Relation between soil solution composition and petiole cellular extract of crops in western Mexico
Relación entre la composición de la solución del suelo y el extracto celular de peciolo de cultivos en el occidente de México

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SUMMARY

Crop fertilization greatly impacts food production. However, insufficient applications can lead to poor yields. On the other hand, an excessive application leads to soil and aquifers pollution. In this paper, field studies were carried out to determine the ranges of mineral concentration and the interaction of the ions in the soil solution (SS) and the petiole cellular extract (PCE) in several cultures established in the states of Guanajuato, Colima and Jalisco, Mexico. The hypothesis states that there is a causal relationship between the mineral composition of the soil solution (SS) and the minerals and total soluble solids (TSS) in petiole cellular extract (PCE). The following cultures were studied in this research: avocado, blueberry, broccoli, cauliflower, raspberry, strawberry, lettuce, cantaloupe, papaya, and pepper. For each culture, PCE samples and SS samples using a press to break tissue and ceramic tip lysimeters were obtained. The results were processed to obtain ranges of variation within 50% of the closest values to the median. Correlations between the several ion concentrations were analyzed using analysis of variance. The results showed values (mg L^{-1}) of NO_3^- (40-620), PO_4^{3-} (17-66), K^+ (3-377), Ca^{2+} (27-582), Na^+ (15.3-500), Mg^{2+} (10-53), Fe^{3+} (0.6-1.8), and Zn^{2+} (2.8-7.4) in soil solution, which allowed obtaining values of NO_3^- (27-9225), K^+ (820-9375), Ca^{2+} (1.0-650), Na^+ (25-620) and TSS (2-13 °Brix) in petiole cellular extract of petiole. Statistically significant correlations were observed between the concentrations of the SS ions regarding the concentrations in PCE in crops suggesting a relationship between the plant nutritive assimilation and cations or anions present in soil solution. The conclusion derived from this study is that ionic concentration ranges registered in the SS and in the PCE provide an approximation to the ranges of nutritional sufficiency for the horticultural crops established in the summer-winter in western Mexico.

Index words: *ionic interaction, nutritional sufficiency ranges, vegetable crops and fruit trees.*

RESUMEN

La fertilización de los cultivos agrícolas presenta un gran impacto en la producción de alimentos. Sin embargo, aplicaciones insuficientes pueden conducir a bajos rendimientos. Por otro lado, excesivas aplicaciones conducen a la contaminación del suelo y acuíferos. En este trabajo de investigación, fueron realizados estudios de campo para determinar los rangos de concentración mineral y la interacción de los iones en la solución del suelo (SS) y el extracto celular de peciolo (ECP) en diez cultivos establecidos en los estados de Guanajuato, Colima y Jalisco, México. La hipótesis apunta a la existencia de una relación causal entre la composición mineral de la SS con la composición mineral y los sólidos solubles totales (SST) en ECP. Los siguientes cultivos fueron estudiados:

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aguacate, arándano, brócoli, coliflor, frambuesa, fresa, lechuga, melón, papaya, y pimiento. Para cada cultivo, fueron extraídos muestras de SS y ECP usando lisímetros de punta de cerámica y una prensa para macerar tejidos. Los resultados fueron procesados para obtener rangos de variación con el 50% de los valores más cercanos a la mediana y se realizaron correlaciones entre las concentraciones de los iones, los cuales fueron analizados mediante análisis de varianza. Los resultados arrojaron valores (mg L^{-1}) de NO_3^- (40-620), PO_4^{3-} (17-66), K^+ (3-377), Ca^{2+} (27-582), Na^+ (15.3-500), Mg^{2+} (10-53), Fe^{3+} (0.6-1.8), y Zn^{2+} (2.8-7.4) en la SS, los cuales permitieron obtener valores (mg L^{-1}) de NO^-_3 (27-9225), K^+ (820-9375), Ca^{2+} (1.0-650), Na^+ (25-620), y SST (2-13 °Brix) en ECP. Se observaron correlaciones estadísticamente significativas entre las concentraciones de los iones de la SS con respecto a las concentraciones en ECP en varios de los cultivos que sugieren una relación entre la asimilación nutritiva vegetal en función de los cationes o aniones presentes en la SS. Se concluyó que los rangos de concentración iónica registrados en la SS y en ECP proporcionan una aproximación a los rangos de suficiencia nutrimental para los cultivos hortofrutícolas establecidos en el verano-invierno en el occidente de México.

Palabras clave: *interacción iónica, rangos de suficiencia nutrimental, hortalizas y frutales.*

INTRODUCTION

The production of fruit and vegetable crops has grown substantially in Mexico. Crops such as avocado, papaya, pepper, brassicas and berries have been produced for 10 years under a wide variety of climatic and soil conditions (Macías-Macías, 2010; Valencia-Sandoval, Duana, and Hernández, 2017; Fiscal, Restrepo, and Rodríguez, 2017; González-Razo *et al*., 2019). The management of nutrients applied through fertigation is an important aspect to consider in maximizing yield and quality of fruits and vegetables (Maboko and Du Plooy, 2017). Fertilizations are often used to increase the amount of salts in certain phenological stages with the purpose of improving some aspects of harvested products (Velos, Malabug, and Manuel, 2013).

