Irrigation management strategies through the combination of fresh water and desalinated sea water for banana crops in *El Hierro*, Canary Islands

Sergio J. Álvarez-Méndez, Isidro Padrón-Armas and Jalel Mahouachi

ABSTRACT

The current lack of natural water resources, mainly due to the absence of sufficient precipitation and the deterioration of irrigation water (IW) quality, urgently requires a search for alternative resources, especially in arid and semiarid areas. Desalination of sea water is well established in numerous regions where water is scarce. To investigate the effects of the combination of regular fresh water and desalinated sea water (DSW) on mineral nutrient changes in crops, an experimental system based on *Musa acuminata* AAA plants was performed in *Frontera* (*El Hierro*, Canary Islands). Data showed that banana crops irrigated with a mixture of fresh water and DSW exhibited an adequate nutritional status and did not suffer any injuries of salt ions (Na^+ and Cl^-) or B toxicity. Moreover, plants may tolerate higher concentrations of these elements and a major supply of the other essential micronutrients. The obtained results suggest that irrigating crops with a combination of fresh water and DSW is a good strategy to respond to the high water requirements, at least under the tested experimental conditions. This strategy could be very helpful in arid regions, as well as in other areas where precipitation is seasonal and scarce, like the Mediterranean or the Canaries.

Key words | banana, chloride, desalination, macronutrients, micronutrients, sodium

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HIGHLIGHTS

- Banana crops irrigated with a mixture of desalinated sea water and groundwater showed an adequate nutritional status.
- No toxicity due to salinity and boron was found in the crops.
- The mixture of fresh water and DSW generated levels of Na^+, Cl^-, CE and SAR lesser than DSW alone and resulted much more suitable for banana crop irrigation.

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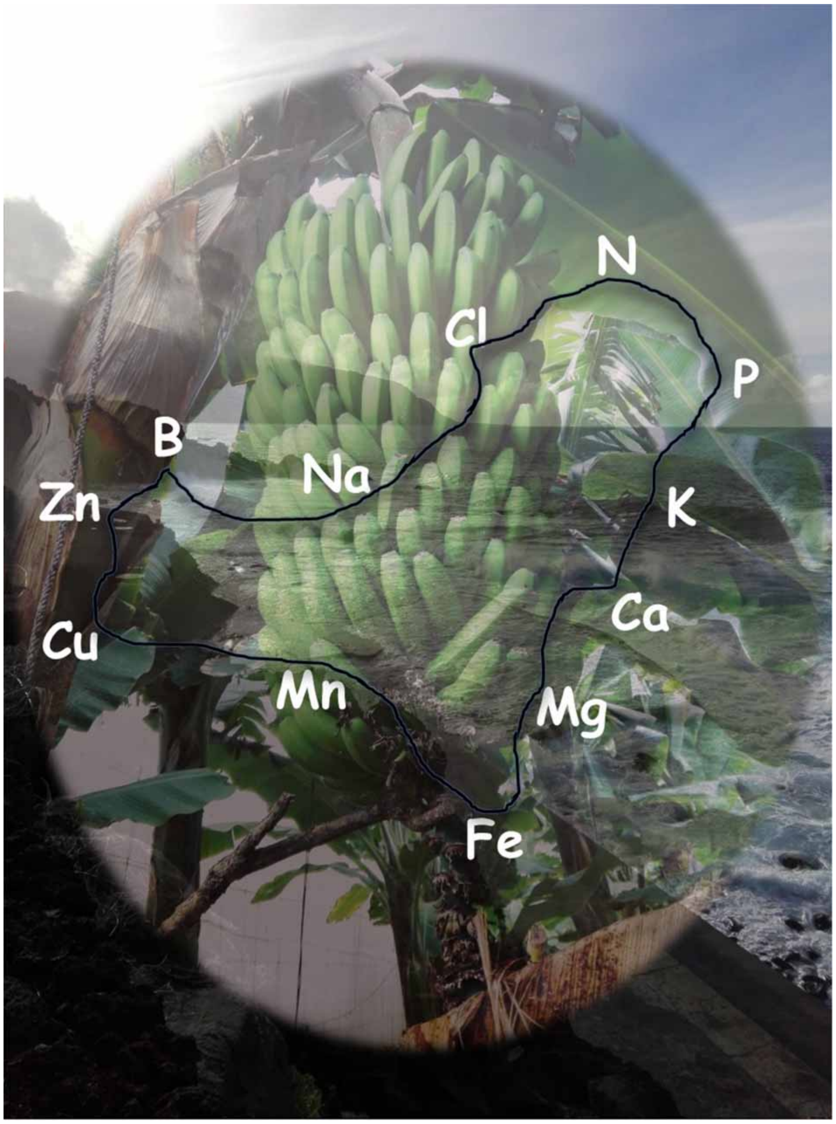
GRAPHICAL ABSTRACT



