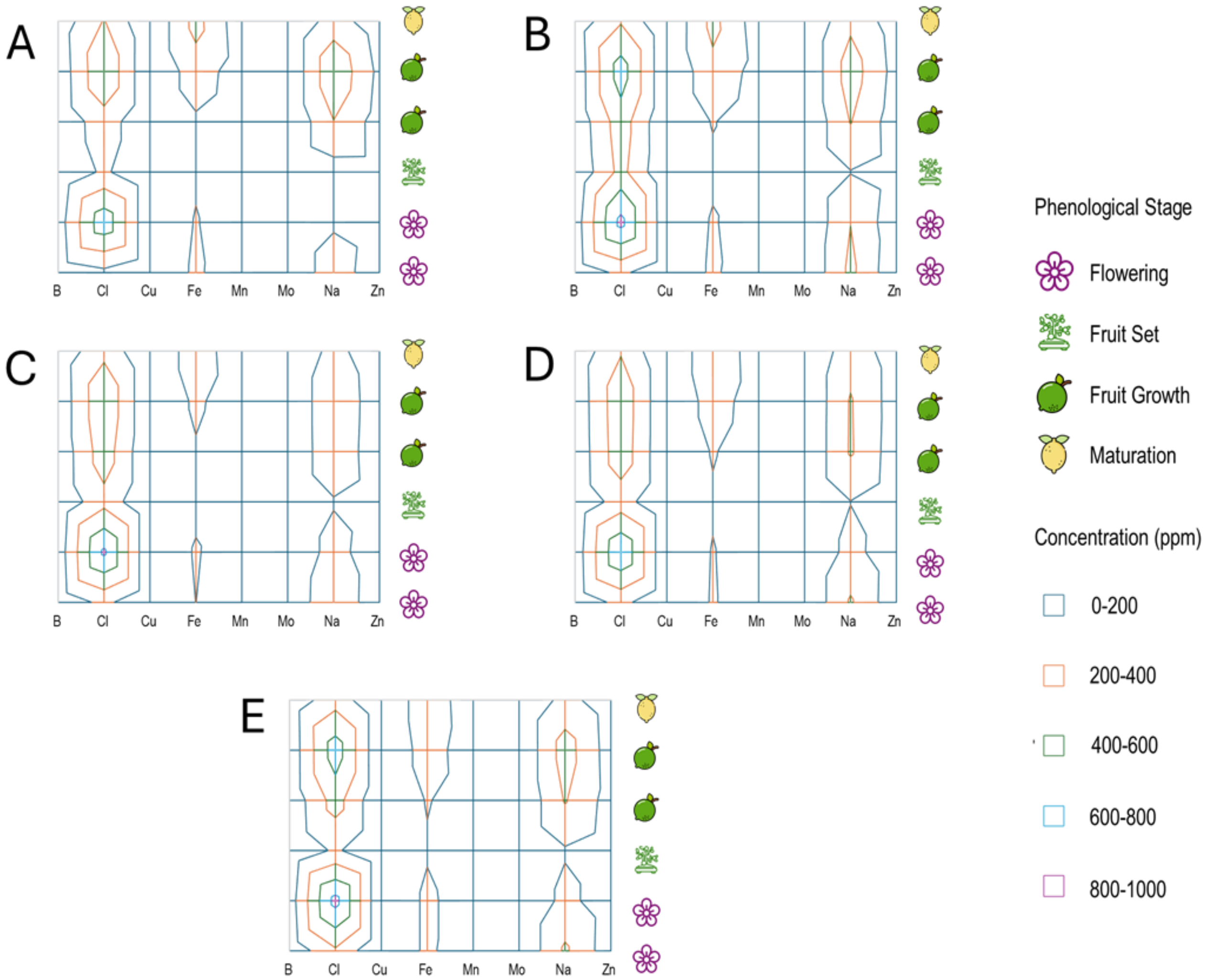

Fig. 7. *Wireframe contour plots depicting the nutrient dynamics of Oligoelements monitored by mobile lysimeters in five clementine varieties in the function of their phenological stage. (A) Sidi Aissa; (B) Cadoux; (C) Nour; (D) Nules; (E) Orogrande*