The technique of fertilization and fertigation are two of the most important techniques in crop production, mainly due to their positive impact on yield and quality of production (Incrocci, Massa, and Pardossi, 2017). However, constant applications of fertilizer salts to soil have led to the contamination of surface and groundwater, as well as to the salinization of the soil itself (Moreira-Barradas, Abdelfattah, Matula, and Dolezal, 2015; Singh, 2020). This corroborates the need for a better control of nutrition programs.

In many cases, the interaction between nutrients in soil solution as in plants, and nutrients balanced supply, have been shown to be more important than increasing certain elements (Cuquel, Motta, Tutida, and Mio, 2011). For a better control of the nutritional contributions in crops, various methods of soil and plant tissue analysis have been implemented. Soil analysis allows the evaluation of the nutritional supply capacity for crops, and, on the other hand, its proper application leads to an improvement and a better planning of fertilization programs (Velos *et al*., 2013; Komosa, Roszyk, and Mieloch, 2017). Soil analysis has been carried out using different monitoring techniques such as laboratory analysis, soil analysis or aqueous extract of substrates, and soil solution extractors (Incrocci *et al*., 2017). This last technique allows a simple way of extracting the soil solution (SS) at different depths, and it is the fastest way of monitoring available ions (Falivene, 2008). Likewise, by analyzing soil solution, the complex interaction between ions in the edaphic environment can be determined (Grattan and Grieve, 1998).

Regarding the analysis of plant tissue, petiole cellular extract method (PCE) gives a way to determine the nutritional status of the plants. This method is carried out by collecting fresh plant material, which yields a quantitative evaluation of nutrients present in soluble inorganic forms in the plant tissue at the time of sampling (Llanderal *et al*., 2020). To establish a nutritional diagnosis, it is necessary to make a comparison using sufficiency ranges obtained under different cultivation conditions, since it has been observed that nutritional variable values obtained from plants vary throughout the day and season of the year, among other factors (Salazar-García, Medina, Ibarra, and González, 2018; Menzel, 2018; Llanderal *et al*., 2020).

There are several researches that propose wide sufficiency ranges through minimum and maximum values of important nutrients such as nitrate and potassium, mainly in dry foliar mass (Hochmuth *et al*., 2012). However, there are few studies that explore the relationship between the composition of the SS and the PCE. In the present study, the results of the monitoring of the ions and nutritional variables in the SS and the PCE extract of 10 economically important crops of western Mexico are presented. The objective was to obtain ranges of mineral concentration from SS and PCE for crops, which in addition to providing basic information on this nutritional aspect can constitute an approximation to obtain sufficiency ranges based on the soil solution.

MATERIALS AND METHODS

Field studies were conducted to determine the mineral concentration ranges and the interaction of ions in soil solution (SS) and petiole cellular extract (PCE) in 10 crops established in western Mexico (Table 1). The studied crops, located in agricultural fields in the states of Colima, Guanajuato and Jalisco, Mexico, were selected for their adequate agronomic management. According to the State Inventory of Forestry and Soil from the National Commission of Forestry (CONAFOR), on these lands predominate the following types of soil: Leptosol in Colima, Regosol in Jalisco and Vertisol in Guanajuato (CONAFOR, 2013a, b, and 2014). Weekly samplings were taken from May 2013 to March 2014. The collection of crop samples began after transplantation, except for avocado and blueberry, which were taken after 5 and 1 years after transplantation, respectively. Sampling for these two crops began in the bud differentiation stage in the middle of July 2013 when avocado plants were about 2 m high on average, while blueberry plants were about 0.4 m high.

Soil solution samples were extracted using (model SSAT-LT-300, Irrometer® Co. Riverside, Calif.) lysimeters following the installation procedure described by Granados *et al*. (2005). Briefly, the lysimeters were inserted immediately after irrigation at a depth of 20 cm and 20 cm away from the stem of the plants. A suction force of 70 kilopascals was applied to each lysimeter using a manual vacuum pump. Soil water samples were collected one day after establishing the vacuum. The nutritional variables and ions analyzed in the soil solution and petiole cellular extract are shown in Table 1.

The petiole cellular extract samples were obtained according to the procedure suggested by Cadahía-López (2008). Briefly, petioles of youngest fully developed leaves number 3, 4 and 5 (numbered from the apex) of plants were collected. The samples were taken from plants close to soil solution sampling point when air temperature ranged from 20 to 30 °C. Each plant was randomly selected. The petiole cellular extract samples were obtained by placing the petioles, separated from the leaf blades, in a press to break the tissues. The resulting cellular juice was collected using a plastic syringe and then discharged into a polyethylene bag.

Sampling for nutritional variables was carried out following the procedure described by Leyva-Ruelas *et al.* (2005). The ions and nutritional variables in the SS and the CPE were analyzed using a portable equipment. Electrical conductivity (EC) was measured using a (Horiba Spectrum Cardy Twin) conductivimeter, pH, using a (Hanna HI98130) potentiometer, and Ca^{2+}, NO_3^-, K^+, and Na^+ minerals were analyzed with (Horiba) ion selective electrodes using different models according to B751, B743, B731, and B722 ions, respectively. PO_4^{3-}, Mg^{2+}, Fe^{3+}, and Zn^{2+} were analyzed using the Spectroquant® NOVA 60A analytical test. For those elements, a colorimetric test was performed in MERCK® cuvettes. Aiming to know the preliminary effect of ions on the vegetal tissue qualitative parameter levels, total soluble solids (TSS) readings were included using an OTAMA refractometer.

