Influence of potassium nanoparticles on yield and bioactive compounds in melon fruit

Influencia de nanopartículas de potasio en el rendimiento y compuestos bioactivos de frutos de melón

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ABSTRACT. Potassium is known as a quality element due to its key role in sugar transport, metabolite biosynthesis, and enzyme activation. This study aimed to determine the optimal dose of potassium nanoparticles (K NPs) in melon plants and evaluate their impact on yield, nutraceutical quality, and K content in the fruits. A field experiment was conducted with melon cv Cruiser, applying four foliar doses of K NPs (100, 200, 300, and 400 mg L^{-1}) and a control treatment (distilled water). The results indicated that foliar application of K NPs significantly affected the nutraceutical quality and K content in melon fruits without impacting crop yield. Melon fruits from plants treated with the intermediate dose (200 mg L^{-1}) showed the highest levels of total soluble solids and firmness. The low dose (100 mg L^{-1}) increased the biosynthesis of flavonoids, total phenols, and antioxidant capacity, while higher doses (300 and 400 mg L^{-1}) reduced bioactive compounds, although they increased the potassium content in the fruits. Foliar application of K NPs is a viable strategy that, when integrated with agronomic practices, can improve the nutraceutical quality of melons without compromising crop yield. However, it is essential to determine the appropriate doses, as low and intermediate doses enhance the fruit's biophysical and nutraceutical quality, while higher doses may have adverse effects on bioactive compounds.
Keywords: Antioxidants, *Cucumis melo* L, foliar fertilization, nanotechnology.

RESUMEN. El potasio es un elemento de calidad, debido a su papel en el transporte de azúcares, biosíntesis de metabolitos y la activación de enzimas. Este estudio tuvo como objetivo determinar la dosis óptima de nanopartículas de potasio (K NPs) en plantas de melón y evaluar su impacto en el rendimiento, la calidad nutracéutica y contenido de K en los frutos. Se realizó un experimento de campo con melón cv Cruiser, aplicando dosis foliares de K NPs (100, 200, 300, y 400 mg L^{-1}) y un tratamiento control (agua destilada). Los resultados indicaron que la aplicación foliar de K NPs afectó significativamente la calidad nutracéutica y el contenido de K en frutos de melón, sin afectar el rendimiento del cultivo. Los frutos de melón de plantas con la dosis intermedia (200 mg L^{-1}), presentaron los valores más altos de sólidos solubles totales y firmeza. La dosis baja (100 mg L^{-1}), incremento la biosíntesis de flavonoides, fenoles totales y capacidad antioxidante, mientras que las dosis más altas (300 y 400 mg L^{-1}) redujeron los compuestos bioactivos, aunque aumentaron el contenido de potasio en los frutos. La aplicación foliar de K NPs es una estrategia viable que integrada con las prácticas agronómicas del cultivo puede mejorar la calidad nutracéutica del melón sin comprometer el rendimiento del cultivo. Sin embargo, es necesario determinar las dosis, ya que la dosis baja e intermedia mejoran la calidad biofisica y nutraceutica del fruto, mientras que las dosis más altas pueden tener efectos adversos sobre los compuestos bioactivos.
Palabras clave: Antioxidantes, *Cucumis melo* L, fertilización foliar, nanotecnología.

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INTRODUCTION

Potassium (K^+) is one of the most important macronutrients and is considered the quality element of crops (Lester *et al.* 2010), it plays various biochemical processes in plants (Akhtyamova *et al.* 2023), such as protein synthesis, sugar transport (Uthman and Garba 2023), stomatal conductance, photosynthesis, respiration, signal transduction and ion homeostasis (Shen *et al.* 2017). In addition, K plays a functional role in the activation of more than 60 carbohydrate synthesis enzymes and proteases in plants (Oosterhuis *et al.* 2014). K ions are involved in the opening and closing of stomata, helping to maintain optimal CO_2 levels for photosynthesis, preventing water loss, and ensuring efficient sugar production in plants (Sheoran *et al.* 2021). The uptake and transport of K within the plant depends on the availability of K in the soil (Rogiers *et al.* 2017); however, despite a high availability of K in the soil especially in calcareous soils, many factors can limit its adequate uptake by plants impacting on poor fruit quality and yield (Jifon and Lester 2011). Among the soil factors, the ionic competition between cations (Ca, Mg) stands out (Weil and Brady 2002), and in the plant, the phenological stages of the crop (Ho 1988). In view of this situation, foliar fertilization with potassium is an alternative to improve the yield and quality of crops (Lo'ay *et al.* 2021). Nanomaterials are finding increasing applications in agriculture as they increase crop yields and reduce environmental pollution (Qibin *et al.* 2024).

