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Original article

Enhancement of soil water characteristics curve (SWCC) and water use efficiency of cucumber (*Cucumis sativus* L.) in sandy soils by using silica nanoparticles

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ABSTRACT

A field experiment was carried out in sandy soil at the Research and Training Station at King Faisal University, Al-Hassa, Saudi Arabia, during the 2016–2017 season, to study the effect of five rates of silica nanoparticle (Si-NP) treatments on soil soluble Si^{4+}, water characteristics curve, yield and water use efficiency of cucumber (*Cucumis sativus* L.) after harvesting. A randomized complete block design with three replicates was used to conduct the study in the greenhouse where the amount of irrigation water was at 100 % evapotranspiration 78 L $Plant^{-1}$ at the end of the season. The nano-silica particle (Si-NP) treatments were Si-NP0 (0 mg kg^{-1}), Si-NP100 (100 mg kg^{-1}), Si-NP200 (200 mg $kg^{-1),}$ Si-NP300 (300 mg kg^{-1}) and Si-NP400 (400 mg kg^{-1}). The results revealed that the Si-NP had a significant effect ($p < 0.0001$) on the soluble silicon (Si mg kg^{-1}), field capacity (Fc, cm^3cm^{-3}), welting point (WP, cm^3cm^{-3}), available water (AW, cm^3cm^{-3}) and moisture content (θs, cm^3cm^{-3}), of the soil after harvesting crop and also, yield (g $plant^{-1}$) and water use efficiency (WUE, g cm^{-3}). The values of all parameters in the study increased with increasing the rates of silicon-nano particles. The main results can be summarized as follows: An increase of soluble Si^{4+} in the soil according to the application of Si-NP leads to a rise of all behaviour water properties in the soil such as FC, WP, AW and θs, which caused the increase in cucumber yield and water use efficiency by 178% as compared with Si-NP0. The higher mean values of all properties were found in plants exposed to Si-NP400 treatment.

1. Introduction

Nanotechnology applications have been emerging intensively for the last decade in enhancing agriculture sustainability and food production. Therefore, agricultural nanotechnology has the potential for (i) minimizing the amount of pesticide usage with nanocarriers through effective targeted delivery to the pests; (ii) making nano-fertilizers and nutrients more available to the plant pores directly, resulting in greater nutrient use efficiency; (iii) incorporating nanoparticles to boost water uptake and use efficiency in plants; (iv) improvement of plant traits against environmental stress and plant diseases as well as (v) establishing nano biosensors for the sluggish release of fertilizers and other agrochemicals, and providing many more benefits (Ditta et al., 2015; Dwivedi et al., 2016; Pulimi and Subramanian, 2016; Usman et al., 2020).

Nanosilica can be extracted from organic sources, mainly plant residuals. Rice husk ash contains 87.7% as SiO_2 (Nguyen et al., 2019; Yuvakkumar et al., 2014) and soil organisms (Puppe et al., 2015; Schaller et al., 2020a). Nanosilica can also be synthesized from inorganic materials by using different techniques to produce stable and uniform sizes (Al-Abboodi et al., 2020; Jafari and Allahverdi, 2014; Mathur and Roy, 2020; Stöber et al., 1968).

Extensive research and reviews have excogitated the vital role of nano-silica on plant physiology and productivity under different biotic and abiotic stresses (Alsaeedi et al., 2018, 2019; Alsaeedi et al., 2017; Jeelani et al., 2020; Karunakaran et al., 2013; Mathur & Roy, 2020; Suriyaprabha et al., 2012; Usman et al., 2020).

Recently a few studies have investigated the effects of nano-silica on the soil's physical and chemical properties. Gutiérrez-Castorena et al. (2005) found a dramatic increase in water holding capacity up to 500%, bulk density, and cation exchange capacity for a siliceous deposit called "jaboncillo" in Mexico. Water available

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for plant and field capacity was increased by about 40% (Schaller et al., 2020a). In a lysimeter experiment, it was found that nano-silica significantly increased the water storage capacity of soils up to 180% by the addition of 3 wt% nano-silica only (Schaller et al., 2020b).