Statistical Analysis

The results obtained were processed on MINITAB Software v.19 (Minitab Inc., State College, PA, USA) to get the ionic concentration ranges of both, SS solution and PCE. These were obtained from the interquartile range Q1-Q3 (quartile 1 and quartile 3), which encompasses 50% of the values closest to the median, and they were organized by phenological stages. Likewise, Pearson correlations were performed between the ions and nutritional variables, which were analyzed by analysis of variance (ANOVA) with significance levels of 0.05 and 0.01.

RESULTS AND DISCUSSION

Table 2 shows the EC range of variation, pH values, and mineral concentration in SS in crops under study. The EC levels ranged from 0.4 to 2.0 dS m^{-1} and the pH values were found in a range of 5.5 to 8.0.

Table 1. Crop conditions and sampling.

Crop	Growing conditions	Location coordinates	Number of samples	Phenological stage	Sampling period (weeks after transplanting)
Avocado (*Persea americana* Mill)	Bare ground under open sky	19° 40' 48 "N 103° 32 '34" W	132	Bud differentiation	240 a 244
				Flowering	245 a 247
				Fruit set	248 a 252
				Fruit development	253 a 272
Blueberry (*Vaccinium* sp.)	Gray plastic mulching under greenhouse tunnel	19° 40' 51" N 103° 32' 44" W	132	Bud differentiation	12 a 17
				Flowering	18 a 21
				Harvest	22 a 41
Broccoli (*Brassica oleracea* var. Italica)	Bare ground under open sky	21° 03' 50" N 100° 38' 02" W	53	Vegetative	1 a 2
				Inflorescence formation	3 a 6
				Pre-harvest	7 a 9
Cauliflower (*Brassica oleracea* var. botrytis)	Bare ground under open sky	20° 56' 12" N 100° 41' 48" W	61	Vegetative	1 a 2
				Inflorescence formation	3 a 6
				Pre-harvest	7 a 10
Lettuce (*Lactuca sativa* L.)	Bare ground under open sky	21° 2' 46" N 100° 37' 34" W	41	Seedling	1 a 2
				Rosette	3 a 6
				Head formation	7 a 9
Cantaloupe (*Cucumis melo* L.)	Gray plastic mulching	19° 03' 37" N 103° 54' 04" W	30	Vegetative	3 a 4
				Pre-harvest	5 a 8
				Harvest	9 a 12
Raspberry (*Rubus idaeus* L.)	Bare ground under greenhouse tunnel	19° 39' 19" N 103° 29' 53" W	116	Vegetative-flowering	3 a 8
				Pre-harvest	9 a 20
				Harvest	21 a 34
Strawberry (*Fragaria* sp.)	White plastic mulching under greenhouse tunnel	19° 55' 03" N 103° 42' 02" W	88	Vegetative-flowering	1 a 8
				Pre-harvest	9 a 16
				Harvest	17 a 26
Papaya Tree (*Carica papaya* L.)	Bare ground under open sky	18° 48' 09" N 103° 45' 19" W	102	Plant development	10 a 13
				Flowering-fruit set	14 a 25
				Production	26 a 36
Pepper (*Capsicum annum* L.)	Silver plastic mulching in Zenithal greenhouse	19° 54' 05" N 103° 35' 15" W	119	Vegetative-flowering	1 a 7
				Fructification	8 a 15
				Pre-harvest	16 a 23
				Harvest	24 a 31

Conductivity levels registered for agronomic variables were between the recommended levels by some authors. Cadahía-López (2005) recommends a limit of 2.7 dS m^{-1} for many cultures in fertigation. However, in strawberry, lettuce and pepper crops, registered values of EC were higher than those proposed by Tanji (1990) who suggests values of 0.9, 1.4, and 1.5 dS m^{-1}, respectively, for the above-mentioned crops or otherwise a significant reduction in growth and yield may occur. On the other hand, there has been reported that CE from SS are in response to the technique used for their extraction. CE extracted from SS using vacuum lysimeters are found at high levels as compared to those collected with techniques which do not use vacuum generation (Cabrera-Corral *et al*., 2016). The pH values fall within the limits of availability of most essential elements in soil for various crops (Liu and Hanlon, 2012). The conductivity and pH recorded suggest normal values for the studied crops.

With the purpose of estimating the level of nutritional sufficiency of registered SS, a comparison between mineral concentration ranges of the SS and the reference levels for different types of soil reported by Cadahía-López (2005) and other authors was made.

The concentration range of the NO_3^- anion in soil solution was recorded in a variable range from 40 to 620 mg L^{-1}. Most changing values were recorded in the pepper crop, 220-620 mg L^{-1} during the flowering-fruiting stage and 40-70 mg L^{-1} in the pre-harvest stage, which can be considered acceptable compared to the one found (396.8-1178 mg L^{-1}) by Llanderal *et al*. (2020) throughout the pepper crop cycle. Rodríguez *et al*. (2020) propose a nitrate sufficiency value of 5 mmol L^{-1} (310 mg L^{-1}) for soil-established pepper crops; however, this value only applies to vegetative growth. In lettuce crops, maximum values of 225-267 mg L^{-1} were recorded. These values are higher than the optimum found in some brassicas (150 mg L^{-1}) (Altamimi *et al*., 2013). The wide variability observed in nitrate concentrations in this study may be due to imprecise applications of nitrogen fertilizers or, to their excessive amounts, which frequently incur in high lixiviation. Yanai *et al*. (1998), observed that in a sandy loam soil of the cambisol type, the application of $(NH_4)_2SO_4^-$ allows NO_3^- loss reduction in the first 20 days after its addition to the soil as compared to $Ca(NO_3)_2$. This is due mainly because nitrification in ammonia fertilizers is slow.