INTRODUCTION

Climate change is currently threatening nature and also the behaviour of human beings. Perhaps the most perceptible indicators of the climatic menace are the rise in temperature and the decrease in rainfall, especially in arid and semiarid regions (Falco *et al.* 2019). The absence of precipitation, the impoverishment of irrigation water (IW) quality induced by excessive fertilization and the overexploitation of aquifers has led to an increasing scarcity of natural water resources. Thus, it is imperative to search for alternative resources to respond to the higher demand of water for domestic, touristic and agricultural uses. Currently, among the non-conventional water resources, the reuse of wastewater and the desalination of brackish and seawater have a leading role (International Water Association 2016). Both tactics have been successfully employed for agriculture purposes. On the one hand, effects of irrigation using sewage water has been evaluated on diverse crops such as tomato (Ashraf *et al.* 2013), pepper (Dagianta *et al.* 2014), grape vineyards (Netzer *et al.* 2014), lettuce (Orta de Velásquez *et al.* 2014), maize, green beans, and alfalfa (Abdel-Shafy & El-Khateeb 2019), and citrus (Abdel-Shafy & El-Khateeb 2021). On the other hand, desalinated sea water (DSW) has also been widely employed in agriculture for irrigation of cotton (Wang *et al.* 2012), banana (Silber *et al.* 2015; Mendoza-Grimón *et al.* 2019), winter vegetables, melon, watermelon, and lettuce (Martínez-Álvarez *et al.* 2017), citrus (Maestre-Valero *et al.* 2020), subtropical crops such as mango, papaya and avocado (Monterrey-Viña *et al.* 2020), and tomato (Antolinos *et al.* 2020).

The Canary Islands, located in the Atlantic Ocean, have a total surface area of 7,447 km^2 and a population slightly greater than two million inhabitants (*Boletín Oficial del Estado* 2019). Agriculture was the main economic activity of the archipelago until the irruption and rise of tourism from the 1960s (Sadhwani *et al.* 2015). Both activities require a significant amount of water resources, albeit fresh water reserves sharply differ between islands. In occidental islands, such as La Palma, 100% of the water currently consumed is groundwater, whereas this percentage dramatically drops to less than 4% in the easternmost islands of La Graciosa, Lanzarote and Fuerteventura (González-Morales & Ramón-Ojeda 2019). Indeed, at the beginning of the 20th century, frequent drought periods triggered water scarcity in the eastern Canary Islands. This circumstance has encouraged the constant search for non-conventional water resources, eventually leading to the installation of the first desalination plant in Lanzarote in 1964 (Gómez-Gotor *et al.* 2018). Since then, most of the islands progressively built their own desalination plants (Gómez-Gotor *et al.* 2018). By 2010, there were more than 300 desalination plants in the Canaries, with Reverse Osmosis (RO) membranes being the technology employed by over 96% of the plants (Sadhwani *et al.* 2015). Desalination plants have also become popular in the southeast of mainland Spain (Navarro 2018). In fact, sea water desalination now plays an important role to fight fresh water scarcity worldwide (Schreiner *et al.* 2014; Zhu *et al.* 2019).

Within the framework of the Canary Islands, the hydrological case of *El Hierro* is peculiar. The island showed an endemic problem of water supply for several centuries, based mainly on the geological features of the island, as well as on human activity. From a geological point of view, El Hierro is the youngest island of the archipelago and it is still volcanically active. The absence of prolonged inactive periods has allowed the accumulation of porous permeable materials both at the surface and beneath the soil, hence retention of water is complicated (Martín-Fernández 2009). Fortunately, healthier human praxis and the irruption of desalination technologies in the Canaries yielded a better management of the water resources. Nowadays, 19% of water consumption in *El Hierro* comes from desalination (González-Morales & Ramón-Ojeda 2019), and is produced by three plants: *La Restinga, Los Cangrejos* and *El Golfo* (Figure 1).