Silicon as a nutrient is widely approved in increasing crop yields and improving the photosynthesis metabolism process for many plants (Detmann et al., 2012; Rastogi et al., 2019). As a result of the remarkable enhancement of metabolism and production, plant water use efficiency will be improved (Haghighi and Pessarakli, 2013; Jeelani et al., 2020; Romero-Aranda et al., 2006; Siddiqui et al., 2014; Wang and Naser, 1994).

The purpose of this paper is to qualify the effects of using synthesis nano-silica (Ni-Si) on the water characteristics curve to increase water use efficiency for cucumber (*Cucumis sativus* L).

2. Material and methods

2.1. Field experiment

The greenhouse experiment was carried out at the Research and Training Station at King Faisal University, Al-Hassa, Saudi Arabia, in 2016–2017. The soil of the experimental site was sandy, low organic matter (OM), moderate pH and salinity (EC_s). Particle size distribution was determined using the method presented by (Klute, 1986). As well as organic matter OM, pH, and EC_s measured according to the methodology described by (Sparks et al., 2020). A randomized complete block design with three replicates, each with five plants, was conducted in the greenhouse. The seedling rate was 2.4 kg ha^{-1}according to Ministry of Environment, Water and Agriculture of Kingdom of Saudi Arabia (2016). Five treatments of synthesized hydrophilic silica nanoparticles (Si-NP) (Aerosil 300 produced by Evonik Industries, Germany) were applied at rates 0, 100, 200, 300, 400 mg Si-NP per kg of soil, which were added to the soil before the transplanting of the cucumber plant. The total of experimental units was 15 units and each unit contained 5 plants. The distance between rows was 50 cm and between every two plants in the same row was 50 cm. The cucumber plants were (cv. Arigon), a variety widely used in the local region (Ministry of Environment, Water and Agriculture of Kingdom of Saudi Arabia, 2016). Each elementary plot consisted of five rows. The individual plot size was 48 m^2 (12 m $\times$ 4 m). All plots were drip-irrigated with water from a well having salinity (EC_i) of 1024 mg l^{-1}. The drip irrigation system consisted of mainline 4″ PVC line and the sub mainline 3″ PVC line, the emitter GR type 4 L h^{-1} and spacing of 0.5 m apart between drippers. Fertilizers (NPK) were supplied equally for all treatments according to the local program of the area (in three doses, the first dose was before planting the seedlings, the second dose was two weeks after the seedling, and the third dose was two weeks after the second dose). Water was added to the plants daily with a total amount of 78 L $Plant^{-1}$ at the end of the season (Doorenbos and Pruitt, 1977). The yield was recorded on the inside three plants per unit.

2.2. Soil water characteristics curve (SWCC)

At the end of the season, soil samples were collected from the root area to perform water characteristics curve measurements in the laboratory. Three volumetric water content points were measured in a laboratory, saturation θ_s using the method described by (Klute, 1986), field capacity *FC*, at pF 2.5, and wilting point *WP*, at pF 4.23. A pressure plate apparatus manufactured by a soil moisture equipment corporation was used with two types of pressure plates 5 bar for *FC* and 15 bar for *WP*. The test was established according to (ASTM D6836-02, 2002; Klute, 2018). pF defined as the logarithm of the soil–water suction expressed in terms of cm of the water column. The other points (pF = 1.8, 2.3, 3, and 3.44) were calculated using the estimation model was developed by (Al-Moghom, 2020).

The available water *(AW)* was calculated as the difference in soil moisture content between field capacity and wilting point (Doorenbos and Pruitt, 1977).