In broccoli, cauliflower, and lettuce crops established between San Luis de la Paz and Celaya, Guanajuato, PO_4^{3-} was found in a range of 17-66 mg L^{-1}. About this, three field experiments conducted in Central Mexico from 1996 through 1998 on clay loam to clay soils near Celaya, these soils contained 11 to 20 mg L^{-1} (Castellanos *et al*., 1999). In this regard, Cadahía-López (2005) mention that for most rainfed soils, normal levels are found between 9 to 35 mg L^{-1}, while the highest levels of phosphorus are for highly irrigated crops on clay soil with a maximum range of 61 to 96 mg L^{-1}. According to these reports, the registered values can be considered acceptable.

The K^+ levels in all cultures were recorded in a range of 3.0 to 377 mg L^{-1}. The lowest values were recorded in pepper, broccoli, cauliflower and lettuce crops, while the highest value was recorded in the blueberry crop. The maximum K^+ values recorded in blueberry crop during the differentiation and flowering stages were above the optimum (150 mg L^{-1}) found by Hart, Strik, White, and Yang (2006) and Komosa *et al*. (2017). Castellanos *et al*. (1999) reported values between 600 to 900 mg L^{-1} in vertisol-type clay loam soils in the central region of Guanajuato, Mexico; high yields of broccoli are achieved in this place. Altamimi *et al*. (2013) observed optimal yields at levels of 13 to 123 mg L^{-1}. The low content of K in SS recorded in some crops may be due to the low retention of this element by the soil. In this regard, Lao *et al*. (2003), mention that ion concentration in soil solution varies according to depth. That is, at 25 cm depth, higher concentrations of cations such as Mg^{2+} and Na^+ are found, compared to those found at depths closer to surface.

Levels of Ca^{2+}, Mg^{2+}, Na^+, Fe^{3+} and Zn^{2+} in soil solution were recorded in the ranges of 27-533, 10-53, 15.3-500, 0.5-1.8 and 2.8-7.4 mg L^{-1}, respectively (Table 2). According to several authors (Cadahía-López, 2005; Robin *et al*., 2008; Smith, Fisher, and Argo, 2004), levels of microelements such as Mg^{2+}, Fe^{3+} and Zn^{2+} were within plant required range for optimal growth in soil and substrate. However, elements such as Ca^{2+}, Mg^{2+}, and Na^+ were recorded at high concentrations. Maximum levels of calcium in papaya crop were twice the optimal values (240 mg L^{-1}) recommended by Madani *et al*. (2013). Similarly, the maximum values recorded for Ca^{2+} in strawberry crop were higher than the limit value (465 mg L^{-1}) recommended by Choi, Latigui, and Lee (2013).

Table 2. Range of variation of the EC, pH and concentration of ions in soil solution.