Pre-treatment of desalinated sea water is crucial for reducing the formation of scale and includes adding coagulants, acids, disinfectants, inhibitors of the precipitation of crystallized mineral and $NaHSO_3$ (Kumar *et al.* 2018). The use of nanofiltration membranes reduces dissolved ions in feed water for RO, thus achieving a high-quality pre-treated water (Burn *et al.* 2015). On the other hand, during post-treatment the concentration of ions (especially Ca^{2+}, Mg^{2+} and SO_4^{2-}) must be fine-tuned to achieve the required quality, especially for agriculture uses (Al-Jabri *et al.* 2015). Traditional remineralization systems are calcite/dolomite filters and lime dosing, although mixing DSW with fresh water is also a common practice for agriculture purposes (Zarzo *et al.* 2013). Besides, irrigation with DSW also leads to long-term damage due to an increase in soil salinity and boron concentration (Díaz *et al.* 2013). However, it should be pointed out that boron phytotoxicity may be reduced when good soil and water management is performed, e.g., mixing DSW with fresh water (Mendoza-Grimón *et al.* 2019).

Banana is the principal crop in the Canary Islands with an average area of 8,639 ha dedicated to its cultivation and a yearly production of around 438 000 tons (ASPROCAN 2020). Dwarf Cavendish banana cultivars cultivated in the Canaries are considerably vigorous, with an average of 5–6 m in height and an elevated leaf area, which demand a high water availability to respond to transpiration

Figure 1 | Location of the three sea water desalination plants in *El Hierro. Source:* IDECanarias, own elaboration.

requirement. In field conditions, such demand of water can reach 15–20 L per day for adult plants, according to our previous experiments (Mahouachi 2007).

In accordance with *El Hierro* water authority (*Consejo Insular de Aguas de El Hierro*), banana orchards are generally irrigated by a mixture of fresh water, taken from water wells (80–85%), and desalinated sea water (15–20%), produced by *El Golfo* desalination plant (*Frontera, El Hierro*). Previous studies about the employment of DSW in banana orchards have focused on boron toxicity (Mendoza-Grimón *et al.* 2019) and on the relationship between yield, irrigation rate and water salinity (Silber *et al.* 2015). Nevertheless, to the best of our knowledge, the effect of the use of DSW on the nutritional content of bananas has never been studied before. Therefore, considering the previous background, the objective of the present study was to assess for the first time the effects of the combination of conventional fresh water and DSW on the nutritional status of bananas (*Musa acuminata* AAA Dwarf Cavendish). For that purpose, a field study was performed throughout two consecutive seasons in orchards in *El Hierro*, where salinity markers and mineral nutrient concentrations in leaves, soil and IW were evaluated.

MATERIALS AND METHODS

Plant material and fertigation system

To evaluate the effects of DSW on mineral nutrient changes in banana, four orchards of this crop established in *Frontera* location (*El Hierro*, Canary Islands), and generally *Musa acuminata* AAA 'Grand Nain' plants were used. This cultivar is widely cultivated in these islands, due to its elevated productivity and excellent adaptation to the sub-tropic conditions (Mahouachi 2007). Plants were daily irrigated by means of a micro-sprinkler irrigation system that also supplies fertilizer in solution. The IW was obtained from the mixture of fresh water with DSW in accordance with the following ratios (fresh water/DSW): 83–86/17–14 (2017), 86–89/14–11 (2018) and 80–85/20–15 (2019). Plant nutrition was preformed following the usual local conditions and the requirement of this crop provided by *Cooperativa of Frontera*. Thus, the amounts of the main supplied fertilizers expressed in g/plant/year were around 143 (N), 57 (P_2O_5), 266 (K_2O) and 102 (CaO).

Experimental conditions and sampling

Soil, IW and banana leaves samples were collected from four banana orchards located between 27°46′29″N 18°00′40″W and 27°45′47″N 18°01′25″W in *El Golfo* area (*Frontera, El Hierro*). The following sampling dates were established to cover a study period of two years: November 2017; July 2018; November 2018; July 2019, and November 2019. For each date and for each orchard, one water sample was directly taken from the mains, five soil samples were taken from a 25 to 35 cm depth at a distance of approximately 1 m from the main banana stems, and the third leaf counting from the apex of five different banana plants were collected. Banana leaves were stored at 4 °C until they were analysed.