Foliar application of nano fertilizers is becoming increasingly important compared to that of traditional fertilizers. This is mainly due to higher plant uptake efficiency and efficacy at low concentrations (Butt and Naseer 2020). K NPs provide sufficient K to the plant and improve photosynthetic processes, and yield (Lo'ay *et al.* 2021); also, K NPs improve crop productivity under salt stress conditions (Mahmoud *et al.* 2022). Salama *et al*. (2024) reported that the application of a K based nanofertilizer to onion (*Allium cepa* L) plants improved yield and the content of bioactive compounds. Likewise, Doaa *et al*. (2019) mention that the application of nano potassium + potassium sulfate increased N, P, and K concentrations in petioles, improved shoot length and diameter, leaf area, significantly increased yield, total soluble solids, total anthocyanins and total sugars in grapevine (*Vitis vinifera*) cv. Flame seedless. Despite the advantages of the use of nanoparticles, it is difficult to determine the optimal dose, since their effects vary depending on several factors such as the type of crop, the nanoform, the duration of exposure, and the interactions with the nanoelement (Guillén-Enríquez *et al.* 2022).

Melon (*Cucumis melo* L.) is known for its excellent nutritional profile, as it contains proteins, lipids, vitamin C, beta-carotene, antioxidants, bioactive polyphenols, and other phytochemical compounds crucial for disease prevention (Rivera-Gutiérrez *et al.* 2021). Given its economic importance and the continuous growth of production in Mexico, there is a production of 648 541.00 ton, with an average yield of 32.82 tons ha^{-1} (SIAP 2023), the objective of the present study was to determine the optimal dose of potassium nanoparticles (K NPs) in melon plants and evaluate their impact on yield, nutraceutical quality, and K content in the fruits.

MATERIALS AND METHODS

Growth conditions

The study was conducted in fields located in Concordia, Coahuila, Mexico (25° 48'31'' north latitude and 103°5'56.4'' west longitude, altitude 1 016 m). The climate in the region is semi-warm, with average annual temperatures ranging from 20 to 22 °C and annual rainfall between 125 and 400 mm. Melon var *Cruiser* was planted and grown according to standard commercial practices for melon production in this region, including fallow, cross-cropping, and leveling. Double-row borders were constructed forming beds at a distance of 4 m between borders and a plant spacing of 30 cm for a density of 16 665 plants per ha. The soil texture is silt loam (40% sand, 46% silt and 14 clay); bulk density 1.56 g cm^3; pH 7.67; water holding capacity 23.4%; electrical conductivity 4.28 dS m^{-1}; organic matter content 0.8%; total nitrogen 4.82 mg kg^{-1}; available phosphorus 4.27 mg kg^{-1}, potassium 603.93 mg kg^{-1}; calcium 6 181.93 mg kg^{-1} and magnesium 202.74 mg kg^{-1}.

The soil is calcareous. Fertilization was according to local recommendations, consisting of 120-60-00 ($N–P_2O_5–K_2O$), applying all the phosphorus and half of the nitrogen at planting and the rest of the nitrogen at flowering. The fertilizers used were $NH_4H_2PO_4$ and NH_4SO_4. Irrigation was provided by gravity. In pre-sowing, one irrigation was applied with a 0.30 m sheet; subsequently, in pre-sowing, one irrigation was applied with a 0.25 m sheet; subsequently, six auxiliary irrigations were applied with 0.09 m sheets each; a total of 0,74 m was applied during the crop cycle.

Treatments and experimental design

The commercial nanofertilizer PHC* NANO K was applied, which is a suspension, where K is available in ionic form, which allows it to be quickly absorbed by the plant (Marquez-Prieto *et al.* 2022). The treatments consisted of five doses of K NPs: 100, 200, 300, and 400 mg L^{-1} and a control treatment (distilled water). In all formulations, 0.1% urea was added as the carrier ion and a non-toxic commercial surfactant (INEX-A®, 0.02% v:v). A completely randomized block design was used, with six replicates, resulting in a total of 30 experimental units. The application of treatments was carried out directly on the plant using a manual sprayer. Four applications were made, the first one 30 days after planting, and the following three applications were made every 15 days.

