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Application of bio-desalinization for reclamation of salt-affected soil under composted cow manure and deficit irrigation with saline water

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Abstract

Application of common leaching and flushing methods is often impractical due to freshwater scarcity, groundwater pollution and a lack of suitable drainage systems. To address these problems, a pot experiment testing the cultivation of *Salicornia persica* Akhani was conducted in three replicates. Three saline irrigation treatments ($EC = 7.2 \text{ dS m}^{-1}$) were used: full irrigation with saline water (SI), deficit irrigation with 75% of SI (DSI_{75}) and deficit irrigation with 55% of SI (DSI_{55}). Two soil conditions also were considered, namely a combination of soil with 10% composted cow manure (CM) and soil without manure (WA). Our results show that the highest values for stem diameter (3.1 mm), height (110.1 mm) and dry weight (0.5 g) were observed in SI–CM. Conversely, the highest values for root length with 16.9 mm and root weight with 0.7 g were obtained for DSI_{75} –CM. The best treatment for water-use efficiency (WUE) was DSI_{75} –CM with 2.6 g l^{-1} , and the lowest WUE of 1.33 g l^{-1} was observed for DSI_{55} –WA. DSI increased all examined chemical parameters. The use of CM only resulted in increased values of carbohydrate, protein and proline, with no significant effects found for other parameters. Significant reductions in both EC (38.6%) and Na^+ (16.8%) occurred in both soil treatments, with reductions under WA higher than reductions under CM. Overall, our results suggest that the proposed methods could be used for decreasing soil salinity levels while simultaneously allowing for the use of saline water for agricultural production.

Keywords Halophytes · Soil amendments · Soil salinity · *Salicornia persica*

Introduction

Expected population growth to 9.1 billion people by 2050 will intensify food security issues around the globe (Béné et al. 2015). Soil salinization and freshwater scarcity exacerbate this challenge, especially in arid and semiarid regions (Min et al. 2014; Talebnejad and Sepaskhah 2015). Aridity, drought, desertification and water shortages are some of the different causes of water scarcity (Pereira et al. 2002). Salinization is a type of soil degradation that occurs

when salts accumulate at the soil surface (Sardinha et al. 2003). Salt-affected soils can be divided into three different branches: saline, sodic and alkaline soils. The development of irrigation in arid environments is a major reason for the increasing salinity problems, potentially leading to fossil salt mobilization and secondary salinization (Smedema and Shiati 2002). The leaching fraction is designed to avoid the accumulation of salt at the soil surface under irrigation. However, this method has two major disadvantages: (1) consumption of (often scarce) freshwater resources and (2) pollution of groundwater and water table increases. Although suitable drainage systems can decrease the disadvantages of leaching techniques, both social opposition to and financial constraints for developing drainage systems can limit the viability of this option. In addition to salinity problems associated with agricultural activities, industrial and municipal processes produce large volumes of saline water (Ayars et al. 2006; Miyamoto and Chacon 2006). Total dissolved salts in these waters can range from 1000 to above 7000 mg l^{-1} , which may be dangerous for the soil, groundwater and environment (Glenn et al. 2009).

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To combat both freshwater scarcity and food security issues, many researchers have suggested the potential for sustainable cultivation of edible halophytes (Böer et al. 2016; Cheeseman 2015; Kalantari et al. 2018; Qureshi 2017; Teh and Koh 2016). Halophytes are salt-tolerant plants that can be separated in two different families including obligate and facultative halophytes. The cultivation of obligate halophytes requires a level of salinity for their optimum growth, while facultative halophytes can complete their life cycle under both saline and non-saline conditions (Flowers and Colmer 2008; Nikalje et al. 2018). The phyto-desalination properties of some halophytes, which can absorb high levels of salt in their biomass, may also improve soil quality, a key aspect of sustainable development. As such, phyto-desalination has been an attractive subject for researchers in previous years (Manousaki et al. 2014; Nouri et al. 2017; Rabhi et al. 2009; Reddy et al. 2010; Sakai et al. 2012).