Physicochemical determinations

1. Foliar analyses: samples of leaves were meticulously rinsed first with tap water and then with distillate water, dried at 60–65 °C, ground, filtered (0.75 mm mesh) and incinerated (450 °C). Then the ashes were dissolved in an aqueous HCl solution and minerals were analysed as follows: nitrogen by Kjeldahl digestion in sulphuric medium with copper and selenium as catalysts, gathering in boric acid and titration with a 0.05 N aqueous sulphuric acid solution (Sáez-Plaza *et al.* 2013a, 2013b); phosphorus by the vanadium phosphomolybdate method (Barton 1948); cations (potassium, calcium, magnesium, sodium, iron, manganese, copper and zinc) by inductively coupled plasma atomic emission spectroscopy (ICP-AES); and finally boron by the azomethine H colorimetric method (Gaines & Mitchell 1979).
2. Water analyses: for water samples pH was measured with a pH-meter GLP-21, dissolved solids by gravimetric method, cations (potassium, calcium, magnesium, iron, manganese, copper and zinc) by ICP-AES, carbonates and bicarbonates by titration with a 0.1 N aqueous HCl solution employing a Titrino plus titrator supplied by Metrohm, chlorides by potentiometric method employing silver-silver chloride electrode as reference and Titrino plus titrator supplied by Metrohm, sulphates by colorimetry with barium chloride as reagent and nitrates by direct measurement at 220 nm (Baird *et al.* 2017).
3. Soil analyses: samples were air-dried and sieved (2 mm mesh). The following parameters were analysed: Olsen phosphorus by extraction with a 0.5 N aqueous sodium bicarbonate solution (pH 8.5, 30 min) and exchangeable cations by extraction with a 1 N aqueous ammonium acetate solution at pH 7 unless carbonates were present, in that case calcium and magnesium were extracted with sodium acetate at pH 8.2 (*Soil Survey Laboratory Methods Manual 1996*).

Statistical analyses

Data representation was carried out with Microsoft® Excel® 2019 MSO (16.0.10356.20006). Statistical analyses were performed using the software IBM® SSPSS® Statistics version 25 for Windows (IMB Corporation, Armonk, NY, USA). Significant differences between DSW and IW parameters were determined using a Mann–Whitney *U* test. Regarding the statistical study of the evolution of foliar nutrients through the experimental period, variables with a normal distribution (according to Shapiro–Wilk test) and homogeneity of variance (according to Levene test), were subjected to analysis of variance (ANOVA). For variables with a non-normal distribution of the residuals or non-homogeneity of the variance, non-parametric Kruskal–Wallis *H* test was performed, and such cases are properly indicated beside figures. Duncan test was used for mean separation. The significance level for all tests was set at $p < 0.05$.

RESULTS AND DISCUSSION

Macronutrients changes

Foliar total N content showed constant values (2.5–2.6%) along the study (Figure 2(a)). Nevertheless, the nitrates content in IW fluctuated between 4.25 and 10.48 ppm, and no significant differences were found with the nitrates originally present in DSW (4.55 ± 0.61 ppm, Table 1). Leaf P levels varied between 0.17 and 0.24%, registering the low content in July 2019 and thereafter getting a recovery of this nutrient (Figure 2(b)). Soil phosphorus content showed a continuous decrease from a maximum of 259 ppm (July 2018) to a minimum of 27.25 ppm (November 2019); however, this reduction did not alter its foliar content. Indeed, Figure 2(a) and 2(b) respectively demonstrate that both N and P foliar concentrations are included in the accepted range of nutrient banana requirement (Lahav & Turner 1989; Robinson & Galán-Saúco 2011).