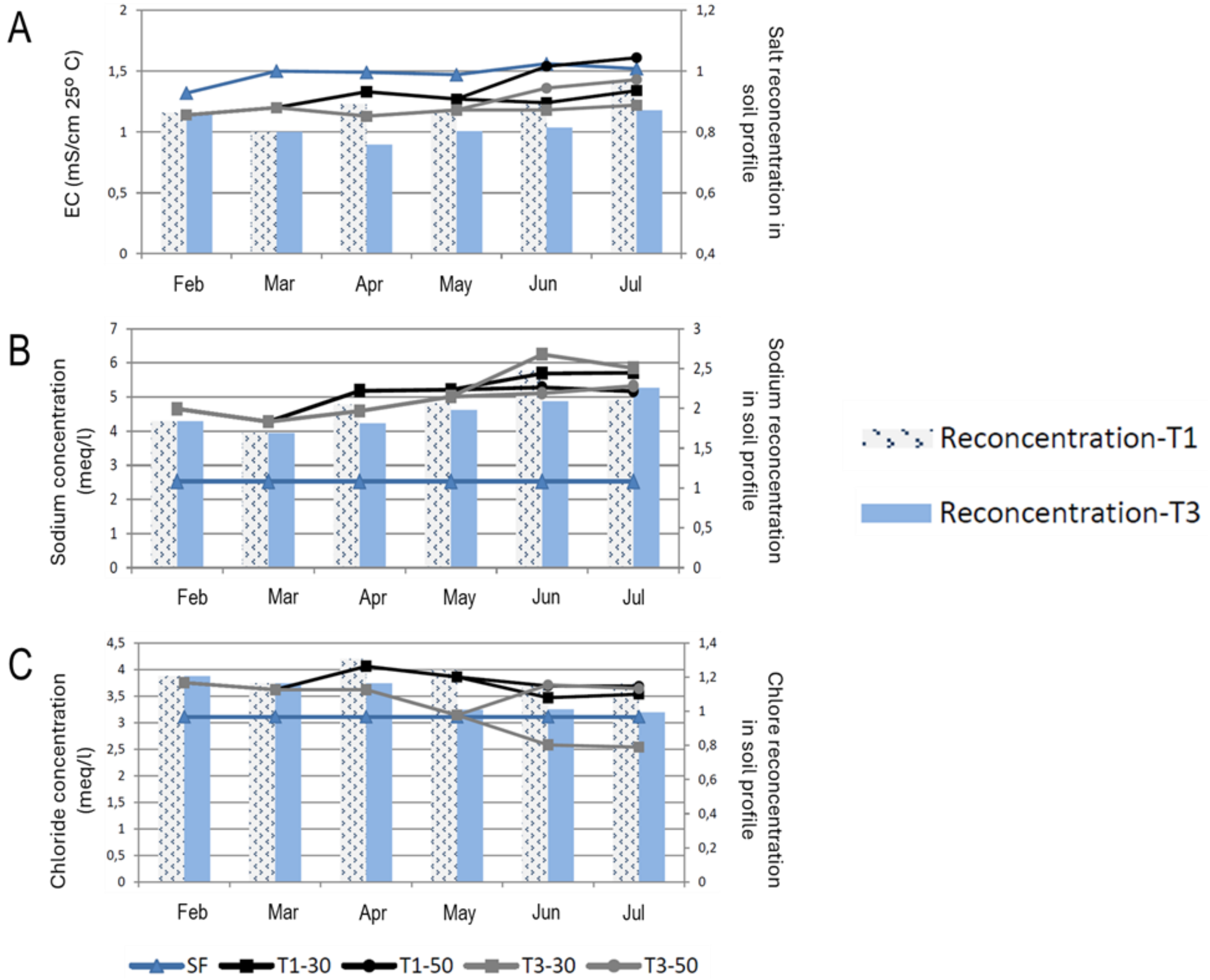

Fig. 8. *Average mineral variations (expressed in concentrations) in soil solution in function of different irrigation treatments- (A) Electrical Conductivity (EC); (B) Sodium (Na); (C) Chloride (Cl). SF = Fertilizer Solution*