Fruit weight and yield

The fruits of all treatments were harvested at commercial maturity. All harvested fruits were weighed using a digital scale (Torrey®, México) with a maximum capacity of 5 kg. Yield was estimated per hectare considering the total weight of fruit in each experimental unit. The polar and equatorial diameter was measured using a digital vernier (Truper®, Mexico) and the result was reported in cm.

Soluble solids and firmness

The determination of total soluble solids (TSS) and firmness was carried out on one fruit per replicate. TSS (°Brix) was measured with a manual refractometer with a measuring range from 0 to 32% (Atago® Master 2311, Tokyo, Japan). Firmness was measured using a penetrometer model FH20000 (Extech®, USA) with an 8 mm measuring head. The method involved peeling the fruit, placing it on a sturdy, level surface, creating four punctures per fruit, averaging the readings, and presenting the findings as the maximum compression force in Newtons (N).

Preparation of extracts for non-enzymatic antioxidants

One melon was randomly chosen from each treatment and replication for the assessment of non-enzymatic antioxidants. Each fruit was sampled by extracting two g of fresh pulp and combining it with 10 mL of 80% ethanol in a plastic tube sealed with a screw cap. The tube was then placed in a rotary shaker (ATR Inc., USA) for 6 hours at 5 °C and 20 rpm. Subsequently, were centrifuged at 3000 rpm for 5 min and the supernatant was removed for analytical tests.

Flavonoids totals

Total flavonoids were determined by colorimetry (García-Nava 2009). Samples were quantified in a UV-Vis spectrophotometer at 510 nm (Metash, UV-6000, Shanghai, China). The standard was prepared with quercetin dissolved in absolute ethanol. Results were expressed as mg QE 100 g^{-1} FW.

Total phenolic content

Total phenolic content was determined by the Folin-Ciocalteau method (Garcia-Nava 2009). Samples were quantified in an ultraviolet (UV)-Vis spectrophotometer at 760 nm (Metash, UV-6000, Shanghai, China). The standard was prepared with gallic acid. The results were expressed in presented in milligrams of gallic acid (GA) equivalent per gram of fresh weight (mg equiv GA g^{-1} FW).

Antioxidant capacity

The assessment of antioxidant capacity was conducted through the in vitro $DPPH^+$ method, with a modification based on the method of Brand-Williams *et al.* (1995). 50 µL of the sample was mixed with 950 µL of $DPPH^+$ solution, and after a 3 min reaction period, the absorbance was measured at 515 nm. A standard curve was created using Trolox (Sigma-Aldrich), and the results were presented in micromoles (µM) of Trolox per gram of fresh weight (µM equiv Trolox g^{-1} FW).

K content

The K concentration in melon pulp was determined by AOAC (1990) guidelines using atomic absorption spectrophotometry with an air-acetylene flame (VARIAN-SPECTR AA 3110, Palo Alto, CA, USA), the results were expressed in mg kg^{-1} dry weight (DW).

Statistical data analyses

The data obtained underwent Bartlett's test to assess variance homogeneity, and normality was examined using the Bartlett and Kolmogorov-Smirnov tests. Following these tests, an analysis of variance (ANOVA) was conducted, identifying differences between treatments where applicable, Tukey's test was used ($p \leq 0.05$). Using the statistical package SAS version 9.1 (Statical Analysis System Institute).

RESULTS

Yield and fruit quality

The foliar application of K NPs did not show significant differences in the variables yield, weight, and equatorial diameter of melon fruits (Table 1).

Table 1. Yield, fruit weight, total soluble solids (TSS), and firmness of melon fruit subjected to different doses of potassium nanofertilizer.

K NPs (mg L^{-1})	Yield (ton ha^{-1})	Fruit weight (kg)	Polar Diameter (cm)	Equatorial Diameter (cm)	Firmness (N)	TSS (°Brix)
Control	11.58	1.43	14.92 b*	13.90	12.33 c	9.83 c
100	13.501	1.44	15.12 ab	14.06	13.26 bc	10.83 bc
200	13.857	1.53	15.15 ab	14.05	15.83 a	12.50 a
300	14.388	1.53	15.40 a	14.19	14.32 ab	11.50 ab
400	15.541	1.58	15.14 ab	14.00	13.32 bc	9.67 c
Significance	NS	NS	*	NS	*	*

*Means with different letters in the same column are statistically different (Tukey $p \leq 0.05$); NS = not significant, * = significant.