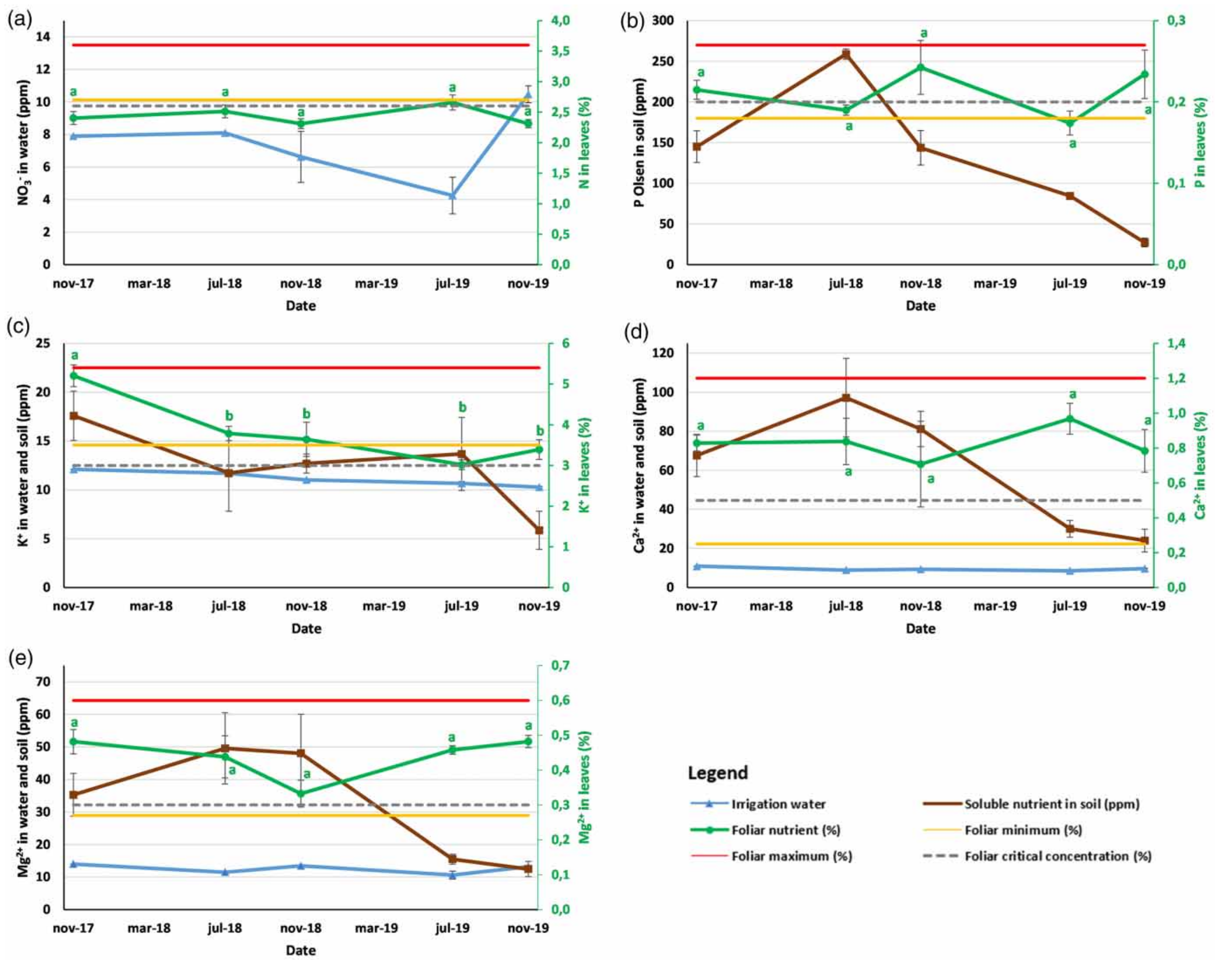


Figure 2 | Representation of the evolution of the N (a), P (b), K (c), Ca (d) and Mg (e) content through the two years study period (x-axis) by means of the NO_3^- (a), K^+ (c), Ca^{2+} (d) and Mg^{2+} (e) concentration (ppm) in irrigation water (blue line, ▲, left y-axis as reference), the P Olsen (b), K^+ (c), Ca^{2+} (d) and Mg^{2+} (e) concentration (ppm) in soil (brown line, ■, left y-axis as reference), and the N (a), P (b), K (c), Ca (d) and Mg (e) percentage in leaves (green line, •, right y-axis as reference; same small letters indicate that no significant differences were found among samplings from different dates). Right y-axis also shows Lahav & Turner's (1989) foliar critical concentration on third leaf counting from the apex (horizontal dashed grey line) and the interval between minimum (horizontal straight orange line) and maximum (horizontal straight red line) values described by Martin-Prevel (1980a, 1980b). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wrd.2021.078.

Table 1 | Values of physicochemical properties of desalinated sea water (DSW) and irrigation water (IW) ($n \geq 7$) sampling from November 2017 to November 2019; mean ± standard error of the mean; asterisks denote significant differences ($p < 0.05$) of IW with respect to DSW

Parameter	Unit	DSW	IW
pH		7.25 ± 0.39	8.65 ± 0.09*
EC 25 °C	mS/cm	0.60 ± 0.01	0.49 ± 0.00*
Dissolved salts	g/L	0.33 ± 0.01	0.34 ± 0.00*
HCO_3^-	mg/L	8.91 ± 0.38	118.20 ± 3.14*
CO_3^{2-}	mg/L	0.00 ± 0.00	9.18 ± 1.45*
Cl^-	mg/L	173.56 ± 8.17	67.38 ± 1.60*
SO_4^{2-}	mg/L	6.69 ± 1.11	21.11 ± 0.27*
NO_3^-	mg/L	4.55 ± 0.61	7.24 ± 0.84
Ca^{2+}	mg/L	1.54 ± 0.26	9.35 ± 0.19*
Mg^{2+}	mg/L	4.93 ± 0.61	12.60 ± 0.43*
Na^+	mg/L	121.89 ± 4.35	63.86 ± 0.66*
K^+	mg/L	5.49 ± 0.17	10.85 ± 0.17*
SAR		11.12 ± 0.80	3.18 ± 0.05*

As shown in Figure 2(c), K^+ concentration varied between 3.0 and 5.4% that are adequate values for banana growth and development under our conditions (Stover & Simmonds 1987; Lahav & Turner 1989; Robinson & Galán-Saúco 2011). The highest foliar level of K^+ (5.4%) at the onset of the experimental period is not troubling and even preferable since it is the greatest mineral required for banana nutrition and consequently fruits of this crop are good source of this element for human nutrition (Kumar et al. 2012). Soluble K^+ in the soil showed similar tendency of change as foliar level, except in the last date when its concentration reached the lowest value (Figure 2(c)).