One member of the halophytes group is *Salicornia*, which is categorized as a C3 annual species plant (Ayala and O'Leary 1995) and as an obligate halophyte. The suitable water salinity range for optimum growth of *Salicornia* is from 11 to 20 dS m⁻¹ (Ohuri and Fujiyama 2011). Osmoregulators in halophytes, especially *Salicornia*, have interesting properties such as sugars and free proline, which prohibits loss of water and ion toxicity of cells (Akcin and Yalcin 2016; Ashraf and Foolad 2007; Bohnert et al. 1995). Furthermore, this plant is suitable for human consumption (Price 2007). Other potentially useful applications of *Salicornia* include livestock feed (Glenn et al. 1998), bioenergy (Akinshina et al. 2016; Falasca et al. 2014), medication (Gunning 2016) and as a nutritive and healthy oil (Liu et al. 2005). Moreover, *Salicornia* can absorb salt from soil and decrease soil salinity and toxicity of ions (Atzori et al. 2019).

Saline irrigation management is a very important factor for desalinization under bio-drainage technique because full irrigation with saline water or drainage water may pollute groundwater (Caraballo et al. 2016; Ostad-Ali-Askari et al. 2017). In these conditions, the application of less-water-intense irrigation strategies, such as deficit irrigation (DI), may play a useful role. DI is an irrigation management for saving water (Al-Ghobari and Dewidar 2018; Galindo et al. 2018) and aims to maximize water productivity rather than maximizing yields (Brar et al. 2018; Jonubi et al. 2018). Additionally, DI may increase the quality of yield and grain size (Dorji et al. 2005; Nakawuka et al. 2017), reduce fungal diseases risks (Guilpart et al. 2017), reduce nutrient leaching through root zone, improve groundwater quality and decrease the need for additional fertilizer applications (Brar et al. 2018; Carlton et al. 2016; Jonubi et al. 2018). In these ways, deficit irrigation with saline water could present a solution for decreasing environments risks by reducing drainage water, while also promoting food and freshwater security (Aly et al. 2018; de Melo et al. 2018; Muschal

2006). However, a reduction in the volume of water used for deficit irrigation also limits the amount of leaching that can occur, thus potentially promoting salt accumulation in the soil (Glenn et al. 2009). The phyto-desalination properties of halophytes could play an essential role for desalinization. As a result, bio-saline agriculture could achieve win-win effects through the improvement in both soil quality and crop production.

Another solution for decreasing the negative effects of saline water irrigation is represented by soil amendments. Composted cow manure is a readily available soil amendment in most areas of the world (Devi et al. 2018; Pamarthy et al. 2016). Increased availability of nutrients in the environment may enhance crop production (Pandey and Patra 2015; Zandvakili et al. 2017), increasing the level of soil organic matter (Bistgani et al. 2018) and reducing environmental footprints (Afshar et al. 2014; Nazli et al. 2016). These features are very advantageous, especially in poor soils in arid and semiarid regions. In this regard, little or no information was found on the optimum levels of deficit irrigation for achieving the best results in biomass production and soil desalination in a short time, especially when simultaneously combined with soil amendments. Hence, in this study, the effect of three different levels of saline irrigation in soil conditions both including and excluding composted cow manure on a native *Salicornia* species (i.e., *Salicornia persica* Akhani) was investigated to address the following objectives:

1. To investigate the response of *Salicornia persica* Akhani to changes in soil conditions and deficit irrigation treatments with saline water.
2. To determine the best treatment combination for maximizing WUE.
3. To evaluate changes in soil salinity and Na⁺ accumulation after the experiment.

Materials and methods

Experimental setup

This research was conducted as a pot experiment with three replicates in a greenhouse at Sistan Agricultural and Natural Resources Research and Education Center located in the south-east of Iran in 2018. The average temperature for day and night was around 33 °C and 14 °C, respectively. Additionally, the relative humidity and natural photoperiod during the experiment were around 57% and 10 h, respectively. The soil texture was clay loam, which was gathered from a working farm in Sistan. The air-dried soil passed through a 2-mm sieve. The physicochemical properties of the soil are displayed in Table 1.