Oligoelements

In the Souss-Massa region, more than 87% of the foliar iron contents measured for five varieties were greater than 100 ppm, therefore classified according to reference levels in citrus fruits as high to very high levels (Fig. S4). For samples taken at the end of June and September, almost 80% of the iron levels were greater than 200 ppm. Foliar manganese levels were generally normal to high as more than 80% were above 25 ppm (Fig. S4A). Manganese deficiencies were more frequent at the start of the campaign, 66% of contents below 25 ppm were recorded for the sampling at the end of February and the end of March (Fig. S4B). Copper deficiencies were very widespread in the region for the five varieties studied. More than 56% of copper contents were less than 5 ppm (Fig. S4C). The distribution of foliar zinc contents revealed that deficiencies in this element were not frequent. More than 82% of the zinc contents measured for the five varieties of clementine trees were above 25 ppm (Fig. S4D). On the other hand, the distribution of both bore (Fig. S4E) and molybdenum (Fig. S4F) contents was normal following reference levels for citrus fruits.

The nutritional status of clementine varieties can vary significantly, affecting fruit quality and yield. A comparative analysis by Fabroni et al. (2016) observed that different clementine varieties exhibited distinct nutrient profiles. Some varieties showed higher concentrations of vitamin C, while others had higher levels of minerals like potassium and calcium.

Phytotoxic elements

Cases of excess chloride in the Souss-Massa region were rare. More than 85% of foliar chloride contents in the five varieties of clementine in the region were below 844 ppm. More than 63% of high contents were recorded towards the end of March (Fig. S5A). On the other hand, Cases of excess foliar sodium were frequent, as more than 36% of the measured levels were greater than 357 ppm (Fig. S5B).

Mineral variations of clementine varieties in terms of phenological stages

The study examined the mineral variations in clementine varieties across different stages of development, with a particular focus on macroelements and oligoelements. Wireframe analysis was used to assess the fluctuations in mineral content, and the results indicated distinct patterns within clementine varieties and across phenological stages (Fig. 6)

In terms of macroelements, fluctuations were primarily observed in calcium (Ca) and nitrogen (N) across the development stages of all clementine varieties. Calcium displayed significant fluctuations throughout all varieties' flowering, fruit growth, and maturation stages. Notably, the highest concentrations of calcium were observed during the flowering and maturation cycles, while lower concentrations were detected in other macroelements, such as potassium (K), magnesium (Mg), and phosphorus (P). These findings suggest that calcium plays a pivotal role in the development and maturation of clementines, with varying degrees of influence from other macroelements (Cronje *et al*., 2011; Nadeem *et al*., 2018).

On the other hand, nitrogen fluctuations were more selective, with variations observed in specific clementine varieties such as Sidi Aissa (Fig. 6A), Cadoux (Fig. 6B), and Nules (Fig. 6D). These fluctuations were predominantly concentrated in the fruit set and growth stages, signifying the potential impact of nitrogen on the growth and development of clementines (Oustric *et al*., 2021). The observed variations in nitrogen content suggest that it may be a critical factor in the growth of some clementine varieties (Hammami *et al*., 2010; Barlas and Kadyampakeni, 2022).

In the case of oligoelements, fluctuations were noted in chlorine (Cl), iron (Fe), and sodium (Na) across all clementine varieties (Fig. 7). High variations in chloride were particularly prominent in the Cadoux (Fig. 7B), Nour (Fig. 7C), and Orogrande (Fig. 7E) varieties. Cadoux exhibited the highest concentrations of iron, indicating its potential role in iron accumulation. Notably, Sidi Aissa displayed the most significant variations in sodium content. These findings highlight the diverse responses of clementine varieties to oligoelements, underscoring the importance of varietal selection for improved mineral content in clementine production (Gonzálvez and de la Guardia, 2013).