2.3. Soluble silicon Si^{4+} measurement

The soluble Si^{4+} in the soil after yield harvest was measured using acetic acid (0.5 mol L^{-1}) as extractant and spectrophotometer on 660 nm for the developed blue color as described by (Crusciol et al., 2018; Frantz et al., 2008; Liang et al., 2015; Snyder, 2001).

2.4. Yield and water use efficiency (WUE)

Yield fruits with marketable size were collected twice a week and recorded as weight per plant. The quantity of used irrigation water was recorded daily during the whole season. The total water quantity per plant was 78 L. Water use efficiency was calculated based on the ratio of fruit yield weight in this study over the used quantity of irrigation water during the season (de Pascale et al., 2011):.

$$WUE(gL^{-1}) = \frac{Yield\ weight(g)}{Water\ volume(Liter)}$$

2.5. Statistical analysis

All data were analyzed statistically by using the XLSTAT software package (Addinsoft, 2021). One-way analysis of variance ANOVA was applied to examine the variation in the studied parameters resulting from Si-NP treatments and soil amendments. Values were reported as the mean of three replicates. Furthermore, differences between means were identified using the least significant difference (LSD) test ($P \leq 0.05$). Correlation coefficients between the examined parameters and soil soluble Si^{4+} content was applied to evaluate the effect of Si-NP as soluble Si^{4+}.

3. Results and discussion

3.1. Soil and silica nanoparticles properties

Major properties of the cultivated soil and used silica nanoparticles in the current experiments are presented in (Table 1). The results indicated that the soil texture is a sandy, lossy structure with a bulk density of (1.58 g cm^{-3}), and pH is slightly alkalinity pH equal to 7.5 while the EC_s is 832 (mg L^{-1}), and organic matter O.M is less than 0.5%. These results cleared that the soil is sandy, not saline, slightly alkaline, and has a low content in organic matter as measurements.

The properties of the used nano-silica in this experiment are listed in (Table 1) according to the manufacturer datasheet. The nano-silica was nano-silica Aerosil 300, where the pH value ranged from 3.7 to 4.5, bulk density was 50 g L^{-1}, Specific surface area SSA ranged from (270–330 m^2 g^{-1}), and the silicon dioxide percentage (SiO_2) was more than 99.8%.

3.2. Analysis of variance ANOVA

The analysis of variance (ANOVA) of the effect of five different soil treatments of nano-silica particles (Si-NP) on the measured parameters (soluble silicon Si, field capacity FC, welting point

Table 1
Some properties of the cultivated soil and silica nano-silica particles.

	Sand	Silt	Clay	ρb	pH	EC_s	O.M
	%	%	%	g cm^{-3}		mg L^{-1}	%
Sandy Soil	99.48	0.25	0.27	1.58	7.5	832	<0.5
	SSA	**pH**	**ρb**	**SiO_2**			
	m^2 g^{-1}		g L^{-1}	%			
Nanosilica Aerosil 300	270–330	3.7–4.5	50	>99.8			

ρb = Bulk density, EC_s = Salinity, O.M = Organic matter, SSA = Specific surface area

WP, available water AW, saturation content θ_s, yield, and water use efficiency WUE) presented in (Tables 2 and 3). Results revealed that highly significant ($p < 0.0001$) positive effects were found with Si-NP treatments for all measured parameters. These results are in line with the findings of previous studies by Gutiérrez-Castorena et al., (2005), Romero-Aranda et al., 2006, Schaller et al. (2020a), and Schaller et al. (2020b). Moreover, Alsaeedi et al. (2017, 2018, 2019) pointed out that nano-silica positively affects plant physiology and productivity under abiotic stressed or unstressed.