Significant differences were observed in the variable's firmness, total soluble solids, and polar diameter. Foliar spraying of K NPs at 200 mg L^{-1} increased firmness by 28.39% and TSS by 27.17% in melon fruits compared to the control; however, when the dose of K NPs was increased, a decrease in these quality parameters was observed. The highest values for polar diameter were found in the 300 mg L^{-1} treatment, exceeding the control by 3.11% (Table 1).

Bioactive compounds

K is one of the nutrients with the greatest influence on the quality parameters of crops. The K NPs foliar application at 100 mg L^{-1} influenced the highest phytochemical biosynthesis of flavonoids, total phenols and antioxidant capacity with increases of 31.25, 23.48 and 8.50%, respectively, in relation to the corresponding controls. However, by increasing the dose from 200 to 400 mg L^{-1} there was a decrease in phytochemical compounds (Figure 1).

Potassium concentration

K concentration presented a significant difference in melon pulp according to the applied treatments. The treatment 400 mg L^{-1} registered the highest K concentration in the fruits, exceeding the control by 34.93% (Figure 2).

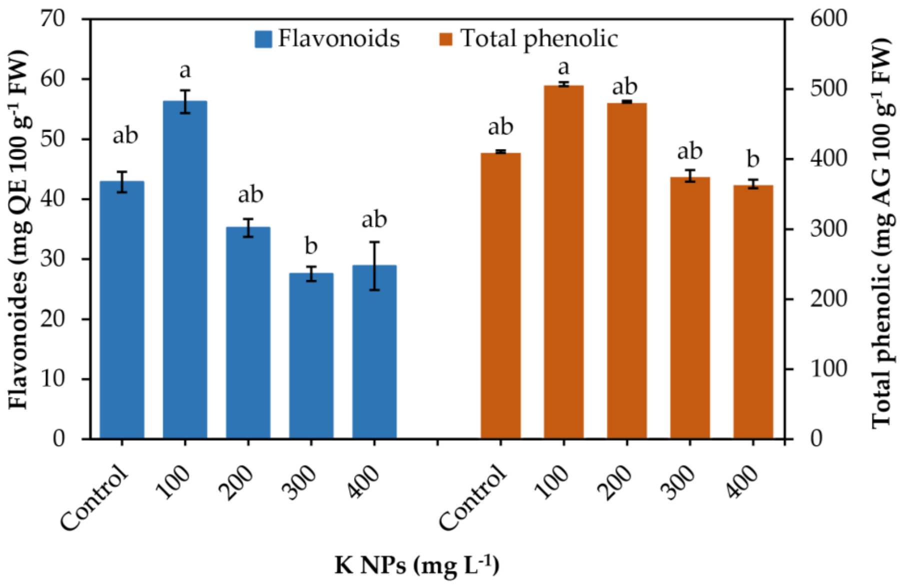

Figure 1. Effect of foliar application of K nanoparticles on flavonoid (■) and total phenolic (■) contents in melon fruits. All values represent means ± standard deviation (N = 30). Bars with different letters are statistically different according to Tukey's test ($p \leq 0.05$).

