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Relationships between soil and plant nutrients of citrus rootstocks as influenced by potassium and wood vinegar application

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Abstract

Purpose Simultaneous application of organic compounds and chemical fertilizers may have an interaction effect on the growth and nutrients uptake by different citrus rootstocks.

Methods We tried to monitor the effect of soil application of 0.2 and 0.4% wood vinegar and 100 mg kg^{-1} potassium (K) on some soil properties and nutrients availability and growth and nutrients uptake of two citrus rootstocks including sour orange (*Citrus aurantium*) and Mexican lime (*Citrus aurantifolia*).

Results Analysis of soil and plant after 90 days growth of rootstocks indicated that wood vinegar increased the soil availability of calcium (Ca), sodium (Na), and manganese (Mn) but it had no effect on the availability of other nutrients. The 0.2% wood vinegar had no effect on the dry weight of Mexican lime and decreased the dry weight of sour orange by 12%. The 0.4% wood vinegar + K decreased the dry weight of sour orange and Mexican lime by 20 and 24%, respectively. The wood vinegar also decreased phosphorus (P), K, and cupper (Cu) uptake by plant that may be due to the effect of wood vinegar on soil electrical conductivity (EC) and changes of soil solution competition. The soils cultivated with sour orange had lower contents of available K, Ca, Na, zinc (Zn), and Cu and a higher content of iron (Fe) compared to Mexican lime. The higher growth of sour orange and thereby higher nutrients uptake (11, 14, 69, 54, 16, and 71% more P, K, Ca, Na, Fe, and Mn, respectively) may be a reason for lower nutrients availability for soil cultivated with sour orange. However, other factors such as root exudations may be considered. Potassium application to soil increased the availability of soil K, Ca, Mn and Zn by 45, 7, 4 and 9%, respectively, but it had no effect on other nutrients. An increase in soluble cations and competition for absorption on root surfaces after an increase in soluble K may be affected cations availability and uptake by plant. Simultaneous application of K and 0.2% wood vinegar increased the uptake od K and Zn.

Conclusion Generally, it can be concluded that wood vinegar and K may affect plant growth and the content of nutrients uptake via the effects on soil pH and EC and nutrients balance; this effect is more considerable on sour orange than Mexican lime.

Keywords Sour orange · Mexican lime · Soil pH · Nutrients availability · Carbonate dissolution · Nutrients competition

1 Introduction

Citrus cultivation is widespread in arid and semi-arid regions of southern Iran with highly calcareous soils. Due to the high amounts of carbonates in the soil, alkaline soil reaction, and low organic matter, citrus trees usually undertake some nutritional difficulty. Najafi-Ghiri et al. (2013, 2017) indicated that most calcareous soils are poor in some plant nutrients and imbalance between nutrients may affect plant growth and development.

Numerous rootstocks are available for citrus trees and the most popular varieties in southern Iran are sour orange and Mexican lime due to the adaptability to a wide range

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of soil conditions and high quality of fruit and resistance to highly alkaline and saline conditions (Louzada et al. 2008; Wutscher 1979).

Rootstocks differ in their ability to uptake essential nutrients from calcareous soils and their translocation to the plant aerial parts. Different results have been reported by some researchers about the effect of rootstocks on the content of nutrients in the aerial parts of citrus trees (Hasanzadeh et al. 2006; Khankahdani et al. 2019; Mohsen et al. 2014). For example, Toplu et al. (2012) with studying of leaf nutrient concentration of "Okitsu," "Clausellina," and "Silverhill" mandarin cultivars budded onto some sour orange, "Carrizo" and "Troyer" rootstocks concluded that the N, K, and Cu content of "Clausellina," P content of "Okitsu" and Na content of "Silverhill" was higher than that in the other cultivars. Kumar et al. (2018) with studying of leaf nutrient content of kinnow mandarin grown on different rootstocks indicated that the maximum content of leaf K, Ca, and Mg content was recorded in plants grown on rough lemon seedling, while N, P, Fe, Zn, Mn, and Cu concentration was higher on sour orange rootstock and this may be due to the difference in root morphological properties and nutrient accumulation pattern.

Wood vinegar or pyroligneous acid is a secondary product of biochar and charcoal production and is produced by the condensation of vapors of organic materials pyrolysis in the limited or no oxygen conditions. Some researchers have been used the wood vinegar for reclaiming degraded soils, plant growth, and nutrients uptake, decreasing N volatilization, accelerating compost production, and plant disease control (Chen et al. 2020; Feng et al. 2020; Shuang et al. 2020; Sun et al. 2020; Wang et al. 2018; Zhang et al. 2020) Wood vinegar due to the acidic nature may dissolve some soil minerals and carbonates and release plant essential nutrients to the soil environment. In the citrus production, the use of wood vinegar as a nematicide is increasing.

Potassium (K) as a macronutrient is required for citrus production and its content in calcareous soils of arid and semi-arid regions may be sufficient due to the high contents of K-bearing minerals like micas and feldspars and low nutrients leaching condition (Najafi-Ghiri et al. 2011). Nowadays, due to the intensive agriculture practices, the use of K fertilizers is increasing. Potassium fertilizers application to calcareous soils may affect some soil physicochemical properties and plant nutrients uptake as well as plant K supply.

We supposed that citrus rootstocks differ in their ability for nutrients absorption and their balance status in plant parts. In addition, wood vinegar due to the acidic nature and its complexing agents and K fertilizers due to the changes in soil solution composition and cation competition for absorption and some soil properties may affect soil nutrients availability, plant yield, and nutrients uptake by citrus rootstocks. Although, there are many investigations about the effects of organic amendments and chemical fertilizers on soil and plant nutrients, little or no information is available about the interaction effect of wood vinegar (as an acidic amendment) and K (as important nutrient for citrus growth) especially in calcareous soils that have an alkaline reaction and Ca-K competition for root absorption is a serious problem.

The main purposes of this investigation were the study of the effect of different levels of wood vinegar and K application to soil on some soil propertied and nutrients availability and also the growth and nutrients uptake of sour orange and Mexican lime rootstocks.