3.2.1. Soluble silicon (Si^{4+})

Table 3 exhibits the level of soluble Si^{4+} in soil under the different Si-NP treatments. Soluble silicone showed a significant increase as Si-NP increased. At Si-NP0, the initial Si content was 21.76 mg kg^{-1} compared with Si content for Si-NP400. The value increased eight times to reach 190.74 mg kg^{-1}. The increases in the Si^{4+} were 280.8%, 440.39%, 642.56%, and 876.56% when the soil received Si-NP100, Si-NP200, Si-NP300, and Si-NP400, respectively, when compared to soil control (Si-NP0). The main cause of this increment was the physical addition of silica as nano-silica as treatment. Almost 50% of the added SiO_2 was used by the plant or lost with deep percolation (Medany and Hadid, 1997; Miyake and Takahashi, 1983).

3.2.2. Felid capacity (FC)

A significant effect of different Si-NP treatments on-field capacity FC was found during the study (Table 2). However, the highest value of FC (0.313 m^3 m^{-3}) was obtained at Si-NP400 and the lowest (0.233 cm^3 m^{-3}) at Si-NP0. The data in Table 3 indicates that the FC levels increased with increasing Si-NP treatments. The percentage increases were 115.88% (Si-NP100), 127.47% (Si-NP200), 130.90 (Si-NP300), and 134.33 (Si-NP400) compared to the control treatments (Si-NP0). Furthermore, a highly positive correlation coefficient (0.93) was found between soluble silicon Si and FC, as depicted in Fig. 1A. That result is because of the effect of nano-silica particle size in increasing the fine soil particles, increasing the micropores percentage and porosity, which are the governors of soil water content at any retention. This result was replicated in many research studies using nano-silica to improve soil hydraulic properties (Bayat et al., 2018; Ben-Moshe et al., 2013; Zhang, 2007).

3.2.3. Wilting point (WP)

Table 2 shows the significant effects of the Si-NP treatments on WP. The highest value of WP (0.065 m^3 m^{-3}) was recorded when used Si-NP400 treatment was, and the lowest value was measured 0.036 (cm^3 cm^{-3}) at Si-NP0, as shown in Table 3. Compared to the control treatment Si-NP0, the water content magnitude at the wilting point was 122.22%, 144.44%, 158.33%, and 180.56% as soil received 100, 200, 300, and 400 mg kg^{-1} of silica-nano particles, respectively. The above results agree with other results obtained by Gutiérrez-Castorena et al. (2005), Schaller et al. (2020a), and Schaller et al. (2020b). Fig. 1B shows a high positive correlation value (0.99) between soluble silica content and water content at WP. That means the Si-NP increased the moisture content at the wilting point of plants, making the plant resistible to the drought stress with longer irrigation intervals and less water percolation below the root zone.

3.2.4. Available water (AW)

Data presented in Table 3 shows a significant effect of different Si-N treatments on AW. In general, soil supplied with higher Si-NP treatments improved water content at AW more than those that under received Si-NP0. Si-NP200, Si-NP300, and Si-NP400 did not show a significant difference between them due to increased WP moisture content. The highest value of AW (0.248 m^3 m^{-3}) was recorded when using the Si-NP400 treatment, and the lower value (0.197 m^3 m^{-3}) was measured when the soil was not treated with Si-NP (Table 3).

Compared to the control treatment (Si-NP0), the AW's percentage increase in moisture content was 114.72%, 124.37%, 125.89%, and 125.89% when soil received 100, 200, 300, and 400 mg kg^{-1} of silica-nano particles, respectively. The correlation was high (0.85) between AW and soluble Si in soil (Fig. 1C). That means the AW increased with increasing Si-NP from zero to 200 mg $kg^{-1,}$ and then the values became stable up to 400 mg kg^{-1}. This finding agrees with other research by Bayat et al., 2019; Ben-Moshe et al.,

Table 2
Statistical analysis of the effects of the nano-silica treatments (Si-NP) on soluble silicon (Si), field capacity (FC), welting point (WP), available water (AW), saturation content (θ_s), yield, water use efficiency (WUE) in the soil after harvesting crop.