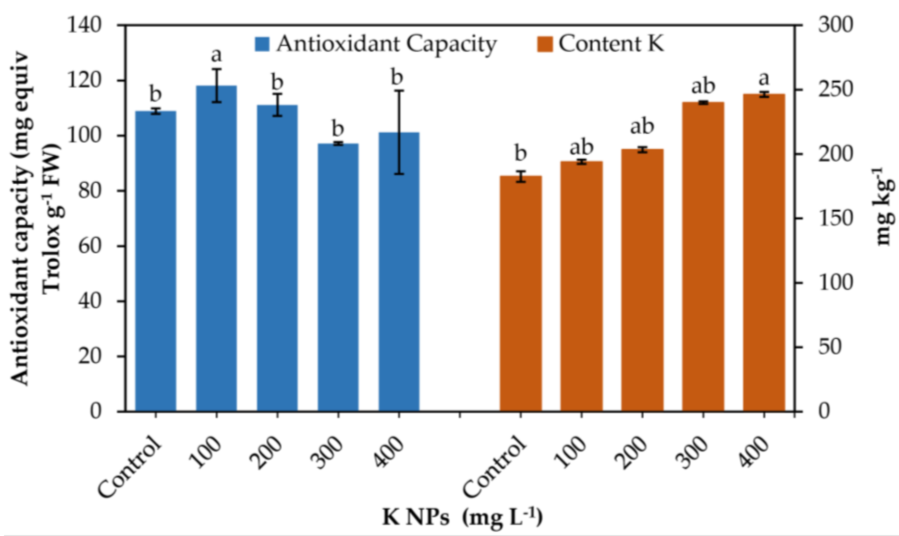

Figure 2. Effect of foliar application of K nanoparticles on antioxidant capacity (■) and K content (■) in melon fruits. All values represent means ± standard deviation (N = 30). Bars with different letters are statistically different according to Tukey's test ($p \leq 0.05$).

DISCUSSION

In the present study, foliar application of K NPs did not significantly modify yield relative to the control. The nule or low response of yield, weight, and fruit size to the foliar application of K NPs is probably due to the high K content in the soil, the level of K in the soil of the study site of the present work was 603.93 mg kg^{-1}. Similar results have been reported by Hartz *et al.* (2005); and Jifon and Lester (2011), who found that at high potassium content in the soil there is no yield response to foliar application with this element, but there is an improvement in fruit quality, due to its role in the transport of sugars, metabolite biosynthesis and enzyme activation (Javaira *et al.* 2012).

Foliar applications of K NPs resulted in increases in TSS and fruit firmness. Adequate K nutrition has been shown to increase soluble sugars and pulp firmness (Abdullah and Alabdaly 2023). Melon fruit consumption is related to TSS, which is responsible for the sweet taste. It has been determined that a melon fruit is of lower quality if it has <9 °Brix. However, if it presents between 9 to 12 °Brix it is of excellent quality, and if it is >12 °Brix it is considered of extra quality (García-Mendoza *et al.* 2019). The higher values in firmness and TSS reflect the crucial role of K in enhancing photosynthesis and transporting sugar to demand sites (Marschner 2012), sugars act as osmoregulatory agents to maintain cell pressure, cell structure, stomatal conductance, and cell potential (Saddhe *et al.* 2021), the above explains the positive relationship between TSS and fruit firmness (Demiral and Köseoglu 2005) as TSS increases the pressure potential (ψp) of fruits (Lester *et al*. 2010). However, at higher potassium doses the TSS and firmness decrease because its excess alters sugar metabolism (Zhang *et al.* 2018, Wu *et al*. 2023), ionic homeostasis (Shen *et al.* 2017), altering normal calcium absorption affecting the integrity of cell walls; moreover, excess K can generate osmotic stress thus decreasing water absorption by the fruit which affects pressure potential (Lester *et al.* 2006). A similar relationship between high doses of potassium and decreased TSS and firmness have been reported by Akhtar *et al.* (2010), Javaira *et al.* (2012) and (Molina *et al.* 1992).

Regarding bioactive compounds, the results indicate that low doses (100 mg L^{-1}) of K NPs increase the contents of total flavonoids, total phenols and antioxidant capacity, contrary to the K content in melon fruit, which increased with high doses (300 and 400 mg L^{-1}). Previous studies have shown that foliar application of K at appropriate doses stimulates the biosynthesis of bioactive compounds (Gaaliche *et al.* 2024, Salama *et al.* 2024). However, high concentrations of K+ in the cytosol of cells inhibit the synthesis of primary compounds derived from nitrogen metabolism, reducing the amount of energy, amino acids, and consequently, proteins and enzymes, necessary for the biosynthesis of compounds of secondary metabolism (Xie *et al.* 2021). In this context, plant exposure to high levels of nanoparticles, regardless of their nature, exhibits an overproduction of ROS (Hatami and Ghorbanpour 2024) that cannot be eliminated at the expense of the consumption of antioxidant-derived compounds produced by plants (Huchzermeyer *et al.* 2022); since ROS play a dual role, at low concentrations, they act as signalers, triggering a moderate stress response in plants and activating the biosynthesis of bioactive compounds, and with overproduction, cellular homeostasis is disturbed, damaging cellular structures, proteins, DNA and lipids (Singh *et al.* 2024).