Table 1 Experimental soil texture

Clay (%)	Silt (%)	Sand (%)	Soil texture	EC (dS m ⁻¹)	pH	Na ⁺ (meq l ⁻¹)	Ca ²⁺	Mg ²⁺	SAR
37	23	40	Clay loam	8.3	8.4	62.3	356	1310	2.2

Plastic pots, which were 15 cm in height and 19 cm in diameter, were filled with 1600 g of soil or soil with 10% composted cow manure (CM) according to treatments, without additional chemical fertilizer. Forty-five seeds of *Salicornia persica Akhani* were planted at March 7, 2018. Each pot was irrigated to field capacity with saline water (Table 2).

The seeds emergence was on March 18, 2018. After that, in two and four weeks after sowing, the plants were thinned. The study was a completely randomized design in a factorial arrangement. All irrigation treatments were done with water of the same salinity level (EC=7.2 dS m⁻¹), namely SI (full irrigation with saline water), DSI₇₅ (25% decrease compared to SI) and DSI₅₅ (45% decrease compared to SI). Additionally, soil treatments included the application of composted cow manure (CM) at 10% of the total mass and without it as a control treatment (WA).

Irrigation requirement

All pots were irrigated with a 2–4 days interval during the experiment. Irrigation for all pots was done the same as SI-WA (control pot) from March 7 until April 5. Application of deficit irrigation treatments began after the early growing period (i.e., April 7). The irrigation volume for control pots was measured before each irrigation time based on mass balance equation by weighing the pots (Eq. 1).

$$\text{ETc} = \text{IR} - \text{Dp} + P + \text{Cp} - \text{Ro} \pm \Delta W. \quad (1)$$

The components of the equation above are evapotranspiration [ETc (mm)], total irrigation [IR (mm)], deep percolation of root zone [Dp (mm)], precipitation [P (mm)], capillary rise [Cp (mm)], runoff [Ro (mm)] and changing in soil water content [ΔW (mm)], respectively (Allen et al. 1998). Equation (1) can be simplified for a pot experiment to give Eq. 2.

$$\text{ETc}_{(i,i-1)} = \text{IR}_{i-1} - \text{Dp}_{i-1}. \quad (2)$$

In (Eq. 2), “ETc” is the evapotranspiration (mm) between two irrigation intervals ($i, i-1$), “IR” means irrigation depth (mm) at the past irrigation interval ($i-1$) and “Dp” is the drainage water volume (mm) for the previous irrigation interval ($i-1$) that discharged from the drainage holes of pots. To measure drainage volume, three plastic buckets collecting water were set under control pots (i.e., SI-WA). Therefore, drainage water can be saved in them while minimizing evaporation. During the experiment, irrigation and drainage water were controlled by weighing the pots as per Wang et al. (2017).

The WUE (kg l⁻¹) was defined as the ratio between dry weight (DW) (g plant⁻¹) and the amount of water applied to the pot (l plant⁻¹) (Behera and Panda 2009).

$$\text{WUE} = \frac{\text{DW}}{\text{IR}}. \quad (3)$$

Measurements and lab activities

At the end of the experiment on 10 May, plant height (mm), stem diameter (mm), root dry weight (g), root length (mm) and dry biomass (g plant⁻¹) were measured (Azhar et al. 2011; Moussavi-Nik et al. 2011; Wang et al. 2017). In addition, some other plant chemical parameters, including carbohydrates (mg g⁻¹), protein (mg g⁻¹), proline (mg g⁻¹), carotenoid (mg g⁻¹), chlorophylls a and b (mg g⁻¹), were determined in the laboratory based on the methods of Csiszar et al. (2007), Zhang et al. (2009), Sikuku et al. (2010) and Saboor et al. (2012).

Soil salinity, pH, Na⁺ and K⁺ of soil were measured at the beginning and end of the experiment. These values were compared to determine the accumulation and effects of salts on soil under different treatment conditions. Additionally, the accumulation of Na⁺ and K⁺ in the plant was measured based on Ashraf and Orooj (2006) to assess the phyto-desalination characteristics of *Salicornia persica* under deficit irrigation and composted cow manure.

Table 2 Chemical properties of used saline water

EC (dS m ⁻¹)	pH	SAR	Na ⁺ (meq l ⁻¹)	Ca ²⁺	Mg ²⁺	K ⁺	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻
7.2	7.6	8.3	30.8	13.1	14.2	0.23	9.1	31.2	23.9

EC electrical conductivity, SAR sodium absorption ratio

Data analysis

In this study, SAS version 9.0 was used to investigate the significant ($p < 0.05$ or $p < 0.1$) or nonsignificant effects of treatments using the Duncan test (Dağdelen et al. 2009).