Source of variation	Degree of Freedom	Mean Squares						
		Si mg kg^{-1}	FC Cm^3 cm^{-3}	WP cm^3 cm^{-3}	AW cm^3 cm^{-3}	θ_s cm^3 cm^{-3}	Yield g $plant^{-1}$	WUE g L^{-1}
Replications	2	99.669	7E-5	5.2E-5	4E-5	3.6E-5	3968.51	0.653
Si-NP Treatment	4	13089.979	0.13	0.0015	0.0058	0.0194	385052.25	63.289
Error	8	35.364	1.6E-4	5.9E-7	1.2E-4	5.8E-5	1789.16	0.294
$P > F$		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Significant		****	****	****	****	****	****	****

****Significant at $p < 0.0001$ levels of probability.

Table 3
The effect of Nano-silica particles treatments (Si-NP0:(0); Si-NP100:(100 mg kg^{-1}); Si-NP200:(200 mg kg^{-1}); Si-NP300(300 mg kg^{-1}); and Si-NP400(400 mg kg^{-1}) on soluble silicon (Si^{4+} mg kg^{-1}), field capacity (Fc, cm^{3}cm^{-3}), welting point (WP, cm^{3}cm^{-3}), available water (AW,cm^{3}cm^{-3}), moisture content (θ_s, cm^{3}cm^{-3}), in soil after cucumber harvesting crop and yield (g plant^{-1}) and water use efficiency (WUE, g L^{-1}).

Treatment	Si^{4+} mg kg^{-1}	FC cm^3 cm^{-3}	WP cm^3 cm^{-3}	AW cm^3 cm^{-3}	θ_s cm^3 cm^{-3}	Yield g plant^{-1}	WUE g L^{-1}
Si-NP0	21.76e	0.233d	0.036e	0.197c	0.296e	592.88e	7.601e
Si-NP100	61.11d	0.270c	0.044d	0.226b	0.325d	852.71d	10.932d
Si-NP200	95.83c	0.297b	0.052c	0.245a	0.353c	1058.73c	13.574c
Si-NP300	139.82b	0.305ab	0.057b	0.248a	0.376b	1264.05b	16.206b
Si-NP400	190.74a	0.313a	0.065a	0.248a	0.398a	1518.94a	19.474a
$LSD_{0.05}$	11.20	0.009	0.001	0.007	0.005	79.641	1.021
CV%	5.84	1.61	1.52	1.66	2.39	3.99	3.99

Means in every column followed by different letters are significantly different at 0.05 levels.
$LSD_{0.05}$ least significant difference at 0.05 level of significance.