2 Materials and methods

2.1 Soil sampling and analysis

Soil sampling was performed from a depth of 0–20 cm of an agricultural filed in southern Iran. It was highly calcareous and classified as sandy, carbonatic, hyperthermic Haplustepts according to Soil Taxonomy (Soil Survey Staff 2014). After air-drying and sieving of the soil (< 2 mm), some properties including particle size distribution (Gee and Or 2002), calcium carbonate equivalent (CCE) (Loppert and Suarez 1996), organic carbon (Nelson and Sommers 1996), soil pH (Thomas 1996), electrical conductivity (EC) (Rhoades 1996), cation exchange capacity (CEC) (Sumner and Miller 1996), total nitrogen (N) (Bremner 1960), and available phosphorus (P) (Olsen 1954), K (Helmke et al. 1996a), iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu) (Lindsay and Norvell 1978a) were determined by the standard laboratory methods. All analyses were performed in three replications.

2.2 Wood vinegar preparation and analysis

The wood vinegar was prepared from the slow pyrolysis of fruit woods at 400 °C under limited oxygen conditions. Some chemical properties of the wood vinegar including pH (using an electrode pH meter), EC, total N (micro-kjeldahl method), P (UV-1800 spectrophotometer, Shimadzu, Japan), K (BWB-XP flame photometer, UK), Fe, Mn, Zn, and Cu (PG 990 atomic spectrophotometer, PG Instruments Ltd. UK) were determined. All analyses were performed in three replications. The characteristics of functional groups of the wood vinegar were determined using Fourier transform infrared spectroscopy (FT-IR) with using KBr pellet method (Shimadzu DR-8001).

2.3 Greenhouse experiment

A factorial greenhouse experiment was done based on a completely randomized design. Factors included two seedling rootstocks (sour orange (*Citrus aurantium*) and Mexican lime (*Citrus aurantifolia*)), wood vinegar application (0, 0.2 and 0.4%) and K application (0 and 100 mg kg^{-1} as K_2SO_4 salt) with five replications. One seedling was sown in each plastic pots containing 5.0 kg of soil. For K treatment, the required K_2SO_4 was mixed with the soils and completely mixed. The K rate was considered according to the preliminary experiment of the used soil and farmers traditional fertilizer program. The soil moisture was maintained near the field capacity content with distilled water by daily pots weighting. The wood vinegar was diluted with water and added to the pots after 3, 6, and 9 weeks after rootstock sowing. After 90 days of plant growth, the aerial parts of plants were harvested and rinsed with deionized water, and then oven-dried for 3 days at 70 °C and weighted. The powdered dried plant samples were heated at 550 °C and digested with 2 N hydrochloric acid and the concentrations of P (Lu 1999), K, Ca, sodium (Na) (ELE Flame photometer, UK), Fe, Mn, Zn, and Cu (AAS; PG 990, PG Instruments Ltd. UK) were determined. The remaining soil samples after plant harvesting were also air-dried, completely mixed and sieved (< 2 mm) and soil pH (Thomas 1996); EC (Rhoades 1996), and the availability of P (Olsen 1954); Ca, Na, and K (Helmke et al. 1996b); and Fe, Mn, Zn, and Cu (Lindsay and Norvell 1978a, b) were determined.

2.4 Data processing

Analysis of data was performed using the SPSS 20.0 computer software (SPSS Inc., Chicago, IL, USA). All statistical tests were considered at the significant level of 0.05. The kurtosis and skewness were used for test of the data normality. Analysis of variance (ANOVA) and Tukey HSD post hoc test were used for the means comparison.

3 Results

3.1 Soil and wood vinegar characteristics

The used soil had a coarse texture with sand content of 55% and clay content of 6% (Table 1). It was highly calcareous (CCE = 60%) with slightly alkaline reaction and low salinity. Organic carbon of the soil was low (1.33%), an indicator of arid and semi-arid regions of southern Iran. The soil had low contents of available N, P, K, and Fe and sufficient contents of Mn, Zn, and Cu.

The used wood vinegar had an acidic reaction (Table 1). Its EC was 5.15 dS m^{-1} and it had low content of soluble N, P, K, and Mn, while its Fe, Zn, and Cu concentrations were 40.4, 5.5, and 2.8 mg kg^{-1} maybe due to the corrosions of production tools. The FT-IR analysis showed intense bands in the regions of 2800–3800, 1600–1700, and 1290 cm^{-1} related to the C-H and O–H, C = O, and C–OH stretching of acetic acid and water (Fig. 1).

Table 1 Some properties of the used soil and wood vinegar

Property	Soil	Wood vinegar
Sand, %	55	-
Silt, %	39	-
Clay, %	6	-
pH	7.87	3.54
EC, dS m^{-1}	0.45	5.15
CEC, cmol(+) kg^{-1}	7.2	-
Calcium carbonate equivalent, %	60	-
Organic carbon, %	1.33	-
Total N, %	0.07	0.05
Available P, mg kg^{-1}	6.1	trace
Available K, mg kg^{-1}	220	0.01
Available Fe, mg kg^{-1}	3.5	40.4
Available Mn, mg kg^{-1}	5.5	trace
Available Zn, mg kg^{-1}	1.7	5.5
Available Cu, mg kg^{-1}	1.1	2.8

3.2 Soil properties and nutrients availability

Analysis of variance (Table 2) indicated that the soil availability of K, Ca, Na, Fe, Zn, and Cu was affected by plant variety, while plant variety had no significant effect on soil EC, pH, and soil P and Mn availability. Wood vinegar had significant effects on soil pH, EC, and the availability of Ca, Na, Fe, and Mn. Potassium application also affected soil pH; EC; and K, Ca, Mn, and Zn availability. Soil pH; EC; and available P, K, and Cu were not affected by the interaction of different treatments, while available Na, Fe, Mn, and Cu were affected by different interactions.