Foliar Ca^{2+} content varied within the recommended range for banana between 0.71 and 0.97% (Figure 2(d)). The accepted levels of this nutrient ranged 0.25–1.20% according to Martin-Prevel (1980a, 1980b). Soluble Ca^{2+} in the soil measured high concentrations and reached a maximum of 1.25% (July 2019); however, at the end of the experimental period a low content (0.25%) of this mineral was observed in the soil. This reduction did not affect the foliar level of this element (Figure 2(d)).

Figure 2(e) illustrate that concentration of foliar Mg^{2+} was practically constant (0.30–0.48%) during the sampling period, and also suitable for banana exigencies as reported by Lahav & Turner (1989). In soil, soluble Mg^{2+} showed the same tendency as Ca^{2+} with higher concentrations until November 2018 and a subsequent decrease in the last two dates, which did not modify the level of this nutrient in the leaves (Figure 2(e)).

It is also worth to mention that the resulting IW obtained from the combination of the conventional and DSW waters exhibited significantly higher concentration of K^+ (10–12 ppm), Mg^{2+} (11–14 ppm) and Ca^{2+} (8.5–10 ppm) compared to those of only DSW (K^+, 5–6 ppm), (Mg^{2+}, 2–7 ppm) and (Ca^{2+}, 0.6–3 ppm), respectively (see Figure 2(c)–2(e) and Table 1). Several studies on desalination reported that the system of RO removes many essential anions and cations, and remineralization should be adopted (Al-Jabri et al. 2015; Burn et al. 2015). In our present study, the mixture of fresh water and DSW recovered all the removed elements by the process of desalination.

Micronutrients changes

Considering previously reported micronutrient concentrations (Fe^{2+}, Mn^{2+}, Cu^{2+} and Zn^{2+}) in banana leaves by Stover & Simmonds (1987), Lahav & Turner (1989), and Robinson & Galán-Saúco (2011), these elements analysed herein showed higher values than the minimum established with the exception of Zn^{2+} and Fe^{2+}, which showed equal or minor concentration. Specifically, the level of foliar Fe^{2+} was slightly lower than the minimum required for banana (80 ppm), and varied between 60 and 70 ppm (Figure 3(a)).

The concentration of Mn^{2+} was situated in the range of 35–55 ppm, higher than the minimum or critical concentration (25 ppm) reported for banana growth (Figure 3(b)).

The foliar Cu^{2+} content was mainly constant (9 ppm), and slightly higher than the minimum needed by this species (6 ppm) except at the beginning of the experimental period when a significant major concentration around 16 ppm was determined (Figure 3(c)).

Finally, the amount of Zn^{2+} in the analysed leaves was low (7 ppm) at the onset of the experiment; however, concentrations close to the critical concentration (18 ppm) were determined thereafter (13.6–18.0 ppm) (Figure 3(d)).

On the other hand, the content of B found in the foliar organs was within the interval 13.3–19.2 ppm, slightly