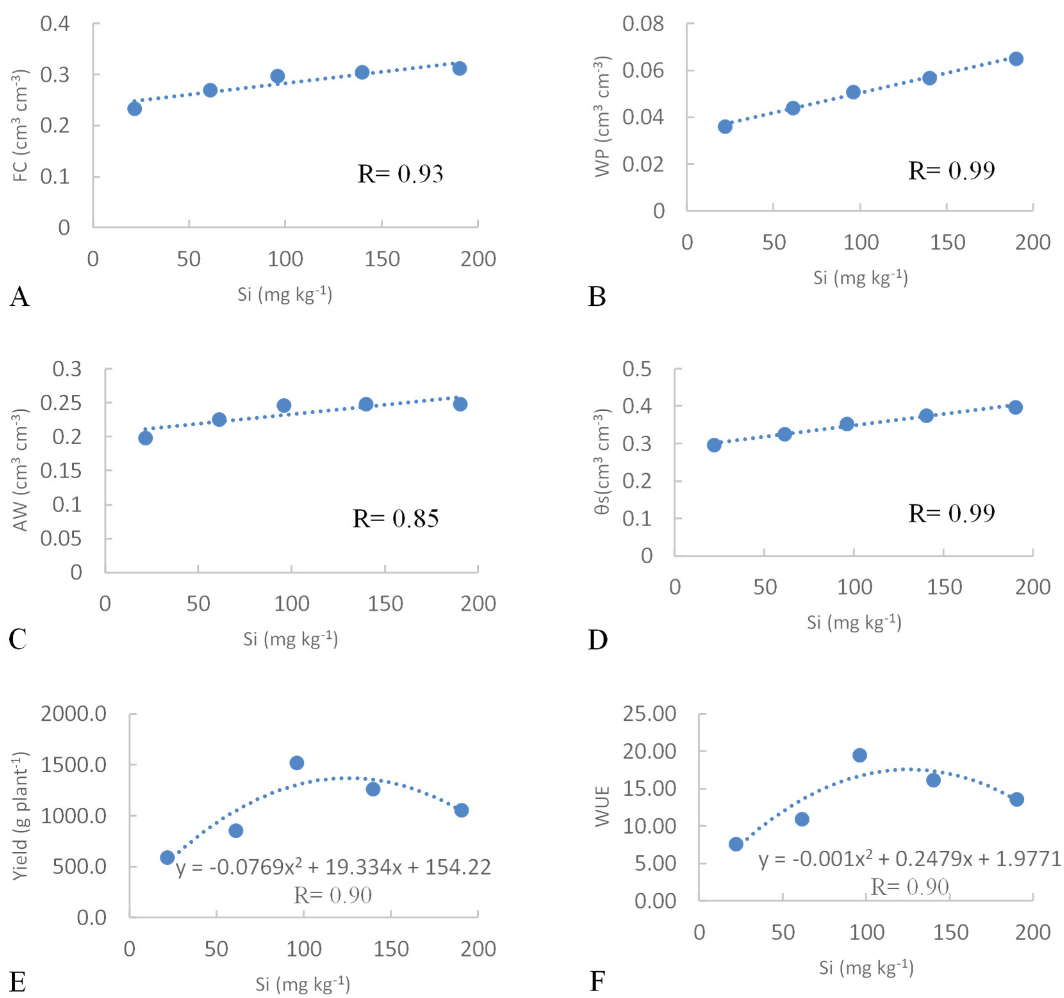

Fig. 1. The correlation coefficients between soluble Si (mg kg^{-1}) in soil and field capacity (FC, A), welting point (WP, B), available water (AW, C), saturation content (θ_s, D), yield of cucumber (Yield, E) and water use efficiency (WUE, F) after treating cucumber plant soil with different rates of nanoparticles of silica.

2013; and Zhang, 2007. The stability of AW after application 200 mg kg^{-1} may be due to the lack of significant change in soil pores with the addition of more Si-NP.

3.2.5. Saturation content of soil (θ_s)

Adding a small quantity of Si-NP to the soil made a tremendous change in soil saturation, as shown in Table 3. The increases in θ_s reached 134.46% (0.398 cm^3 cm^{-3}) for SI-NP400 compared with Si-NP0. The means of θ_s value were 0.325, 0.353, 0.376 and 0.398 cm^3 cm^{-3} when the soil received 100, 200, 300, and 400 mg kg^{-1} from Si-NP. Table 2 shows that a highly significant (p < 0.0001) with a positive high correlation coefficient (0.99) was found between soil soluble Si and moisture content in the soil, as seen in Fig. 1D. That data indicated the direct and high effect of nano-silica on the hydraulic properties of soil. This increase was due to the increase in the microporosity percentage and the increase of negative charges from nano-silica particles, making the soil retain more water. Many researchers similarly presented these results and reported an increase in saturation in different soil types (Bayat et al., 2019; Pérez-Hernández et al., 2020; Ren and Hu, 2014; Schaller et al., 2020a).