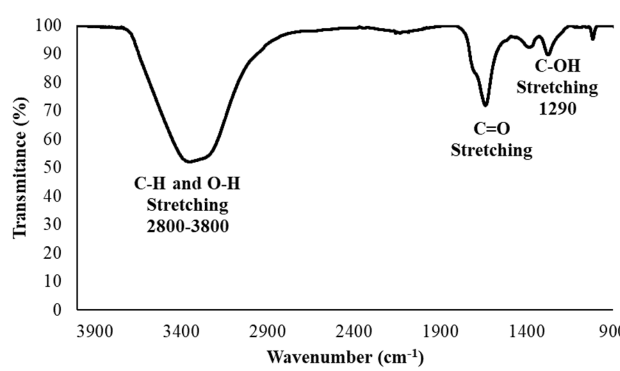

Fig. 1 The FT-IR spectrum of the used wood vinegar

Table 2 Analysis of variance for the effects of plant variety (A), wood vinegar (B), K application (C), and their interactions on some soil properties and nutrients availability

Source of variation	Degree of freedom	pH	EC	Soil P	Soil K	Soil Ca	Soil Na	Soil Fe	Soil Mn	Soil Zn	Soil Cu
Factor A	1	0.004	0.004	0.096	2160**	1927**	1654**	0.216*	0.088	0.337**	0.099**
Factor B	2	0.047*	0.013**	0.712	260	10447**	1659**	0.145*	8.79**	0.035	0.001
Factor C	1	0.088*	0.070**	0.913	233127**	2940**	4	0.150	0.840**	0.280**	0.001
A×B	2	0.010 ns	0.001	0.255	60	467	226**	0.154*	0.413**	0.026	0.005
A×C	1	0.000 ns	0.001	0.963	327	1307**	0.4	0.001	0.337*	0.253**	0.001
B×C	2	0.021 ns	0.001	0.215	47	260	61	0.279**	0.260*	0.029	0.004
A×B×C	2	0.022 ns	0.002	0.373	187	327*	130*	0.012	0.418**	0.038	0.005
Error	48	0.013	0.001	0.267	106	934	40	0.043	0.052	0.018	0.003

** and * represent 0.01 and 0.05 levels of significance, respectively

3.3 pH and EC

Wood vinegar application at rates of 0.2 and 0.4% significantly decreased mean value of soil pH from 7.86 to 7.79 and 7.76, respectively. Potassium application was also decreased mean value of soil pH from 7.84 to 7.76.

The soil EC was increased with application of 0.4% wood vinegar (from 0.4 to 0.44 dS m^{-1}, as mean), but 0.2% wood vinegar application had no effect on it. An increase in mean value of soil EC from 0.38 to 0.45 dS m^{-1} by K application was also observed.

3.3.1 Potassium

The mean K contents of the soils cultivated with sour orange and Mexican lime were 284 and 296 mg kg^{-1}, respectively with significant difference. Potassium application increased soil available K from 228 to 352 mg kg^{-1}.

3.3.2 Calcium

Soluble Ca in the soils cultivated with sour orange and Mexican lime was increased with 0.4% wood vinegar application (by 17%), while 0.2% wood vinegar application had no effect on it (Table 3). Irrespective of wood vinegar application, K application had no effect on the Ca concentration of soils cultivated with sour orange. However, K application increased Ca concentration of soils cultivated with Mexican lime that received 0.2 and 0.4% wood vinegar (by 10 and 20%, respectively).

3.3.3 Sodium

Soil soluble Na was increased with 0.4% wood vinegar application, but 0.2% wood vinegar application had no effect on it (Table 3). Soil soluble Na was not affected by plant variety except for soils received K and 0.2% wood vinegar (115 and 139 mg kg^{-1} for soils cultivated with sour orange and Mexican lime, respectively).

3.3.4 Manganese

Wood vinegar application at rates of 0.2 and 0.4% increased soil available Mn and the highest values were found in soils received K and 0.2% wood vinegar (7.30 to 7.08 mg kg^{-1} for soils cultivated with sour orange and Mexican lime, respectively) (Table 3). Potassium application increased Mn availability of soils cultivated with sour orange that received 0.4% wood vinegar (from 6.28 to 6.92 mg kg^{-1}) and soils cultivated with Mexican lime received 0.2% wood vinegar (from 6.46 to 7.08 mg kg^{-1}).

Table 3 Soil nutrients availability as influenced by citrus rootstocks, wood vinegar, and K application

Variety	Wood vinegar	K	Soil Ca (mg kg^{-1})	Soil Na (mg kg^{-1})	Soil Mn (mg kg^{-1})
Sour orange	WV0	K0	193de	122cde	5.48 g
		K1	197de	121cde	5.74 g
	WV0.2%	K0	189de	117de	7.04abc
		K1	191de	115e	7.30a
	WV0.4%	K0	226bc	134abc	6.28ef
		K1	234b	138ab	6.92abcd
Mexican lime	WV0	K0	199de	129bcd	5.90 fg
		K1	207 cd	124cde	5.62 g
	WV0.2%	K0	183e	129bcd	6.46de
		K1	221bc	139ab	7.08ab
	WV0.4%	K0	232b	146a	6.66bcde
		K1	256a	143a	6.58cde

Means followed by different letters are significantly different at $p<0.05$ by Tukey HSD

3.3.5 Iron

Potassium application decrease the available Fe content in soils treated with 0.4% wood vinegar (by 10%), while this effect was not observed in other wood vinegar treatments (Fig. 2, left). As shown in Fig. 2 (right), wood vinegar application, irrespective of plant variety, had no effect on Fe availability. In addition, without wood vinegar application, soils cultivated with sour orange had higher content of available Fe than those cultivated with Mexican lime.

3.3.6 Zinc

Availability of Zn was not affected by wood vinegar application, but K application increased its content in soils cultivated with Mexican lime by 17% (Fig. 3).

3.3.7 Copper

The availability of soil Cu was not affected by wood vinegar and K application, but the soils cultivated with Mexican lime had 9% more Cu content that those cultivated with sour orange.

3.4 Relationships

Significantly negative relationships were observed between pH and soil available K, Ca, Mn, and Zn (Table 4). In addition, available K, Ca, Na, Mn, and Zn were correlated with soil EC.

3.5 Plant dry weight and nutrients concentration and uptake

Analysis of variance (Table 5) indicated that all nutrients concentration in plant was affected by plant variety. Wood vinegar application also affected the concentration of P, K, Na, Mn, Zn, and Cu in plant. Potassium application had effect on the concentrations of K, Na, and Zn in plant. All nutrients except Na was also affected by the interaction od these factors.