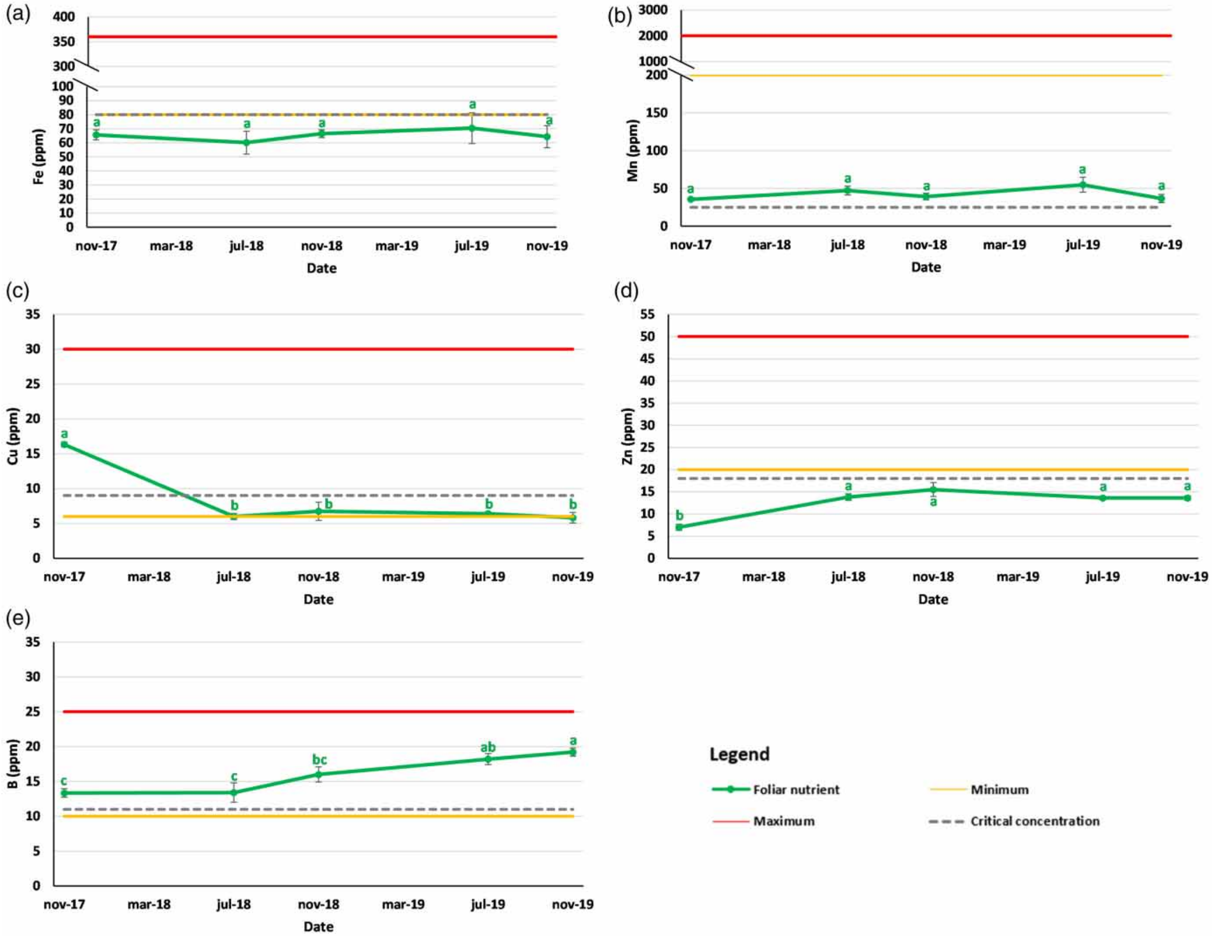


Figure 3 | Representation of the evolution of the Fe (a), Mn (b), Cu (c), Zn (d) and B (e) content through the two years study period (x-axis) by means of the Fe (a), Mn (b), Cu (c), Zn (d) and B (e) concentration (ppm) in leaves (green line, •, y-axis; same small letters indicate that no significant differences were found among samplings from different dates, according to Kruskal–Wallis *H* test). It is also shown Lahav & Turner's (1989) foliar critical concentration on third leaf counting from the apex (horizontal dashed grey line) and the interval between minimum (horizontal straight orange line) and maximum (horizontal straight red line) values described by Martin-Prevel (1980a, 1980b).

higher than the minimum value of reference (10 ppm) and lower than the maximum tolerated by this crop (25 ppm) (Figure 3(e)). The concentration of foliar B determined under our conditions using the mixture of fresh water and DSW did not entail any injury in the plants and roughly coincides with the observation of no toxicity reported by Mendoza-Grimón *et al.* (2019) even with the use of DSW by RO in banana crops.

The total of micronutrients analysed in banana leaves generally showed levels close or slightly higher than the minimum and far from the optimal requirement; thus, these findings may suggest that a major addition of these elements as fertilizers should be appropriate for banana nutrition.

Variables related to salinity

The levels of Na^+ in banana leaves generally varied between 0.020 and 0.024% throughout the period of study, excepting a minor concentration (0.015%) temporarily found at July 2019 (Figure 4(a)). These values are higher than those reported in young plants (0.014–0.018%) irrigated by only fresh water (Mahouachi 2009). It is interesting to note that the analysed IW contains around 61.78–67.60 ppm of Na^+ (Figure 4(a)); nevertheless, DSW registered much higher concentrations (121.89 ± 4.35 ppm) (Table 1).