Results and discussion

Physiological responses

Figures 1 and 2 show the effects of irrigation and soil treatments on the physiological traits and biomass of *Salicornia*. The plant height varied from 38.7 to 110.1 mm plant⁻¹, stem diameter varied from 2.2 to 3.13 mm plant⁻¹, and dry biomass varied from 0.20 to 0.51 g plant⁻¹, with the highest values observed in SI–CM and lowest ones in DSI₅₅–WA. There were mostly nonsignificant differences between SI and DSI₇₅ during vegetative growth of *S. persica*, while DSI₅₅ shows significant decreases compared to the SI conditions

SI: Full irrigation with saline water, DSI75: 75% of SI and DSI55: 55% of SI

Fig. 2 Effects of irrigation and soil treatments on dry biomass of *S. persica*. *Values are means $\pm$ s.e. Means with the same letter are not significantly different (Duncan test, level of significance shown in each graph)

in all traits with the exception of root length. Our results are in accordance with the findings of other studies on severe deficit irrigation, with decreases in characteristics such as plant height, stem diameter and biomass compared to control treatments (Bekmirzaev et al. 2019). On the other

SI: Full irrigation with saline water, DSI75: 75% of SI and DSI55: 55% of SI

Fig. 1 Effects of irrigation and soil treatments on physiological traits of *S. persica*. *Values are means $\pm$ s.e. Means with the same letter are not significantly different (Duncan test, level of significance shown in each graph)

hand, reported crop yield and characteristics under mild water stress show similar result compared to full irrigation (Chuanjie et al. 2015).

The highest values for the root length and root weight were achieved in DSI₇₅-CM, and the lowest were observed in DSI₅₅-WA. Root length in this experiment varied

between 7.5 and 16.9 mm plant⁻¹, and root dry weight varied between 0.4 and 0.7 g plant⁻¹. Plants that face mild water stress try to absorb more water to continue their growth, and as a result, the length and weight of root increase. Enhancement of root properties under water stress is reported by other researchers for cotton (Oweis

SI: Full irrigation with saline water, DSI₇₅: 75% of SI and DSI₅₅: 55% of SI

Fig. 3 Effects of irrigation and soil treatments on bio-chemical traits of *S. persica*. *Values are means $\pm$ s.e. Means with the same letter are not significantly different (Duncan test, level of significance shown in each graph)

et al. 2011; Rao et al. 2016), ornamental plants (Chyliński et al. 2007; Sánchez-Blanco et al. 2019; Shober et al. 2009), maize (Gheysari et al. 2017) and wheat (Xue et al. 2003).

Chemical traits of *Salicornia*

Chemical responses of *S. persica* under treatments are presented in Fig. 3. In this study, carbohydrates ($5.7\text{--}9.28\text{ mg g}^{-1}$), protein ($5.56\text{--}12.09\text{ mg g}^{-1}$), proline ($0.06\text{--}0.15\text{ mg g}^{-1}$), carotenoid ($0.06\text{--}0.08\text{ mg g}^{-1}$), chlorophyll *a* ($0.13\text{--}0.22\text{ mg g}^{-1}$) and chlorophyll *b* ($0.10\text{--}0.14\text{ mg g}^{-1}$) were investigated. Deficit irrigation had significant effects on chemical parameters. The highest and lowest values for them were obtained in DSI₅₅ and SI, respectively. This is supported by many studies that water stress may strongly increase these parameters (Ebtedaie and Shekafandeh 2016; Sun et al. 2016). Chemical parameters play some important roles in osmoprotecting, repairing damage of tissue and supporting growth (Llanes et al. 2018). Additionally, drought-tolerant cultivars have higher levels of metabolite than drought-sensitive cultivars (Nyarukowa et al. 2016). On the other hand, some researchers found that with increasing salinity levels, proline content rise, while chlorophyll and carotenoid reduce for *Salicornia prostrata* and *Suaeda prostrata* (Akcin and Yalcin 2016) and for peppermint (Xu et al. 2016).