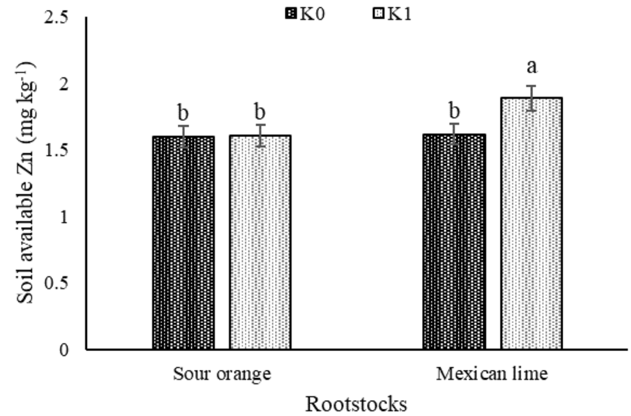

Fig. 3 Soil available Zn as influenced by interaction of rootstocks and K application. Columns with different letters are different at $p < 0.05$ by Tukey HSD test

Analysis of variance (Table 6) indicated that K and Zn uptake by plants was affected by the interaction of rootstock, wood vinegar and K application. Interaction of wood vinegar and K had significant effects on the uptake of all nutrients. Interaction of rootstock and wood vinegar also had significant effects on the plant uptake of all nutrients except P and Zn. The uptake of Mn and Zn was also affected by the interactions of rootstock and K application.

3.5.1 Dry weight

Regardless of wood vinegar and K application, the dry weight of sour orange was significantly more than that of

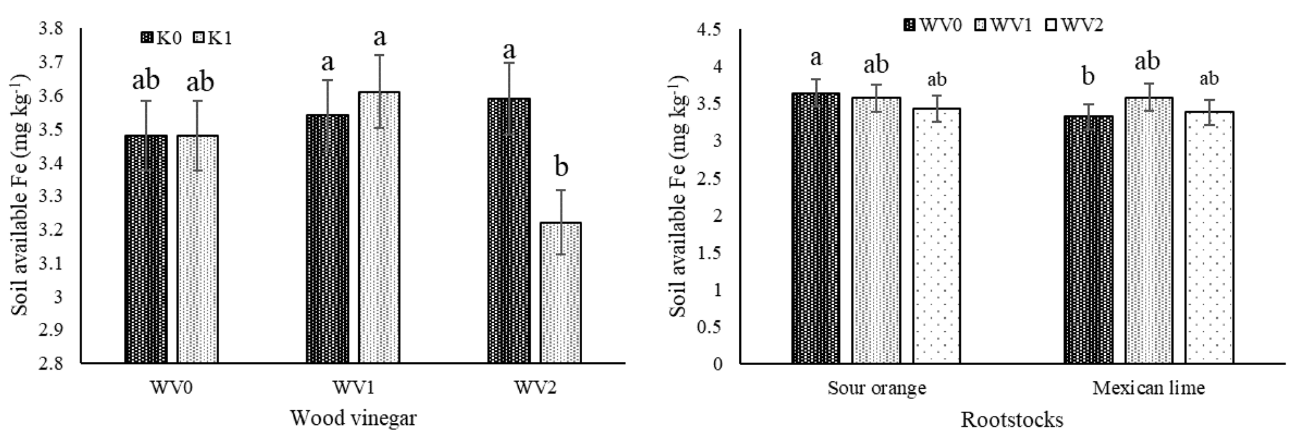

Fig. 2 Soil available Fe in pots cultivated with citrus rootstocks as influenced by interactions of wood vinegar and K application (left) and rootstocks and wood vinegar (right). Columns with different letters are different at $p < 0.05$ by Tukey HSD test

Table 4 Pearson's correlation coefficient between soil EC and pH and nutrients availability in soils cultivated with citrus rootstocks

	P	K	Ca	Na	Fe	Mn	Zn	Cu
pH	−0.017	−0.278*	−0.275*	−0.118	0.115	−0.272*	−0.286*	0.172
EC	0.202	0.737**	0.786**	0.564**	−0.238	0.288*	0.522**	0.100

** and * represent 0.01 and 0.05 levels of significance, respectively

Mexican lime (9.24 vs. 6.90 g pot^{-1}) (Fig. 4). Wood vinegar application at rates of 0.2 and 0.4% decreased dry weight of sour orange by 12 and 16%, respectively, while it had no significant effect on the dry weight of Mexican lime. Potassium application decreased the dry weight of sour orange and Mexican lime that received 0.4% wood vinegar by 14 and 29%, respectively.

3.5.2 Phosphorus

Wood vinegar application at rate of 0.4% significantly decreased P concentration of sour orange from 0.219 to 0.209%, while 0.2% wood vinegar had no effect on it (Table 7). Wood vinegar application had no effect on the P concentration of Mexican lime. In addition, P concentration of Mexican lime was significantly higher than that of sour orange. Plant P concentration was not affected by potassium application.

Phosphorus uptake by sour orange and Mexican lime was 0.021 and 0.019 g pot^{-1}, with significant difference. Application of K and 0.4% wood vinegar decreased P uptake by plant from 0.020 to 0.015 g pot^{-1} (Table 8).

3.5.3 Potassium

Wood vinegar and K application had no effect on the K concentration of sour orange (Table 7). Wood vinegar had no effect on the K concentration of Mexican lime, but K application increased K concentration of Mexican lime received 0.2% wood vinegar (from 1.48 to 1.88%). Generally, with K application, the K concentration of Mexican lime was significantly higher than that of sour orange. Such difference was not observed in treatments with no K application. The K uptake by plant was affected by the interaction of plant variety, wood vinegar and K. The highest (0.152 g pot^{-1}) and lowest contents (0.088 g pot^{-1}) of K uptake was obtained for sour orange received K and Mexican lime received K and 0.4% wood vinegar, respectively (Table 8).

3.5.4 Calcium

For all treatments (except 0.2% wood vinegar and K treatment), the Ca concentration of sour orange was significantly higher than that of Mexican lime (Table 7). Wood vinegar application had no effect on the Ca concentration of two rootstocks and K application only increased Ca concentration of Mexican lime received 0.2% wood vinegar (from 1.51 to 1.86%).