The mineral content of clementine varieties varies throughout the development stage. Nutrient levels were generally highest in the early stages of fruit development and declined as the fruit matured. This is because the tree uses nutrients to build the fruit structure and accumulate flavor compounds (Pinney *et al*., 1998). For

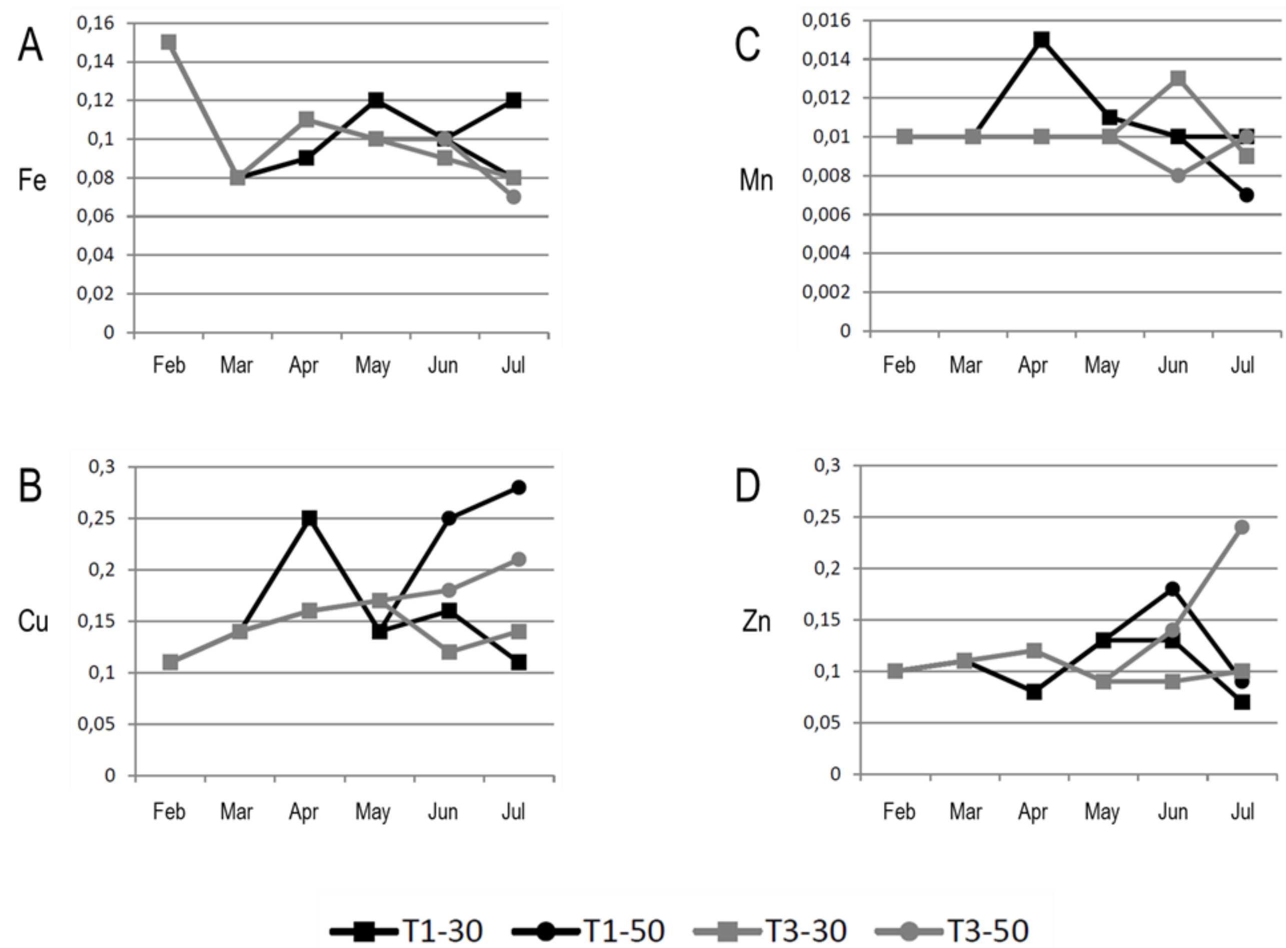

Fig 9. *Variation in soil mineral elements in the " Nules " experimental plot grafted on "Citrus macrophylla"*