	EC	pH	NO_3^-	PO_4^{3-}	K^+	Ca^{2+}	Mg^{2+}	Na^+	Fe^{3+}	Zn^{2+}
	dS m^{-1}		- - - -	- - - -	- - - -	mg L^{-1}	- - - -	- - - -	- - - -	- - - -
					Avocado					
Bud differentiation	0.5† - 0.8‡	5.8-7.2	150-357	------	45.8-145	132-360	------	75.3-190	------	------
Flowering	0.5-0.7	5.9-6.4	135-280	------	42.8-207	180-307	------	62.0-140	------	------
Fruit set	0.4-1.2	5.5-6.1	207-400	------	88.3-212	122-360	------	33.0-165	------	------
Fruit development	0.4-0.6	6.8-7.6	112-300	------	17.0-34.3	64-200	------	15.3-41.8	------	------
					Blueberry					
Bud differentiation	0.5-1.6	5.9-7.1	110-467	------	96.0-192	120-200	------	24-92	------	------
Flowering	0.5-0.8	5.5-6.1	262-572	------	96.8-377	120-150	------	58-90	------	------
Harvest	0.4-0.6	6.7-7.3	130-287	------	18.3-37.0	49.0-147	------	17-50	------	------
					Broccoli					
Vegetative	0.9-1.6	7.5-8.0	120-393	17-32	38-72	125-233	19-37	76-160	0.6-0.9	4.4-6.7
Inflorescence formation	1.2-1.7	7.0-7.5	180-440	39-47	49-72	210-340	17-44	120-190	1.1-1.7	3.7-6.3
Pre-harvest	1.0-1.3	6.8-7.2	101-255	46-54	40-60	142-290	13-33	112-225	0.9-1.6	2.8-4.7
					Cauliflower					
Vegetative	1.1-2.1	7.8-8.0	190-368	22-39	32-75	107-203	17-53	107-213	0.6-0.9	4.3-7.0
Inflorescence formation	1.2-2.0	7.2-7.6	247-453	34-44	49-68	220-533	14-41	140-230	1.0-1.4	4.0-7.4
Pre-harvest	0.8-1.1	6.9-7.2	66-190	55-66	35-54	130-260	Oct-22	150-190	1.0-1.8	2.8-3.9
					Lettuce					
Seedling	1.1-1.4	7.6-7.8	139-267	17-25	28-46	136-217	18-36	108-140	0.5-1.1	4.7-7.2
Rosette	0.9-1.5	7.2-7.7	88-230	36-54	24-41	135-340	16-31	120-185	1.0-1.8	3.7-5.4
Head formation	0.9-1.1	6.7-7.0	112-225	43-60	24-33	195-315	20-26	132-222	0.7-0.9	3.9-5.0
					Cantaloupe					
Vegetative	1.0-1.2	6.6-7.2	93-141	------	26-36	143-214	------	65-82	------	------
Pre-harvest	0.9-1.2	7.5-8.2	97-227	------	Nov-50	305-410	------	56-78	------	------
Harvest	0.9-1.2	7.4-7.6	147-397	------	Sep-18	312-570	------	41-75	------	------
					Raspberry					
Vegetative-flowering	0.5-0.8	5.9-6.5	227-620	------	48-150	107-300	------	41-192	------	------
Pre-harvest	0.5-1.0	5.7-70	130-450	------	23-195	157-247	------	42-84	------	------
Harvest	0.4-0.6	6.6-7.3	89-227	------	17-37	36-175	------	21-61	------	------
					Strawberry					
Vegetative-flowering	0.7-1.3	5.5-6.4	280-612	------	34-90	127-180	------	32-61	------	------
Pre-harvest	0.6-1.0	6.8-7.3	227-462	------	24-56	98-150	------	31-52	------	------
Harvest	1.0-1.3	6.4-7.2	242-502	------	25-55	51-142	------	20-41	------	------
					Papaya					
Plant development	1.0-1.8	6.6-7.0	117-220	------	137-190	295-585	------	135-272	------	------
Flowering-fruit set	0.9-1.6	6.3-6.9	117-177	------	23-51	160-412	------	62-200	------	------
Production	1.0-1.1	6.8-7.6	89-382	------	Dec-70	290-455	------	38-63	------	------
					Pepper					
Vegetative-flowering	1.1-1.3	6.8-7.3	96-220	------	21-55	260-380	------	250-430	------	------
Fructification	1.1-1.4	6.2-7.5	220-620	------	Dec-38	170-290	------	300-500	------	------
Pre-harvest	0.9-1.1	7.0-7.6	40-70	------	4.0-8.5	49-115	------	150-295	------	------
Harvest	1.0-1.2	6.4-7.6	79-140	------	3.0-6.0	27-59	------	150-225	------	------

† = Quartil 1. ‡ = Quartil 2.

The before mentioned values show evidence of high availability of calcium in the different soils related to this study. Na^+ was found in values higher than the maximum tolerable recommended for irrigation water for both open field and greenhouse crops (<100 mg L^{-1}) (Breś, Kleiber y Trelka, 2010). Grattan and Grieve (1998) mentions that high concentrations of Na^+ in the soil solution can decrease the ionic strength of other nutrients and cause nutritional disorders in plants. In this regard, Lao *et al*. (2003) mention that ion concentration in soil solution varies according to depth. That is, at 25 cm depth, higher concentrations of cations such as Mg^{2+} and Na^+ are found, compared to those found at depths closer to surface.

Table 3 shows ranges of variation for ion concentration in PCE, pH, and total soluble solids (TSS) by phenological stage. In general, a decrease in the concentration of the ions was observed according to the different stages, which agrees with that observed by Hochmuth *et al.* (2012) in eleven horticultural crops. The ranges of concentrations for NO_3^-, K^+, and Ca^{2+} in PCE in crops under study were within the frequent value ranges found by Cadahía-López (2008), in the PCE analysis of horticultural crops. In specific, the NO_3^- concentration ranges obtained are similar to sufficiency ranges reported for strawberry (200-900 mg L^{-1}) and pepper (500-1600 mg L^{-1}) crops, however, they differ for broccoli (500-1600 mg L^{-1}), cauliflower (290-740 mg L^{-1}), lettuce (350-600 mg L^{-1}), and cantaloupe (700-1200 mg L^{-1}) crops (Hochmuth *et al*., 2012). K^+ concentration was found within sufficiency ranges for broccoli (2200-6500 mg L^{-1}), strawberry (1500-3500 mg L^{-1}), and cantaloupe (3000-5000 mg L^{-1}) crops, while in pepper crop the concentration obtained was higher (2000-3500 mg L^{-1}) than the sufficiency range (Hochmuth *et al*., 2012). It is worth mentioning that the reference ranges of Ca^{2+} levels in PCE in horticultural crops are not reported in the literature. However, a comparison with respect to the total Ca^{2+} content in leaf tissue reported by Hochmuth *et al*. (2012), shows that broccoli, lettuce, and cantaloupe crops have higher content Ca^{2+} compared to that of strawberry and pepper crops, which agrees with the PCE content of this study. Regarding ion concentration on different crop stages, in general, it is observed that the highest concentrations were found in the first phenological stages. In this regard, it has been reported that the concentrations of some elements such as nitrate, tend to be higher in early (vegetative) stages in fruit crops; in later stages, a pronounced decline is observed, which is even higher in fruit formation and growth stages. This decline in K^+ levels is due to the increase in the mineral translocation from leaves towards fruits (Wira, Jamil, and Armizatul, 2013).