Foliar fertilization with K NPs can contribute to supplementing the average daily potassium intake ranging from 2000 to 3900 mg in people without kidney problems (Choi and Ha 2013); however, it is necessary to complete the requirements with sources (Asaduzzaman *et al*. 2018), since K plays an important role in the human body and maintains the normal functioning of muscles, heart, and nerves through acid-base balance, enzyme activation, and kidney function (Crawford and Harris 2011), its concentration in harvested agricultural products is a quality parameter in itself.

CONCLUSIONS

The nutraceutical quality of melon fruits is strongly influenced by the dose of K NPs used. At low concentrations of K NPs, there is a marked enhancement of non-enzymatic antioxidant activity. However, at higher doses, there is an inhibitory effect on the activity of these antioxidants, together with an increase in potassium concentration in melon flesh. It is not recommended to apply high doses of K NPs, as this leads to an overproduction of ROS, causing cellular stress that negatively affects the yield and nutraceutical quality of the crop. Foliar fertilization with K NPs is a viable strategy to enhance the biosynthesis of bioactive compounds in melon fruits.

CONFLICT OF INTEREST

The authors have no competing interests to declare that are relevant to the content of this article.

LITERATURE CITED

Abdullah SK, Alabdaly MM (2023) Influence of spraying potassium, sugar alcohol, and boron on yield and quality of melon under protected cultivation. In IOP Conference Series: Earth and Environmental Science. IOP Publishing. 4p. 042035. https://doi.org/10.1088/1755-1315/1262/4/042035

Akhtar ME, Khan MZ, Rashid MT, Ahsan Z, Ahmad S (2010) Effect of potash application on yield and quality of tomato (*Lycopersicon esculentum* Mill.). Pakistan Journal of Botany 42(3): 1695-1702.

Akhtyamova Z, Martynenko E, Arkhipova T, Seldimirova O, Galin I, Belimov A, Vysotskaya L, Kudoyarova G (2023) Influence of plant growth-promoting rhizobacteria on the formation of apoplastic barriers and uptake of water and potassium by wheat plants. Microorganisms 11: 1-13. https://doi.org/10.3390/microorganisms11051227

AOAC (1990) Association of Official Analytical Chemists. Official Methods of Analysis, 15th Ed. Association of Official Analytical Chemists: Washington, DC, USA. 771p.

Asaduzzaman M, Talukder MR, Tanaka H, Ueno M, Kawaguchi M, Yano S, Asao T (2018) Production of low-potassium content melon through hydroponic nutrient management using perlite substrate. Frontiers in Plant Science 9: 1-18. https://doi.org/10.3389/fpls.2018.01382

Brand-Williams W, Cuvelier ME, Berset C (1995) Use of a free radical method to evaluate antioxidant activity. LWT-Food Science and Technology 28(1): 25-30. https://doi.org/10.1016/S0023-6438(95)80008-5

Butt BZ, Naseer I (2020) Nanofertilizers. In: Javad S (eds) Nanoagronomy. Springer, Cham. https://doi.org/10.1007/978-3-030-41275-3_8

Choi HY, Ha SK (2013) Potassium balances in maintenance hemodialysis. Electrolyte Blood Press 11(1): 9-16. https://doi.org/10.5049/ebp.2013.11.1.9

Crawford A, Harris H (2011) Balancing act: Na^+ sodium K^+ potassium. Nursing 41: 44-50. https://doi.org/10.1097/01.nurse.0000397838.20260.12

Demiral MA, Köseoglu AT (2005) Effect of potassium on yield, fruit quality, and chemical composition of greenhouse-grown galia melon. Journal of Plant Nutrition 28: 93-100. https://doi.org/10.1081/pln-200042179

Doaa MH, Sefan RF, El-Boray MS (2019) Effect of potassium nano fertilizer on yield and berry qualities of 'Flame Seedless' grapevines. Journal of Plant Production 10(11): 929-934. https://doi.org/10.21608/jpp.2019.68553

Gaaliche B, Yahmed BJ, Benmoussa H, Mimoun BM (2024) Fruit yield and quality of fig (*Ficus carica* L.) are affected by foliar sprays of potassium sulfate. Journal of Agricultural Science and Technology 26(3): 623-635. http://dx.doi.org/10.22034/JAST.26.3.623

García-Mendoza V, Cano RP, Reyes-Carrillo JL (2019) Harper-type melon hybrids have higher quality and longer post-harvest life than commercial hybrids. Revista Chapingo Serie Horticultura 25(3): 185-197. https://doi.org/10.5154/r.rchsh.2019.05.008

García-Nava M (2009) Cuantificación de fenoles y flavonoides totales en extractos naturales. Universidad Autónoma de Querétaro Revista Académica 1: 1-4.