Calcium uptake by sour orange and Mexican lime was 0.187 and 0.111 g pot^{-1}, with significant difference. Dual application of 0.4% wood vinegar and K application decreased the Ca uptake by plant from 0.160 to 0.120 g pot^{-1} (Table 8).

3.5.5 Sodium

Concentration of Na in sour orange was significantly higher than that in Mexican lime (1367 vs. 1193 mg kg^{-1}) (Fig. 5). Wood vinegar application at rate of 0.2% had no effect on Na concentration but 0.4% wood vinegar application significantly increased plant Na concentration from 1233 to

Table 5 Analysis of variance for the effects of plant variety (A), wood vinegar (B), K application (C), and their interactions on plant nutrients concentration

Source of variation	Degree of freedom	Dry weight	Plant nutrient concentration							
			P	K	Ca	Na	Fe	Mn	Zn	Cu
Factor A	1	82.2**	0.034**	0.947**	2.62**	451193**	892,887**	1850**	911**	248*
Factor B	2	5.96**	0.003**	0.034*	0.018	76330**	1246	135**	103**	66.4**
Factor C	1	3.18	0.001	0.473**	0.020	66030*	3564	0.105	172**	0.030
A×B	2	2.33	0.001	0.034*	0.067**	17365	21,235**	310**	37.7*	66.3**
A×C	1	0.798	0.001	0.088**	0.041*	29099	28115**	235**	367**	0.008
B×C	2	5.94**	0.001	0.006	0.052**	13185	23824**	62.1*	73.9**	24.9**
A×B×C	2	0.417	0.002*	0.047**	0.083**	31735	3564	9.42	34.0	1.14
Error	48	0.904	0.001	0.009	0.008	10107	3956	16.5	11.0	3.69

** and * represent 0.01 and 0.05 levels of significance, respectively

Table 6 Analysis of variance for the effects of plant variety (A), wood vinegar (B), K application (C), and their interactions on plant nutrients uptake

Source of variation	Degree of freedom	P ($\times 10^{-3}$)	K	Ca	Na	Fe	Mn	Zn	Cu
Factor A	1	6.82**	0.003**	0.088**	290**	152**	0.546**	0.001	0.001
Factor B	2	8.31**	0.002**	0.003**	2.94	1.12	0.005	0.008**	0.007**
Factor C	1	1.13	0.001	0.001	0.290	2.17*	0.008	0.002	0.001
A×B	2	47.1	0.001*	0.003**	8.24*	2.67**	0.015**	0.003	0.002**
A×C	1	1.67	0.001	0.001	0.008	1.59	0.012*	0.012**	0.001
B×C	2	4.68**	0.002**	0.003**	10.2**	5.17**	0.025**	0.015**	0.004**
A×B×C	2	1.90	0.001*	0.001	3.82	0.120	0.001	0.004*	0.001
Error	48	6.38	0.001	0.001	1.67	0.407	0.003	0.001	0.001

** and * represent 0.01 and 0.05 levels of significance, respectively

1350 mg kg^{-1}. The plant Na concentration was significantly increased with K application from 1247 to 1313 mg kg^{-1}.

Sodium uptake by sour orange and Mexican lime was 12.6 and 8.2 mg pot^{-1}, with significant difference. Potassium application decreased Na uptake by plants received 0.4% wood vinegar (Table 8).

3.5.6 Iron, Mn, Zn, and Cu

Dual application of 0.2% wood vinegar and K significantly increased the plant concentrations of Fe, Mn, Zn, and Cu (Table 8). Potassium application significantly decreased plant Cu concentration of plants received 0.4% wood vinegar. The plant Zn concentration was 20.9 mg kg^{-1} and all wood vinegar and K applications increased its content to 24.1–30.3 mg kg^{-1}.

Two rootstocks differed in their Fe and Mn uptake and sour orange's uptake of Fe and Mn was 5.9 and 0.46 mg pot^{-1}, respectively, while those for Mexican lime were 2.7 and 0.27 mg pot^{-1}, respectively. The Zn and Cu uptake was not affected by rootstock. The lowest Fe uptake was found in plants received 0.4% wood vinegar and K (Table 8). Potassium application decreased Fe and Mn uptake of plants received 0.4% wood vinegar. Zinc uptake was affected by the interaction of plant variety, wood vinegar, and K and the highest (0.281 mg pot^{-1}) and lowest values (0.155 mg pot^{-1}) were observed in Mexican lime received K and 0.2 and 0.4% wood vinegar, respectively (Table 7). Potassium application increased Cu uptake of plants received no wood vinegar and decreased those received 0.4% wood vinegar (Table 8).

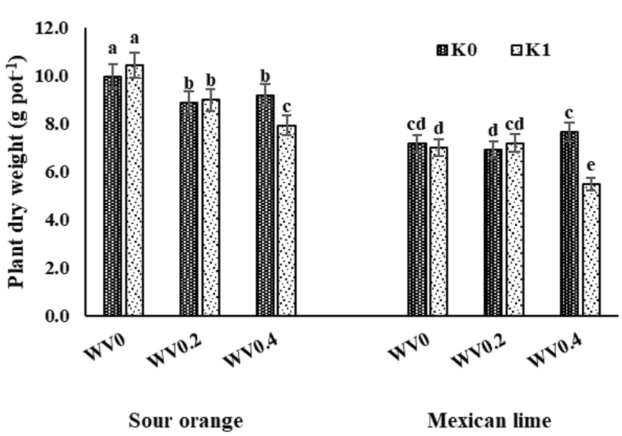

Fig. 4 Dry weight of citrus plants as influenced by the interaction of rootstock, wood vinegar and K application. Columns with different letters are different at $p<0.05$ by Tukey HSD test

3.6 Relationships between soil and plant nutrients

There was significant relationship between soil available nutrient and plant nutrient concentration. This relationship was found for K ($r=0.52$, $p<0.01$), Fe ($r=0.30$, $p<0.01$), Zn ($r=0.48$, $p<0.01$), and Cu ($r=0.27$*, $p<0.05$). It should be considered that competition among different nutrients for absorption, plant ability to accumulate or translocate nutrients in plant and other factors may induce no significant relationships between soil and plant nutrients.