On the other hand, high concentrations of Na^+ in PCE were recorded mainly in broccoli, cauliflower, lettuce, and pepper crops (Table 3). It should be noticed that, in the first three cultures, these values were in correspondence to the concentration of this element in SS, however, this was not the case for pepper crop (Table 2). In this regard, it has been documented that, regardless of Na^+ supply, there are several crops that translocate low concentrations of this non-essential element to reproductive or storage structures, such as seeds, fruits, or storage roots, or other consumable portions of many staple crops. In contrast, vegetative structures, such as leaves and petioles subject to greater transpiration and greater xylem flux, tend to accumulate Na^+ at reasonably high levels without adversely affecting fruit productivity or quality. This occurs at the expense of a low concentration of K^+ in the soil solution. This has been observed mainly in vegetative stage of growing vegetables (Subbarao, Ito, Berry, and Wheeler, 2003), such as lettuce and some brassicas.

Table 4 shows correlations between the SS ions and PCE variables. In general, it can be observed that EC showed positive correlations with most of the ions recorded, but particularly with anion NO_3^-. The pH showed positive correlations with the Ca^{2+} and NO_3^- ions, however, it showed negative correlations with K^+, Na^+ and PO_4^{3-} in several crops, which suggests the impact of pH on the bioavailability of these ions. The decrease of pH in soil solution, associated with a higher concentration of P, has been observed by Choi *et al*. (2013), who attribute this acidification to the reaction of H_2PO_4 anion with Ca^{2+}, delivering calcium monophosphate with the consequent release of H^+ ions. The correlation between pH and K^+ may be a function of N present in solution. Gratieri, Cecílio, Barbosa, and Pavani (2013) observed that, by increasing the concentration of K^+ with respect to N, this led to an increase in the pH of the fertigation solution. The lowest pH value (4.7) resulted from fertigation with a solution containing 20 and 6 mmol L^{-1} of N and K^+, respectively, while the highest pH (5.7) resulted from 12.6 and 10 mmol L^{-1} of N and K^+ concentrations, respectively.

Table 3. Range of variation for pH, total soluble solids, and ion concentration in petiole cellular extract (PCE).

	NO_3^-	K^+	Ca^{2+}	Na^+	pH	TSS
	- - - - - - - -	- - - - - - - -	mg L^{-1}	- - - - - - - -		°Brix
Sensitivity ranges[†]	40-1500	1000-12000	40-2000	10-1000	---	---
			Avocado			
Bud differentiation	187[‡] - 505[§]	3200-5000	5.0-9.2	58.5-160	4.8-6.5	4.0-8.6
Flowering	120-405	1600-4000	7.0-10	67.5-98.5	4.6-4.9	7.1-9.0
Fruit set	160-490	2400-3450	2.7-11	45.3-100	4.1-4.4	7.1-9.8
Fruit development	140-375	1825-2500	1.0-4.2	29.5-42.5	5.0-5.6	2.8-4.8
			Blueberry			
Bud differentiation	95.8-292	1875-4225	20-61	36.8-100	2.7-4.0	Oct-13
Flowering	32.5-55.3	1450-5125	19-45	52.3-70.0	1.8-2.5	Oct-13
Harvest	27.5-117	820-1400	6.0-28	25.0-43.8	2.4-2.8	4.0-6.0
			Broccoli			
Vegetative	5300-8350	2650-3300	200-488	250-620	5.8-6.2	5.5-6.4
Inflorescence formation	3800-4700	2600-3600	260-610	180-280	5.9-6.1	5.0-6.0
Pre-harvest	3050-3675	2800-3200	450-650	215-328	5.6-5.8	5.0-6.0
			Cauliflower			
Vegetative	4725-9825	2275-3200	66-153	245-298	6.1-6.5	5.0-6.1
Inflorescence formation	3275-4125	2500-3200	125-133	197-300	6.1-6.7	5.0-6.1
Pre-harvest	2200-3100	2400-3000	190-410	310-400	5.8-5.9	4.8-5.4
			Lettuce			
Seedling	1950-3150	2225-2700	97-168	110-338	5.8-5.9	4.0-5.0
Rosette	2250-2800	2450-3650	94-165	135-235	5.4-6.0	3.2-4.0
Head formation	1850-2075	2950-3325	104-125	198-305	5.3-5.4	3.0-3.3
			Cantaloupe			
Vegetative	6775-9225	3575-4800	35-102	81-132	5.3-5.7	2.0-2.3
Pre-harvest	2550-5175	2700-3625	117-422	107-162	5.4-6.2	2.0-3.0
Harvest	1475-6550	2275-4150	255-1135	127-337	5.3-5.8	2.0-2.8
			Raspberry			
Vegetative-flowering	1775-4225	2875-5200	128-273	60-225	5.1-5.3	3.0-4.1
Pre-harvest	898-4400	3500-5175	65-110	40-82	4.9-5.5	3.0-6.0
Harvest	2275-4600	2450-4125	17-83	34-85	5.2-5.5	2.0-3.0
			Strawberry			
Vegetative-flowering	287-860	2875-4450	43-97	42-81	4.7-5.5	6.2-7.6
Pre-harvest	1575-2525	2550-4550	20-40	29-43	5.1-5.5	3.9-6.2
Harvest	720-1275	2000-3125	15-37	36-66	4.9-5.2	3.8-5.0
			Papaya			
Plant development	400-1325	4875-9375	160-602	69-235	5.6-6.0	3.4-4.2
Flowering-fruit set	420-1300	3075-8125	31-115	46-130	5.3-6.3	3.0-4.7
Production	512-2100	2275-3225	42-187	65-162	5.7-6.0	2.0-3.0
			Pepper			
Vegetative-flowering	1800-4700	5300-8000	6.0-16	82-220	5.4-5.9	3.0-4.2
Fructification	900-1500	7000-8700	1.0-4.0	59-88	4.8-5.8	3.2-6.8
Pre-harvest	1210-3150	4700-6800	1.0-2.5	53-65	5.4-6.2	2.3-4.0
Harvest	2100-4050	4100-5550	1.0-3.8	56-87	5.7-6.1	2.0-3.0