Guillén-Enríquez RR, Zuñiga-Estrada L, Ojeda-Barrios DL, Rivas-García T, Trejo-Valencia R, Preciado-Rangel P (2022) Effect of nano-biofortification with iron on yield and bioactive compounds in cucumber. Revista Mexicana de Ciencias Agrícolas 13(28): 173-184. https://doi.org/10.29312/remexca.v13i28.3272

Hartz TK, Johnstone PR, Francis DM, Miyao EM (2005) Processing tomato yield and fruit quality improved with potassium fertigation. HortScience 40(6): 1862-1867. https://doi.org/10.21273/HORTSCI.40.6.1862

Hatami M, Ghorbanpour M (2024) Metal and metal oxide nanoparticles-induced reactive oxygen species: Phytotoxicity and detoxification mechanisms in plant cell. Plant Physiology and Biochemistry 108847. https://doi.org/10.1016/j.plaphy.2024.108847

Ho LC (1988) Metabolism and compartmentation of imported sugars in sink organs about sink strength. Annual Review of Plant Biology 39: 355-378. https://doi.org/10.1146/annurev.arplant.39.1.355

Huchzermeyer B, Menghani E, Khardia P, Shilu A (2022) Metabolic pathway of natural antioxidants, antioxidant enzymes, and ROS providence. Antioxidants 11(4): 761. https://doi.org/10.3390/antiox11040761

Javaira S, Khan MQ, Bakhsh I (2012) Effect of potassium on chemical and sensory attributes of tomato fruit. Journal of Animal and Plant Sciences 22(4): 1081-1085.

Jifon, JL, Lester GE (2011) Effect of foliar potassium fertilization and source on cantaloupe yield and quality. Better Crops 95: 13-15.

Lester GE, Mon JL, Makus DJ (2006) Supplemental foliar potassium applications with or without a surfactant can enhance netted muskmelon quality. Hortscience 41(3): 741-744. https://doi.org/10.21273/HORTSCI.41.3.741

Lester GE, Jifon JL, Makus DJ (2010) Impact of potassium nutrition on postharvest fruit quality: Melon (*Cucumis melo* L.) case study. Plant and Soil 335: 117-131. https://doi.org/10.1007/s11104-009-0227-3

Lo'ay AA, EL-Ezz SFA, Awadeen AA (2021) Effect of different foliar potassium fertilization forms on vegetative growth, yield, and fruit quality of kaki trees grown in sandy soil. Scientia Horticulturae 288: 110420. https://doi.org/10.1016/j.scienta.2021.110420

Mahmoud AWM, Samy MM, Sany H, Eid RR, Rashad HM, Abdeldaym EA (2022) Nanopotassium, nanosilicon, and biochar applications improve potato salt tolerance by modulating photosynthesis, water status, and biochemical constituents. Sustainability 14(2): 723. https://doi.org/10.3390/su14020723

Marquez-Prieto AK, Palacio-Marquez A, Sanchez E, Macias-Lopez BC, Perez-Álvarez S, Villalobos-Cano O, Preciado-Rangel P (2022) Impact of the foliar application of potassium nanofertilizer on biomass, yield, nitrogen assimilation and photosynthetic activity in green beans. Notulae Botanicae Norti Agrobotanici Cluj-Napoca 50(1): 1-12. https://doi.org/10.15835/nbha50112569

Marschner P (2012). Marschner's mineral nutrition of higher plants. Academic Press. 3rd Ed. London. UK. 651p.

Molina E, Salas R, Martínez I, Cabalceta G, Cabalceta E (1992) Fertilización potásica del cultivo del melón (*Cucumis melo* L cv Honey Dew) en Guanacaste, Agronomía Costarricense 16(1): 107-113.