Na⁺ accumulation in plants under WA was around 9% higher than CM. In other words, under WA conditions plants accumulated higher amounts of Na⁺ (Fig. 4). Furthermore, the highest value of Na⁺ was obtained in DSI₇₅ with 202 (meq l⁻¹) for WA and 179 (meq l⁻¹) for CM. Accumulation of K⁺ in plant shows contrasting results compared with

Table 3 WUE, used and saved saline water during the experiment

Treatments	Plant water use (l plant ⁻¹)	Plant dry biomass (g plant ⁻¹)	WUE (g l ⁻¹)	Saved water %
SI-WA	0.22	0.38	1.73	—
SI-CM	0.22	0.51	2.32	—
DSI ₇₅ -WA	0.18	0.35	1.94	17.4
DSI ₇₅ -CM	0.18	0.47	2.61	17.4
DSI ₅₅ -WA	0.15	0.2	1.33	31.3
DSI ₅₅ -CM	0.15	0.27	1.80	31.3

Na⁺. The values of K⁺ accumulation for CM treatments were 160% higher than WA in different irrigation treatments. Additionally, deficit irrigation shows a significant effect ($p < 0.01$) on K⁺ accumulation, and the highest value (25.8 meq l⁻¹) was observed in DSI₅₅-CM. Other studies reported that ions accumulation increases under water and salinity stresses (Álvarez and Sánchez-Blanco 2015). Enhancement of salinity levels led to an increase and decrease in sodium and potassium concentrations, respectively (Atzori et al. 2017). The use of vermicompost can reduce the accumulation of Na⁺ and increase the K⁺/Na⁺ ratio in peppermint (Xu et al. 2016).

Water-use efficiency (WUE)

An amount of 0.22–0.15 l plant⁻¹ of saline water was used during the experiment. The highest and lowest values of used water belong to SI and DSI₅₅, respectively (Table 3). Consumption of saline water under DSI₇₅ and DSI₅₅ was 17.4% and 31.3% lower than SI, respectively. As our results show,

Fig. 4 Effects of irrigation and soil treatments on ion accumulation in plant. *Values are means $\pm$ s.e. Means with the same letter are not significantly different (Duncan test, level of significance shown in each graph)

plant dry biomass varied between 0.51 and 0.20 g plant⁻¹, and application of CM caused an increase of 33% in dry biomass in different irrigation treatments, approximately. In other words, CM reduced the negative effect of deficit irrigation.

The WUE values varied from 1.33 g l⁻¹ (DSI₅₅-WA) to 2.61 g l⁻¹ (DSI₇₅-CM). Table 3 shows that application of CM could improve WUE around 34% compared to respective treatments under WA. In addition, the WUE value of DSI₇₅-WA was 12.1% higher than SI-WA, and DSI₇₅-CM was 12.5% higher than SI-CM. The comparison of WUE values between DSI₇₅-CM with 2.61 g l⁻¹ and SI-WA with 1.73 g l⁻¹ shows a 50.9% enhancement for DSI₇₅-CM. This indicates that the combination of DSI₇₅ and CM not only reduces the water used but also could increase the WUE compared to control conditions. Increasing WUE under deficit irrigation has been reported for different crops (Chuanjie et al. 2015; Yuan et al. 2019). Moreover, in both glycophytes and halophytes, salinity conditions are often correlated with an increased WUE. In glycophytes, the increased WUE in

salinity conditions has been related to a reduced stomatal conductance (Atzori et al. 2016) and to decreased water consumption (Atzori et al. 2019), whereas in halophytes, i.e., *A. tricolor* and *A. cruentus*, the increased WUE was due to reduction in stomatal density (Srinivas et al. 2018).

Soil salinity

The electrical conductivity, pH, Na⁺ and K⁺ in the soil after the experiment are presented in Fig. 5. Our results indicate that the soil salinity and ion accumulation significantly decreased under all treatments compared with the beginning of the experiment, with values for EC and Na⁺ of 8.3 dS m⁻¹ and 62.3 meq l⁻¹, respectively. However, full irrigation with saline water decreased EC more than deficit irrigations. This may occur due to the following reasons: The greater volume of drainage water under full irrigation can enhance both the leaching process of desalination and better growth of plant under full irrigation compared to DSI₅₅. The soil EC values at the end of experiment for DSI₇₅ and