[†]Cadahía-López, 2008. Frequent Intervals Found in PCE Analysis. [‡] = Quartil 1. [§] = Quartil 2. TSS = total solid soluble.

Highly significant positive correlations were also recorded between NO_3^- and K^+ ions, and NO_3^- and Ca^{2+} in SS, mainly in broccoli, cauliflower, blueberry, raspberry, and lettuce crops. Likewise, highly significant positive correlations between NO_3^- and Zn^{2+} were observed. These results allow us to verify important interactions of NO_3^- with several of the cations present in the soil solution. The foregoing suggests that the NO_3^- anion has a determining effect on the concentration of cations in the soil solution, primarily attributable to the ion exchange and electrochemical equilibrium processes that NO_3^- undergoes as it is weakly adsorbed at the exchange sites of soil (Yanai *et al*., 1998), but also due to its anionic dominance in the nutrient medium (Yanai *et al*., 1996).

The concentration of NO_3^- in the PCE with respect to the concentration in the SS showed positive correlations in the broccoli and cauliflower crops. This suggests that an increase in soil solution concentrations corresponds to higher assimilation by plants. However, statistically significant negative correlations were found in raspberry, cantaloupe, and pepper crops, suggesting that higher application rates do not reflect higher assimilations. About this, it has been found that the concentration of nutrients in the PCE is a function of the level of demand of ions for some physiological processes, such as nutrient uptake, bioassimilation, and storage (Llanderal *et al*., 2020), while decrease in ions in soil solution, generally is due to leaching towards lower depths, or to high assimilation by plants in certain phenological stages (Komosa *et al*., 2017). The foregoing supposes the occurrence of a negative correlation when high mineral applications are combined with periods of low plant demand. There

Table 4. Pearson's correlations between ions and nutritional variables in soil solution and petiole cellular extract.

	Avocado	Blueberry	Broccoli	Cauliflower	Lettuce	Cantaloupe	Raspberry	Strawberry	Papaya	Pepper
					Soil solution (SS)					
EC(SS) *Vs* NO_3^-(SS)	0.2	0.42*	0.663**	0.54**	-0.01	0.195	0.224	0.149	0.064	0.331
pH(SS) *Vs* K^+(SS)	-0.757**	-0.491*	0.174	0.28	0.429**	0.323	-0.439**	-0.508*	-0.159	-0.346
NO_3^-(SS) *Vs* Zn^{2+}(SS)	------	------	0.839**	0.45*	0.394*	------	------	------	------	------
PO_4^{3-}(SS) *Vs* pH(SS)	------	------	-0.55**	-0.58**	-0.441*	------	------	------	------	------
K^+(SS) *Vs* NO_3^-(SS)	0.117	0.6**	0.739**	0.615**	0.51**	-0.042	0.406*	0.416	0.041	0.381
Ca^{2+}(SS) *Vs* NO_3^-(SS)	0.016	0.269	0.764**	0.093	0.253	0.869**	0.572**	0.269	0.34	0.445*
Na^{2+}(SS) *Vs* pH(SS)	-0.573**	-0.438*	-0.148	-0.266	-0.193	0.398	-0.427*	-0.596*	-0.179	-0.419
					Soil solution (SS) *Vs* Petiole cellular extract (PCE)					
EC(SS) *Vs* Na^+(PCE)	0.313	0.454*	-0.022	-0.232	0.103	-0.422	0.384*	-0.062	0.111	0.628**
pH(SS) *Vs* TSS(PCE)	-0.817**	-0.567**	0.37*	0.341	0.514**	0.196	-0.559**	-0.767**	0.02	-0.465*
NO_3^-(SS) *Vs* NO_3^-(PCE)	0.095	0.384	0.558**	0.454*	-0.126	-0.702*	-0.403*	-0.171	-0.222	-0.433*
NO_3^-(PCE) *Vs* Ca^{2+}(PCE)	0.167	0.055	-0.45**	-0.451*	0.146	-0.39	-0.278	0.16	-0.018	-0.029
PO_4^{3-}(SS) *Vs* pH(PCE)	------	------	-0.46**	-0.76**	-0.516**	------	------	------	------	------
K^+(SS) *Vs* K^+(PCE)	0.567**	0.514*	-0.159	0.19	-0.074	-0.296	0.145	0.04	0.567*	0.472*
K^+(SS) *Vs* TSS(PCE)	0.79**	0.817**	0.014	0.146	0.03	-0.246	0.535**	0.5*	0.476*	0.651**
Ca^{2+}(SS) *Vs* Ca^{2+}(PCE)	0.774**	0.021	0.161	0.437*	0.522**	0.793**	0.356*	0.663**	0.636**	0.383
Ca^{2+}(SS) *Vs* NO_3^-(PCE)	-0.043	0.042	0.266	-0.282	-0.112	-0.77**	-0.338**	-0.003	-0.075	-0.105
Na^+(SS) *Vs* Na^+(PCE)	0.741**	0.204	0.287	0.333	0.263	-0.616*	0.851**	0.547*	0.511*	0.529*