3.2.6. Yield

The analysis of variance showed a significant effect of Si-NP applications in improving the final yield of cucumber $p < 0.0001$, as indicated in Table 2. Si-NP400 showed the maximum yield of 1518.94 g plant^{-1}, while treatments of Si-NP0, 100, 200, and 300 showed 592.88, 852.71, 1058.73, and 1264.05 g plant^{-1}, respectively, as shown in Table 3. Si-NP400 showed a 156.20% increase, Si-NP300 increased 113.21%, and Si-NP200 also showed an increase of 78.57%. Finally, Si-NP100 showed an increase in the yield of 43.83% when compared with the control treatment. A highly significant correlation coefficient (R = 0.90) was found between yield and soil soluble Si, as shown in Fig. 1E using a second-order polynomial equation (Sellam and Poovammal, 2016; Surya and Aroquiaraj, 2018). These results are confirmed by many references and research such as (Alsaeedi et al., 2019, 2017; Etesami and Jeong, 2018; Javaid et al., 2019), where they proved the beneficial impact of silicon addition to the plant in increasing the yield productivity and physiological performance during the plant's life..

3.2.7. Water use efficiency (WUE)

Table 2 shows high significance for Si-NP treatments on WUE. The increase in WUE reached 156% for Si-NP400. Table 3 shows an increase WUE value by 43.8%, 78.5%, 113.1% for Si-NP100, 200, 300 respectively as comparison with Si-NP0. A high correlation between soluble Si in soil and WUE (0.90) was proven using a second polynomial equation, as seen in Fig. 1F. Due to the improvement in yield productivity by enhancing the photosynthesis and lowering leave transpiration, the positive effect of nano-silica on WUE was approved previously by many researchers and studies (Haghighi and Pessarakli, 2013; Romero-Aranda et al., 2006; Siddiqui et al., 2014; Wang and Naser, 1994).

3.3. Soil water characteristic curve (SWCC)

Nanosilica treatments increased the water content of cultivated sandy soil at all pF levels, as shown in Fig. 2. The difference of the water content ratio at pF equal zero at (θ_s) for Si-NP0 and Si-NP400 was 34%. This ratio was increased as the pF value increased to reach 78% at pF 4.23 (WP). That means that the effect of the nano-silica application was more influential in the micropores than the large and medium pores. This finding is supported by other research (Ogunkunle et al., 2021; Zhang, 2007). The above results parallel with other results obtained by (Schaller, et al., 2020a and b), where they showed improvement in water storage capacity with nano-silica additions.

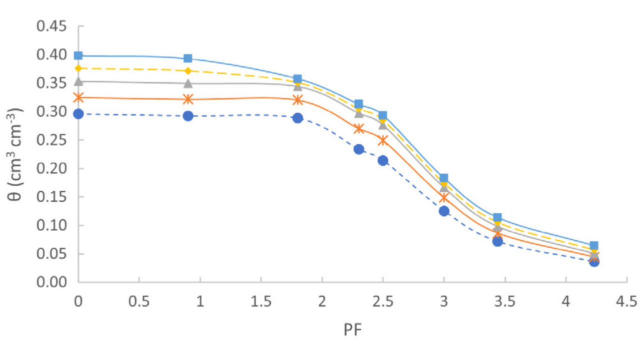

Fig. 2. Effect of Si-NP treatment on the moisture characteristic curve.

4. Conclusion

Under the circumstances of harsh weather, irrigation water scarcity, and poorly soil hydraulic properties. The soil amendment becomes a necessity to improve crop productivity and increase profitability. Nano silica is widely available and economically affordable, making it an excellent alternative as a soil amendment or conditioner. This study concluded that the addition of nano-silica partials to sandy soil significantly boosted the value content of micropores in soil. Consequently, increased moisture content at all retention curves includes FC, WP, AW, and θ_s. That ultimately led to an increase in cucumber yield per plant and improve WUE. As the role of silicon in plants is already well examined in protecting the plant from biotic and abiotic potential stresses, further deep studies are needed to examine the effect of nano-silica on soil hydraulic, soil physio-chemical properties, and nutrient mobility and availability in different types of soils.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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