Fig. 5 Effects of irrigation and soil treatments on soil parameters at the end of experiment. *Values are means $\pm$ s.e. Means with the same letter are not significantly different (Duncan test, level of significance shown in each graph)

DSI₅₅ were 13.7% and 27.2% higher compared to SI, respectively. Similar results were observed for pH and K⁺. The soil pH and the accumulation of K⁺ for DSI₇₅ and DSI₅₅ were 1.02% and 1.6% and 54.2% and 67%, respectively, higher than SI. However, the accumulation of Na⁺ showed some different results: The highest value for Na⁺ was observed in DSI₇₅-CM (67.1 meq l⁻¹), and the lowest value was observed in DSI₅₅-WA (41.8 meq l⁻¹). These results may be related to interaction effects between saline water and Na⁺ absorption under CM treatment. CM can improve cation exchange capacity of soil (Jalali and Ranjbar 2009; Walker and Bernal 2008). Additionally, it has a high value of Ca²⁺ and Mg²⁺. Therefore, soil particles might have absorbed those ions and released Na⁺. It seems SI could transfer the Na⁺ through drainage water, while in the DSI₇₅ or DSI₅₅ we do not have any drainage water. Therefore, Na⁺ just was extracted from soil by plant forces. The volume of saline water in DSI₅₅ was lower than other treatments. As a result, accumulation of Na⁺ decreased in DSI₅₅ compared to SI or DSI₇₅. Although the application of CM could enhance the plant growth compared to WA, on average, the use of CM increased EC, Na⁺ and K⁺ by 26.9%, 46.2% and 22.2%, respectively, compared to WA. On the other hand, soil pH decreased 1.8% under the use of CM compared to WA. However, this reduction was not significant.

The concentration of Na⁺ and Cl⁻ and the value of EC were significantly decreased under phyto-desalination with other kinds of halophytes including *Artemisia argyi* L., *Limonium bicolor* K., *Melilotus suaveolens* L. and *Salsola collina* P (Sakai et al. 2012). *Tecticornia indica* and *Suaeda fruticosa* had suitable results for soil desalination (Rabhi et al. 2009) as well as *T. indica* and *S. fruticosa* that electrical conductivity and soluble sodium decreased significantly under their cultivation (Rabhi et al. 2010). Additionally, for other kinds of halophytes such as *Atriplex nummularia*, similar results were reported (de Melo et al. 2018). Interaction effects between *Salicornia europaea* and three different rates of ameliorant to improve saline-alkaline soil showed that the beneficial effects of cow dung were higher than others, and it could reduce the Na⁺ stress (Li-ping et al. 2015). In addition, composted cattle manure was reported as one of the best amendments for increasing agronomic and environmental behavior (Horta et al. 2018).

Conclusion

One of the points of desalination methods is to achieve suitable results in a short time, as well as considering environmental conditions. Therefore, in this study, a short-time experiment was designed to investigate the effects of the combination of saline irrigation at three different levels and

soil conditions (both excluding and including composted cow manure) on *S. persica* growth and soil desalination. The overall results illustrate that the combination of SI and CM could produce the highest values for dry weight, height and stem diameter. On the other hand, the combination of DSI₇₅ and CM increased WUE, root length and weight compared to SI-CM. The application of deficit irrigation led to the increasing of chemical traits in *S. persica*. The results show that accumulation of Na⁺ in plants under WA was 9% higher than CM. The DSI₇₅ treatment could encourage the plant to absorb more Na⁺ with 14.5% and 5.1% compared to SI and DSI₅₅, respectively. The accumulation of K⁺ in plants under CM was 160% higher than WA. The application of DSI₅₅ and DSI₇₅ increased the K⁺ concentration with 104% and 60.2% compared to SI. Soil electrical conductivity significantly decreased from 8.3 dS m⁻¹ (i.e., before the experiment) to 5.1 dS m⁻¹ in average of all treatments, with the highest and lowest reductions associated with SI-WA (4.1 dS m⁻¹) and DSI₅₅-CM (6.4 dS m⁻¹), respectively. Although the application of CM could increase crop growth, the EC values were higher under CM treatments compared to WAs. The positive effects of our suggested methodology should be investigated in long-term experiments under field conditions.

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