4 Discussion

4.1 Rootstock effect

Different plant varieties can change the soil availability and uptake of nutrients via root exudations (effect on pH and complexing agents). There was no significant difference in P availability between soils cultivated by sour orange and Mexican lime, but soils cultivated by sour orange had lower contents of K, Ca, Na, and Zn (4, 5, 8, and 9%, respectively) and higher content of Fe (4%) compared to those cultivated by Mexican lime. As shown in Table 2, these rootstocks had no effect on soil pH, thus it seems that the difference in the availability of soil nutrients by rootstocks may be due to the difference in nutrients uptake or root complexing

Table 7 Plant nutrients concentration and uptake as influenced by the interaction of citrus rootstocks, wood vinegar and K application

Plant variety	Wood vinegar	K	Plant nutrient concentration (%)			K uptake (g pot^{-1})	Zn uptake (mg pot^{-1})
			P	K	Ca		
Sour orange	WV0	K0	0.219d	1.30e	2.07a	0.130abc	0.195bcd
		K1	0.233cdef	1.46cde	2.12a	0.152a	0.230abc
	WV0.2%	K0	0.240bcdef	1.33de	2.02ab	0.119bc	0.222abcd
		K1	0.227def	1.35de	1.97ab	0.122bc	0.190bcd
	WV0.4%	K0	0.215ef	1.28e	2.00ab	0.118bc	0.216abcd
		K1	0.209f	1.41de	1.95ab	0.112bcd	0.159 cd
Mexican lime	WV0	K0	0.284ab	1.52bcd	1.57c	0.109bcd	0.160 cd
		K1	0.272abc	1.72ab	1.53c	0.120bc	0.235ab
	WV0.2%	K0	0.265abcd	1.48cde	1.51c	0.102 cd	0.192bcd
		K1	0.297a	1.88a	1.86b	0.134ab	0.281a
	WV0.4%	K0	0.255abcde	1.44cde	1.60c	0.110bcd	0.199bcd
		K1	0.255abcdef	1.61bc	1.56c	0.088d	0.155d

Means followed by different letter are significantly different at $p < 0.05$ by Tukey HSD

compounds exudation. After study of dry weight of sour orange and Mexican lime (9.24 and 6.90 g pot^{-1}, respectively) and nutrients concentration in the shoots of two rootstocks, it is concluded that sour orange absorbed more P (11%), K (14%), Ca (69%), Na (54%), Fe (116%), and Mn (70%) than Mexican lime. Toplu et al. (2012) indicated that sour orange rootstock increased Ca and Na concentrations of its scion leaves (Mundarian) as compared to other rootstocks that is consistent with these findings. On the other hand, due to the high contents of base cations (Ca, Mg, K, and Na) in the soil solution of calcareous soils, these cations may reach to root surfaces via mass flow due to the plant transpiration (White 2001; Yang and Jie 2005). While, sour orange has more leaf surface area (Najafi-Ghiri et al. 2022) and thereby more transpiration rate than Mexican lime, the concentration of Ca, K, and Na may be higher in its aerial parts. Sour orange, despite its more P (11%), Fe (116%), and Mn (70%) uptake than Mexican lime, had no significant effect on these nutrients concentration in soil, and it seems that it has an ability to absorb more nutrients from soil via an increase in the availability of these nutrients in soil. According to a study by Raiesi and Moradi (2021), it is indicated that sour orange has an ability to mobilize P of calcareous soils from poorly available pools and this is the vital mechanisms of this rootstock rather than other citrus rootstocks (including swingle citrumelo and troyer citrange) for P acquisition. By comparison of nutrients concentration in soil and their uptake contents, it can be said that sour orange due to more K, Ca, and Na uptake induces a decrease in the concentration of these nutrients in soil. It is important that more P and K uptake by sour orange is due to its more dry weight and P and K concentrations in sour orange is lower than Mexican lime. This is consistent with finding of Toplu et al. (2012) who concluded that sour orange has less ability to uptake P and K rather that other citrus rootstocks. The Na concentration in sour orange and Mexican lime is in the range reported by Toplu et al. (2012) for different citrus rootstocks, and this element absorbs by plant only due to its occurrence in the rhizosphere. Generally, sour orange has an ability to accumulate more Na in the aerial parts than Mexican lime and this has been reported by Kaplankıran et al. (1995) and Toplu et al. (2012).

It seems that Mexican lime is more efficient than sour orange for Zn and Cu uptake and absorbs more Zn and Cu

Table 8 Plant nutrients concentration and uptake as influenced by the interaction of wood vinegar and K application

Wood vinegar	K	Nutrient concentration (mg kg^{-1})				Nutrient uptake (g pot^{-1})		Nutrient uptake (mg pot^{-1})			
		Fe	Mn	Zn	Cu	P	Ca	Na	Fe	Mn	Cu
WV0	K0	528ab	42.1b	20.9c	13.9ab	0.021a	0.160a	10.7a	4.7a	0.37ab	0.115b
	K1	499b	42.1b	27.9ab	16.0a	0.022a	0.164a	11.0a	4.5a	0.37ab	0.134a
WV0.2%	K0	490b	45.6ab	26.4ab	16.8a	0.020a	0.142ab	9.6b	3.9ab	0.36ab	0.129a
	K1	550a	49.0a	30.3a	16.9a	0.021a	0.155a	10.6ab	4.5a	0.40a	0.135a
WV0.4%	K0	567a	46.4ab	24.8b	13.6b	0.020a	0.153a	11.2a	4.9a	0.40a	0.115b
	K1	491b	42.7b	24.1b	11.3c	0.015b	0.120b	9.4b	3.5b	0.30b	0.076c

Means followed by different letters are different at $p < 0.05$ by Tukey HSD test