*$P \leq 0.05$. **$P \leq 0.01$.

is evidence that some plant species, mainly forest species, show a blockage in nitrate uptake when its concentration is significantly high in the presence of ammonium; the blockage is attributed to the inhibitory effects of ammonia (Gessler *et al*., 1998). The exact explanation for such a response in horticultural species is still an area of opportunity.

In contrast, significant positive correlations were recorded between the concentration of K^+ in the SS with respect to K^+ in the PCE in crops such as avocado, blueberry, papaya, and pepper, while highly significant positive correlations between levels of K^+ in the SS and TSS in the PCE were registered in blueberry, pepper, papaya, strawberry and raspberry crops. In some crops, this above shows a high K^+ uptake response by increasing the soil concentration of the element. However, crops such as broccoli, cauliflower and lettuce did not show higher assimilation even when SS increased (Table 2). Voogt (2002) mentions that is important distinguish between the composition of the nutrient solution to be supplied to a crop and the composition of the root environment. Like in hydroponics, it is the solution in the growing media, or in soil the soil solution. This author indicates that the nutrient solution composition must reflect the uptake ratios of individual elements by the crop and as the demand between species differs. In this regard, it has been documented that when a nutrient solution is applied continuously, plants can take up the ions in very low concentrations, likewise, it has been reported that, under these same conditions, high proportions of the nutrients are not used by plants or their assimilation does not impact their productivity (Trejo-Téllez and Gómez-Merino, 2012). On the other hand, a negative correlation was registered between the pH of SS and the concentration of K^+ in PCE in the blueberry crop, while negative correlations between TSS and pH in SS were observed in avocado, blueberry, raspberry, and pepper crops (Table 4). The negative effect of soil acidity on foliar K^+ levels has been documented in blueberry crops in different types of soil (Hart *et al*., 2006). Positive impact of potassium fertilization on the yield and quality of some crops, like berries, has been reported (Hart *et al*., 2006). K^+ is attributed a fundamental role in the discharge of sucrose from phloem in vine crops (*Vitis vinifera* L.) (Rogiers *et al*., 2017). In papaya fruits sprayed with K^+ from 3% on, TSS levels were significantly increased and the severity of fruit damage caused by *Fusarium moniliforme* was reduced (Rathnayake, Sarananda, and Abesekara, 2010). The effect of K^+ on pH of tomato, blueberry and raspberry fruits is also reported (Fontes, Sampaio, and Finger, 2000). The previous results show the importance of considering pH levels as they affect the K concentration levels in soil, and these in turn, TSS concentration.

In Table 4, a statistically significant positive correlation is found between the concentration of Ca^{2+} present in SS and its content in PCE for all crops. The highest statistical significance was registered in lettuce, raspberry, strawberry, papaya, and cantaloupe crops, while in broccoli, blueberry and pepper crops no significant difference was observed. This suggests an important correspondence between levels of Ca^{2+} applied to the soil with assimilation levels in several crops under study. In this regard, Dayod, Tyerman, Leigh, and Gilliham (2010) mention that, regardless of the available amount of Ca in the soil, the movement of Calcium within plants is subject to other factors, including transpiration, which is variable among plant species and is a function of weather. This would explain the low positive correlation registered in some crops.

CONCLUSIONS

The previous results constitute a first approximation to sufficiency values for NO_3^-, PO_4^{3-}, K^+, Ca^{2+}, Mg^{2+}, Fe^{3+} and Zn^{2+} ions in soil solution (SS) and petiole cellular extract (PCE) for crops studied in the summer-winter in western Mexico. The foregoing is clear from the fact that, in general, the concentration ranges of the ions in the SS and PCE were within acceptable ranges. Na^+ levels were found at relatively high levels for some crops; however, no significant interactions were observed with the remaining elements that make up SS or PCE. The correlations between ions in SS suggest important interactions of NO_3^- anions with cations such as Ca^{2+}, K^+ and Zn^{2+} in the SS, while correlations between ions that make up the SS and PCE content, show negative correlations of NO_3^- anions in some crops, but positive in the remaining ions. It is worth noticing the positive correlation between K^+ of SS with the levels of TSS in PCE in some crops.

ETHICS STATEMENT

Not applicable in this section.

CONSENT FOR PUBLICATION

Not applicable in this section.

AVAILABILITY OF SUPPORTING DATA

The data that support the findings of this study are available from [TRADECORP MEXICO company] but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of [TRADECORP MEXICO company].

COMPETING INTERESTS

The authors declare that they have no competing interests in this section.

AUTHOR'S CONTRIBUTIONS

Methodology, formal analysis and writing: N.F.F. Conceptualization, draft preparation and editing: K.A.R. Supervision, project administration and funding acquisition: A.B.M.

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