Oosterhuis DM, Loka DA, Kawakami EM, Pettigrew WT (2014) The physiology of potassium in crop production. Advances in agronomy 126: 203-233. https://doi.org/10.1016/b978-0-12-800132-5.00003-1

Qibin R, Shan C, Zhang P, Zhao W, Zhu G, Sun Y, Quanlong ER, Jiang Y, Shakoor N, Rui Y (2024) The combination of nanotechnology and potassium: applications in agriculture. Environmental Science and Pollution Research 31: 1890-1906. https://doi.org/10.1007/s11356-023-31207-y

Rivera-Gutiérrez RG, Preciado-Rangel P, Fortis-Hernández M, Betancourt-Galindo R, Yescas-Coronado P, Orozco-Vidal JA (2021) Zinc oxide nanoparticles and their effect on melon yield and quality. Revista Mexicana de Ciencias Agrícolas 12(5): 791-803. https://doi.org/10.29312/remexca.v12i5.2987

Rogiers SY, Coetzee ZA, Walker RR, Deloire A, Tyerman SD (2017) Potassium in the grape (*Vitis vinifera* L.) Berry: Transport and function. Frontiers in Plant Science 8: 1-19 https://doi.org/10.3389/fpls.2017.01629

Saddhe AA, Manuka R, Penna S (2021) Plant sugars: homeostasis and transport under abiotic stress in plants. Physiol. Plant 171(4): 739-755. https://doi.org/10.1111/ppl.13283

Salama DM, Khater MA, El-Aziz AME (2024) The influence of potassium nanoparticles as a foliar fertilizer on onion growth, production, chemical content, and DNA fingerprint. Heliyon 10(1): 1-15. https://doi.org/10.1016/j.heliyon.2024.e31635

Shen C, Wang J, Jin X, Liu N, Fan X, Dong C, Shen Q, Xu Y (2017) Potassium enhances the sugar assimilation in leaves and fruit by regulating the expression of key genes involved in sugar metabolism of Asian pears. Plant Growth Regulation 83: 287-300. https://doi.org/10.1007/s10725-017-0294-z

Sheoran P, Goel S, Boora R, Kumari S, Yashveer S, Grewal S (2021) Biogenic synthesis of potassium nanoparticles and their evaluation as a growth promoter in wheat. Plant Gene 27: 100310. https://doi.org/10.1016/j.plgene.2021.100310

SIAP (2023) Cierre de la producción agropecuaria. Sistema de Información Agroalimentaria y Pesquera. https://www.gob.mx/siap/prensa/cierre-de-la-produccion-agropecuaia?idiom=es. Data consulted: september 25, 2024.

Singh L, Sadawarti RK, Singh SK, Rajput VD, Minkina T, Sushkova S (2024) Efficacy of nano-zinc oxide and iron oxide formulations on shelf life of strawberry. Eurasian Journal of Soil Science 13(3): 254-262.

Uthman A, Garba Y (2023) Citrus mineral nutrition and health benefits: a review. Citrus Research-Horticultural and Human Health Aspects. https://doi.org/10.5772/intechopen.107495

Weil RR, Brady NC (2002) The nature and properties of soils. Fifhteenth Edition. Pearson. Columbus. 1071p.

Wu K, Hu C, Wang J, Guo J, Sun X, Tan Q, Zhao X, Wu S (2023) Comparative effects of different potassium sources on soluble sugars and organic acids in tomato. Scientia Horticulturae 308: 111601. https://doi.org/10.1016/j.scienta.2022.111601

Xie K, Cakmak I, Wang S, Zhang F, Guo S (2021) Synergistic and antagonistic interactions between potassium and magnesium in higher plants. The Crop Journal 9(2): 249-256. https://doi.org/10.1016/j.cj.2020.10.005

Zhang W, Zhang X, Wang Y, Zhang N, Guo Y, Ren X, Zhao Z (2018) Potassium fertilization arrests malate accumulation and alters soluble sugar metabolism in apple fruit. Biology Open 7(12): bio024745. https://doi.org/10.1242/bio.024745

Zörb C, Senbayram M, Peiter E (2014) Potassium in Agriculture – Status and Perspectives. Journal of Plant Physiology 171(9): 656-669. https://doi.org/10.1016/j.jplph.2013.08.008