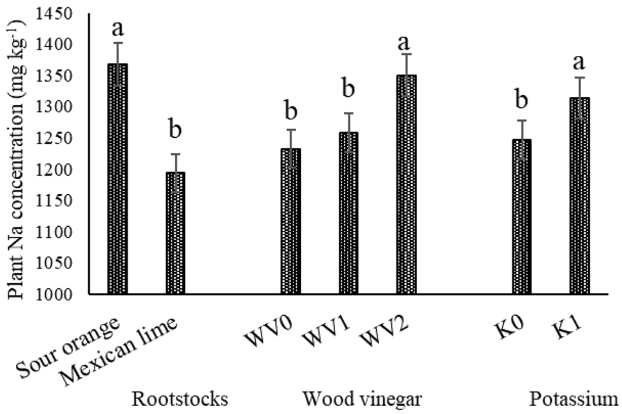

Fig. 5 Plant Na concentration as influenced by rootstocks, wood vinegar and K application. Columns with different letters are different at $p < 0.05$ by Tukey HSD test

with no significant effect on their concentration in soil. Generally, it can be said that root exudates of sour orange can increase the solubility of Fe and Mn and decrease the solubility of Zn and Cu in soil, but this may be different for Mexican lime. Havlin et al. (2005) stated that high weight organic compounds may form insoluble complexes with Zn and Cu and a reason for decrease in soil Zn and Cu concentrations by sour orange may be related to the exudation of high weight organic compounds from its roots. Differences in the effect of root exudates of two citrus genotypes on the rhizospheric processes have been reported by Vives-Peris et al. (2018)

4.2 Wood vinegar effect

Wood vinegar application at rate of 0.4% decreased plant P concentration and increased plant Na concentration. This may be explained by the effect of wood vinegar on mineral dissolution especially $CaCO_3$ and Na-containing minerals. An increase in soil soluble Ca and thereby precipitation of soluble P as Ca-P may decrease plant P availability and its uptake by plant. Wood vinegar at rate of 0.2% increased plant Zn and Cu concentration, while 0.4% wood vinegar application had no considerable effect on it. The fate of Zn and Cu in soil is complex and organic compounds depending of their nature like molecule weight may solubilize Zn and Cu or precipitate them (Havlin, Beaton, Tisdale and Nelson 2005). Wood vinegar may affect soil nutrients availability and their uptake by plant via effect on soil pH and salinity and thereby plant dry weight and nutrients uptake. Soil pH is an important soil characteristic affecting soil nutrients availability (Havlin, Beaton, Tisdale and Nelson 2005). Calcareous soils due to its alkaline reaction are deficient in P, Fe, Mn, Zn, and Cu (Adhami et al. 2006; Najafi-Ghiri et al. 2013). Changes of soil pH of calcareous soils is sometimes impossible due to the high buffering capacity. In the current investigation, regardless of rootstock variety, wood vinegar application at rates of 0.2 and 0.4% decreased soil pH by 0.07 and 0.10 unit, respectively. Soil salinity also is an important soil property affecting plant growth and nutrients uptake. Soil salinity was affected by wood vinegar application. Salinity of soils cultivated by sour orange and Mexican lime increased with 0.4% wood vinegar application by 9 and 15%, respectively. The main reasons for this increase are the dissolution of minerals especially Ca and Mg carbonates and soluble compounds of wood vinegar (EC = 5.15 dS m^{-1}). Contrary to our findings, Zhang et al. (2020) indicated that wood vinegar application had no significant effect on soil properties (except soil organic carbon) and nutrients availability, and it decreased blueberry fruit yield. Sun et al. (2020) found up to 0.3 unit reduction in soil pH and up to 11% increase in the rice grain yield with 10 ton ha^{-1} of wood vinegar application to rice paddy soils. A significant increase in soil salinity with use of wood vinegar has been reported by Wang et al. (2022).

4.3 Potassium effect

Potassium application may affect other nutrients availability in soil and uptake by plants via its effect on soil pH, plant growth (due to pH change and K uptake), and competition with other nutrients for uptake by root and translocation to aerial parts. Regardless of rootstock and wood vinegar, K application decreased soil pH by 0.08 unit and this is due to the exchange of increased soluble $K+$ with exchangeable $H+$. Potassium also increased soil EC by 18%. In addition, it had no significant effect on plant growth (except for Mexican lime with 0.4% wood vinegar application that decreased plant yield by 29%). Regardless of rootstock and wood vinegar, K application had no effect on soil P and Na and their uptake by plant. An inconsistent result has been reported by Ashraf et al. (2010) who concluded that addition of 100 kg ha^{-1} K from K2SO4 to some Pakistan soils increased P uptake by kinnow and it had no effect on some soils maybe due to the increase in plant growth by K and S supply. Wakeel (2013) also reported the effect of K and Na competition for uptake by plant via high affinity potassium transporter (HKTs) and nonselective cation channels (NSCCs) that is in agreement with our findings and in the current research K application despite an increase in soil K availability had no effect on plant uptake of K and Na. This is inconsistent with finding of Volf et al. (2022) for soybean growth in a sandy soil. Potassium ions enter to soil water and increase soluble K and due to the equilibration among different K forms (soluble, exchangeable, and non-exchangeable), some K ions diffuse to exchangeable (readily available) and non-exchangeable (slowly available) sites. This is in agreement with findings of Ashraf et al. (2010) for kinnow.

4.4 Rootstock, wood vinegar, and K interaction effect

Wood vinegar and K application may have different effect on the nutrient uptake and growth of citrus rootstocks. Generally, wood vinegar application had no effect on the availability of P, K, Zn, and Cu of soils cultivated with sour orange or Mexican lime. Availability of Na by wood vinegar was not affected in soils cultivated by sour orange while its value was increased in soils cultivated by Mexican lime. Wood vinegar application decreased the availability of Fe in soils cultivated by sour orange by 6% and it had no effect on the Fe availability of soils cultivated with Mexican lime. This is not in agreement with findings of Jeong et al. (2015) who concluded that the use of wood vinegar (diluted 500- and 1000-fold) to some rice paddy soils had no effect on soil N, P, K, Na, Ca, and Mg and plant yield. This contradictory finding may be due to the difference in plant species, soil condition, and wood vinegar dilution rate. Wang et al. (2022) also found contradictory results and stated that wood vinegar had little effect on coastal saline–alkali soils, and it may be used in combination with biochar for efficient remediation of soil.