Foliar Cl^- exhibited quite stable concentrations (0.11–0.18%) during the experimental period. These concentrations are much lower than the reported critical levels

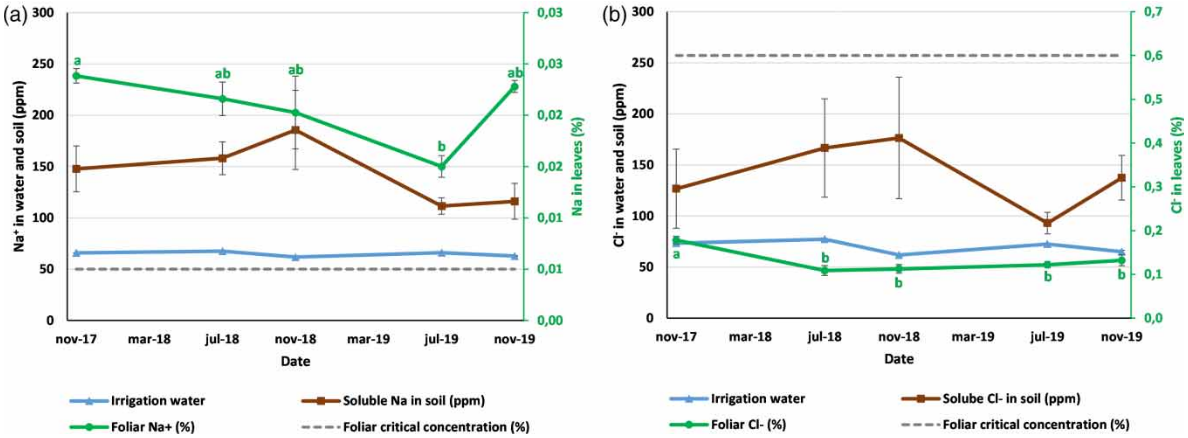


Figure 4 | Representation of the evolution of the Na^+ (a) and Cl^- (b) content through the two years study period (x-axis) by means of the Na^+ (a) and Cl^- (b) concentration (ppm) in irrigation water (blue line, ▴, left y-axis as reference) and soil (brown line, ▪, left y-axis as reference), and Na^+ (a) and Cl^- (b) percentage in leaves (green line, •, right y-axis as reference; same small letters indicate that no significant differences were found among samplings from different dates, whereas different small letters show when significant differences were found among samplings from different dates, according to Kruskal–Wallis *H* test). Right y-axis also shows Lahav & Turner's (1989) foliar critical concentration on third leaf counting from the apex (horizontal dashed grey line). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wrd.2021.078.

(0.60%) and no risk of leaf injuries can be triggered in banana under these conditions (Figure 4(b)). Levels of Cl^- in the soil varied between 93 and 176 ppm without significant changes throughout the experimental period. In the IW, concentrations of Cl^- (67.38 ± 1.60 ppm) were significantly lower than its content in the DSW (173.56 ± 8.17 ppm) (Table 1).

Regarding salinity indicators, the electrical conductivity (EC) values were almost constant in IW (0.49 ± 0.00 ms·cm^{-1}) although DSW had a slightly higher EC (0.60 ± 0.01 ms·cm^{-1}) compared to the conventional water, which could result in a better water quality for crop requirement (Table 1).

In addition, the sodium adsorption ratio (SAR) in IW was practically constant, yielding values around 3.18 ± 0.05 and much lower than its value (11.12 ± 0.80) in DSW (Table 1).

Overall, the mixture of conventional water and DSW finally generated levels of Na^+, Cl^-, CE and SAR less than DSW alone and resulted in IW much more suitable for banana crop irrigation.

Finally, significant differences were also found in other physicochemical properties of both kinds of water studied, such as pH (8.65 ± 0.09 for IW vs. 7.25 ± 0.39 from DSW), dissolved salts (0.34 ± 0.00 g/L for IW vs. 0.33 ± 0.01 g/L for DSW), bicarbonate content (118.20 ± 3.14 mg/L for IW vs. 8.91 ± 0.38 mg/L for DSW), carbonate content (9.18 ± 1.45 mg/L for IW vs. 0.00 ± 0.00 mg/L for DSW) and sulphate content (21.11 ± 0.27 mg/L for IW vs. 6.69 ± 1.11 mg/L for DSW), as illustrated in Table 1. As expected, the amount of all those anions was inferior in DSW compared to IW.

CONCLUSIONS

Banana crops irrigated with combined fresh water and DSW displayed an adequate nutritional status and no risk of salt ions (Na^+ and Cl^-) or B toxicity was detected, and even plants may tolerate higher concentrations of these elements and major supply of the other essential micronutrients. Collectively, the data presented herein might suggest that the irrigation with a mixture of the available fresh water and DSW is a successful alternative to respond to the elevated increase of fresh water demand worldwide. This strategy is not only beneficial in arid zones, but also in other areas where precipitation is seasonal and scarce, such as the Mediterranean or the Canaries.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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