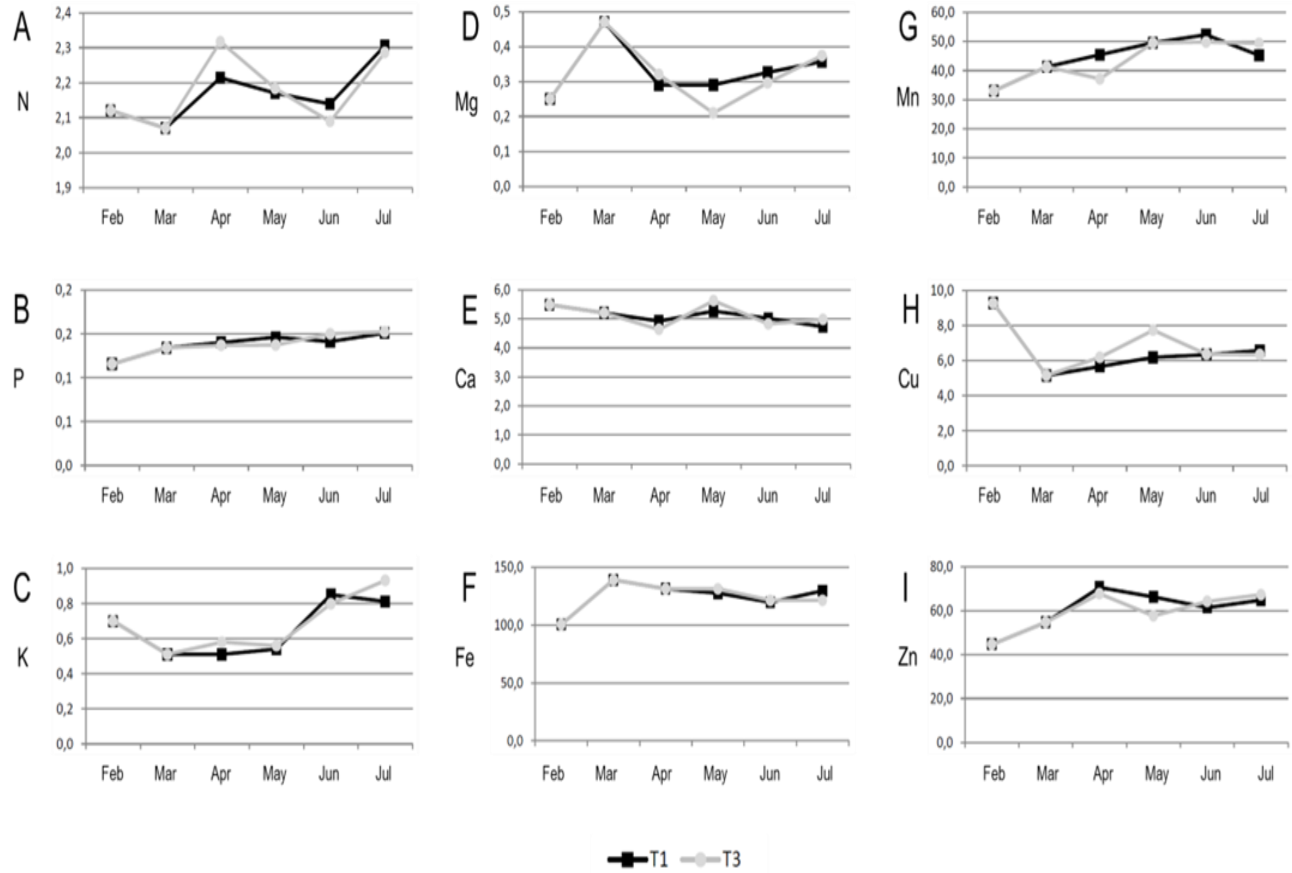

Fig. 10. *Variation in foliar mineral elements in the " Nules " experimental plot grafted on "Citrus macrophylla"*

instance, a study by Poiroux‐Gonord *et al*. (2013) found that the potassium content of clementine fruits was highest at the early stages of development and declined by about 30% by the time the fruits were ripe. The same findings regarding calcium content were emphasized by Sachan and Kumar (2022). The phenological stage plays a pivotal role in mineral content fluctuations (Rop *et al*., 2010; Fawole and Opara, 2013). Specifically, significant variations in macroelements and oligoelements were predominantly observed during the flowering and fruit growth stages. These findings suggest that these stages are crucial in influencing mineral content (Rop et al., 2010), and specific management practices may be needed to optimize mineral accumulation during these critical developmental phases.

Experimental usage of mobile lysimetry in fertilization management and monitoring

Salt profile

In fertilization management using mobile lysimetry, the salt profile constitutes an effective index for controlling the salt content in the root zone, the reconcentration, and the leaching of salts, particularly sodium and chloride. Therefore, the electrical conductivity, the sodium and chloride levels in the soil solution, in the fertilizer solution, and the soil were analyzed throughout the experimental period (Fig. 8)