Wood vinegar due to the acidic nature (pH 3.54) and dissolution of $CaCO_3$ in the used highly calcareous soil may increase soluble Ca concentration. On the other hand, less Ca uptake by sour orange and Mexican lime by 21 and 5% (due to reduction in plant yield with wood vinegar application) may also increase soil Ca concentration. Release of some occluded Na by carbonates dissolution and exchange of soluble Ca with exchangeable Na may be a reason for increase of soluble Na. Although, some researchers showed that organic acids are able to dissolve K-bearing minerals and release K, but in calcareous soils this process may be not considerable due to the neuralization of organic acids with carbonates (Najafi-Ghiri et al. 2019). In addition, wood vinegar application decreased K uptake by sour orange and Mexican lime by 19 and 13%, respectively. Thus, wood vinegar is not able to dissolve K-bearing minerals and release K in soils cultivated with both rootstocks. An increase in available K and no change in total K by wood vinegar application (diluted 500-fold) to a saline–alkali soil has been reported (Wang et al. 2022).

Wood vinegar had no effect on the soil Fe availability but 0.4% wood vinegar application decreased it in K-received soils. Despite less Fe uptake by plants receiving K and wood vinegar, it seems that reduction in soil Fe is due to precipitation of Fe with organic compounds or soluble carbonates. No significant change in soil Zn and Cu availability with soil pH reduction may be due to the formation of insoluble complexes of these elements with organic compounds (Havlin et al. 2005) of wood vinegar. However, Mn has more soluble compounds with organic complexing agents than Zn and Cu (Havlin et al. 2005). This is inconsistent with findings of Zhou et al. (2022) who concluded that wood vinegar application increased the availability of Zn by lowing soil pH, which facilitated plant uptake. They concluded that the optimal Zn extraction was occurred by use of 1% wood vinegar application, which increased the Zn extraction by 164%.

As shown in Table 4, the availability of K, Ca, and Mn had negative correlations with soil pH. Najafi-Ghiri et al. (2017) found significantly negative correlation between pH and P, K, and Mn availability in some citrus cultivated soils of southern Iran.

Potassium application affected soil Ca and increased its content in soils cultivated with Mexican lime and 0.4% wood vinegar application by 12% that this may be due to the reduction of plant growth (by 29%) and thereby less Ca uptake (30%). Although some research (Ashraf et al. 2010) indicated that K application had no significant effect on Ca uptake by kinnow, Jakobsen (1993) reported a decrease in bivalent cations uptake by plant after soil K application due to imbalance in soil nutrients. The soil Fe availability and its uptake by plant was decreased by 10 and 29%, respectively after K application, and this was more considerable in soils received 0.4% wood vinegar. A decrease in Fe uptake by plant may be due to the negative effect of K on plant growth and competition among cations for uptake, but a decrease in soil Fe availability despite its less uptake may be due to the precipitation of Fe after exchange of exchangeable Fe with soluble K. A change in soil Mn availability with K application was not found in soils cultivated with Mexican lime but K application increased Mn availability (by 10%) in soils cultivated with sour orange maybe due to the reduction of Mn uptake. considering no reduction in sour orange growth with K, a decrease in Mn uptake may be due to the competition between K and Mn for uptake by roots that decreased Mn concentration in plant by 8%. A 17% increase in soil Zn availability by K application was obtained with Mexican lime. In addition, a 20% increase in Zn uptake was observed with K application. In fact, K application despite a decrease in plant growth, increased Zn concentration of sour orange by 32%. This considerable increase in soil and plant Zn may be due to the effects of K on soil pH decrease and also stimulation of plant roots to acidic and complexing compounds secretion. Wang and Harrell (2005) concluded that K application to calcareous soils reduced Zn sorption by soil compounds due to competition for sorption sites. No effect of K on soil Cu availability was found but Cu uptake was decreased (by 33%) with K and 0.4% wood vinegar application. This may be due to the K and Cu competition for uptake by plant roots. In a study (Volf et al. 2022), it was shown that K application to a sandy soil decreased the concentrations of Ca, Mg, and micronutrients in leaves of soybean and had no significant effect on plant growth. They concluded that high application of K in sandy soils can disrupt the balance of nutrient uptake by soybean plants. In fact, by K application, the competition among cations for absorption at sites on the root surfaces and also the specific permeability of the root membrane to some cations may affect the uptake and translocation of other cations from root to aerial parts in plants (Firmano et al. 2020; Mengel and Kirkby 2001; Volf et al. 2022).

5 Conclusions

Little or no information is available about the soil nutrients status and their uptake by citrus after wood vinegar and K application to soil. In the current research, we tried to monitor the soil nutrients availability and growth and nutrients uptake by sour orange and Mexican lime after 0.2 and 0.4% wood vinegar and 100 mg kg^{-1} K. Wood vinegar application had significant effects on some chemical soil properties like the increase in soil EC and the decrease in soil pH as well as the increases in available Ca, Mn, and Na. Potassium application may decrease soil pH due to the exchange of K ions with exchangeable H and increase soil EC and available K, Ca, Mn, and Zn as a result of pH decrease. Wood vinegar application may disrupt citrus growth that is more pronounced for some sensitive varieties like sour orange rather than Mexican lime. It may affect the nutrients content in plant that in the current research, P and K contents decreased, while the Na and Mn contents increased. However, due to the negative effects of wood vinegar on plant growth, the P, K, Ca, Zn, and Cu uptake may be decreased. Potassium application had no significant effect on plant growth but it may increase the K, Na, and Zn concentration in the plant. The main effect of K application to nutrients uptake may be due to the competition among cations for absorption on root surfaces. Simultaneous application of wood vinegar at high rate and K may induce a considerable decrease in all nutrients uptake. This may be due to the effect of these compounds on the soil salinity and changes the nutrients balance in soil and plant that may have a severe effect on plant growth. Generally, it is recommended the low rates of wood vinegar application in calcareous soils with K and P deficiency. On the other hand, due to the more negative effect of wood vinegar on sour orange rather than Mexican lime, the application of wood vinegar for citrus plants may be recommended with respect to the rootstock variety.

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Declarations

Conflict of interest The authors declare no competing interests.

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