The electrical conductivity (EC) of the fertilizer solution oscillated around an average of 1.5 mS/cm, a value considered adequate for the fertilization of citrus fruits. As for the electrical conductivity of the soil solution, it was generally lower than the EC of the nutrient solution and changed depending on the depth of solution extraction (30 cm and 50 cm) and the irrigation treatments (T_1 and T_3). Regarding the latter, applied at the level of the experimental plot, we noted that for an irrigation flow of 2 l/hour/dripper (T_1), the salinity is higher compared to an irrigation flow of 8 l/hour/dripper (T_3) on the two depths studied (Fig. 8A). The same trend was observed for the salts reconcentration in the root zone. This confirms the important effect of the irrigation regime (dose × frequency) on salinity at the root profile level (Nagaz *et al*., 2012; Slama *et al*., 2019). By comparing salinity at different depths, we found that the salinity is higher at a depth of 50 cm for the two irrigation treatments.

Sodium (Na^+) ions were more concentrated in the solutions extracted to a depth of 30 cm for the two irrigation treatments. Regarding irrigation, Na^+ ions are exposed to upward migration and consequently tend to accumulate in the surface horizons (Soltner, 2005). In the experimental plot, the reconcentration of Na^+ ions in a depth ranging from 30 to 50 cm from the soil profile varied between 1.69 and 2.47 (Fig. 8B), while the reconcentration was higher for the T_1 treatment. Regarding soil sodium, Figure 8B shows that during the entire experimental period, its level varied between 0.37 and 0.72 meq/100 g of soil. The soil irrigated using 8 l/hour drippers (T_3) had significantly higher sodium levels than the soil irrigated with T_1 treatment (2.3 l/hour/dripper).

The concentration of the soil solution in chloride (Cl^-) ions varies between 2.54 to 4.06 meq/l depending on the irrigation treatment and the depth of extraction (Fig. 8C). With an irrigation flow rate of 2 l/hour/dripper (T_1), the Cl^- concentration in the soil solution was approximately the same for the two sampling depths. On the other hand, with an irrigation flow of 8 l/hour/dripper (T_3), chloride ions were more concentrated at a depth of 50 cm. The reconcentration of chloride ions over a depth ranging from 30 to 50 cm from the root profile varied between 0.99 and 1.30. Figure 8C shows that chloride ions tend to be re-concentrated more in the soil profile in the case of irrigation with a flow rate of 2 l/hour/dripper.

pH profile

In the experimental plot, the analyses showed a pH of the solution which varied between 7.5 and 8.2 (Fig. S6). These pH values were high because of potential limitations in the absorption of phosphorus and microelements, especially iron (Ramzani *et al*., 2016). Comparing the pH values in the soil solution and the soil, Fig. S5 shows that the pH in the soil was significantly higher compared to the soil solution, but studying the correlation did not showcase a significant relationship.

Mineral profile

Monitoring the concentration of trace elements in the soil solution throughout the experimental period showed a low availability of iron (Fig. 9A), manganese (Fig. 9C), and a high availability of zinc (Fig. 9B) and copper (Fig. 9D). Based on the low availability of iron and manganese in the soil solution, foliar sprays with trace elements were made twice between March and April.

Foliar profile

According to reference standards, Monitoring foliar nitrogen concentrations in the "Nules" variety showed that they were low to very low. These contents varied between 2 and 2.28% (Fig 10A). The foliar phosphorus contents showed normal concentrations throughout the experimental period despite the low quantities of phosphate ions measured in the soil solution (Fig. 10B). Moreover, Leaf potassium levels during the experimental period were normal at the start of the cycle (February). Moreover, potassium concentrations decreased between March and May, giving values below 0.7%. Leaf potassium levels measured between June and July are normal (greater than 0.71%) (Fig. 10C). Monitoring of foliar magnesium concentrations shows that they were normal (0.25%-0.45%) throughout the experimental period. Except for the concentration measured in May for treatment T3 (Fig. 10D). Furthermore, foliar calcium concentrations were high, greater than 5% (Fig. 10E). Similarly, leaf iron levels were high throughout the experimental period (> 100 ppm) (Fig. 10F). Regarding the foliar concentrations of manganese (Fig. 10G), copper (Fig. 10H), and zinc (Fig. 10I), they were all in the normal range.

Mobile lysimetry is an innovative tool that can provide real-time data on soil and foliar conditions in citrus orchards. In a pioneering study by Rao *et al*. (2013), mobile lysimeters were employed to monitor salinity, pH, and mineral content in both soil and leaves. Similarly, Atta *et al*. (2020) used mobile lysimetry to monitor the salinity levels in the soil and leaves of citrus trees. They found that the salinity levels in the soil were higher in areas of the orchard that had received more fertilizer. They also found that the salinity levels in the leaves were higher in trees that were growing in areas with higher soil salinity. In addition, A study by Levy *et al*. (2013) used mobile lysimetry to monitor the effects of different fertilization programs on soil nutrient levels. This technology enables precision fertilization management by allowing growers to make timely adjustments in response to changing nutrient and salinity levels (Atta *et al*., 2020).

Conclusion

This innovative study used mobile lysimetry to optimize citrus (*C. clementina* Hort. Ex Tanaka*)* fertilization in Morocco, demonstrating the crucial role of precise nutrient management for high yields and minimal environmental impact. The research pinpointed optimal fertilization strategies by monitoring soil and leaf nutrients in clementines under varying irrigation and emphasized the need for sustainable practices. Mobile lysimetry offers a powerful tool for achieving both productivity and sustainability in citrus cultivation, aligning with global concerns about resource conservation. Further research on its long-term effects on soil, trees, and fruit is crucial. Integrating it with smart farming tech like remote sensing and AI could optimize nutrient, water, and pest management. Scalability and economic feasibility studies are needed for wider adoption across farm sizes.

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Supplementary Information

The figures (S1- S6) and Table (S1) in the text of this study are given supplementary information. The author is responsible for the content or functionality of any supplementary information. Any queries regarding the same should be directed to the corresponding author. The supplementary information is downloadable from the paper's webpage and will not be printed in the print copy.

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Conflict of interest

The authors declare that they have no conflict of interest.

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