Different irrigation regimes influence soil salt ion and soil nutrient status in *Lycium ruthenicum* cultivation

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Abstract

In arid areas, irrigation with the available brackish water is common because of scarce freshwater resources. However, the impact of different irrigation regimes on soil salt ion and soil nutrient status have rarely been studied in the Qaidam Basin of northwestern China. To investigate this, two treatments (flood and drip irrigation) were established in a randomized block design on *Lycium ruthenicum* grown on a farm in the Qaidam Basin, and soil salt ion and soil nutrients at different soil depths were measured. The soil water content (SWC) was higher at each soil depth under flood compared with drip irrigation, except for top soil (0-5 cm), and the variations of SWC with soil depth differed between flood and drip irrigation. Moreover, soil salt ion content was higher under flood than drip irrigation at each soil depth, while soil nutrient contents were higher under drip irrigation, and were reduced remarkably as soil depth increased under both irrigation types. Consequently, drip irrigation with brackish water can reduce soil salinization and maintain high soil nutrient levels for irrigated *L. ruthenicum* in arid regions. In the context of brackish water irrigation, drip irrigation is relatively more appropriate for the cultivation of *L. ruthenicum* than flood irrigation.

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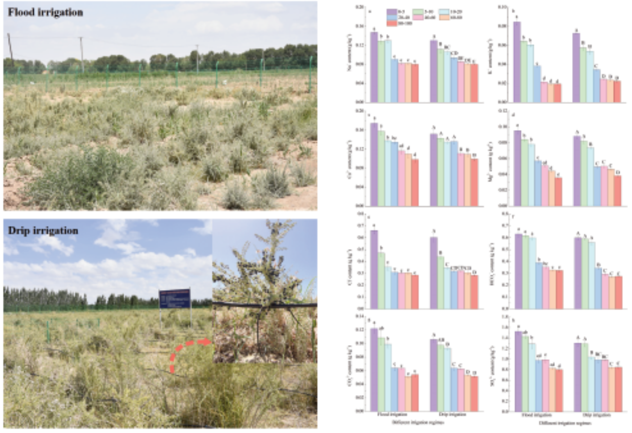

Graphical abstract.

Introduction

Freshwater resources are highly restricted in arid and semiarid areas, and severely limits agricultural and economic development in such regions (Kharrou *et al.*, 2013). Over the past 50 years, the global consumption of freshwater for irrigation has continued to increase, accounting for approximately 70% of all freshwater use (Tian *et al.*, 2017). To address the issue of freshwater scarcity in arid and semiarid regions, the use of brackish water for irrigation has become essential. In China, for instance, there is an estimated 20 billion cubic meters of brackish water available, with about 65% being exploitable (Wei *et al.*, 2021). As a result, brackish water irrigation has been implemented in several regions, such as Hebei, Xinjiang, and Qinghai (Liu *et al.*, 2019). However, long-term irrigation using brackish water may cause salt accumulation in soil and lower crop production. This can result in soil salinization and deterioration of groundwater quality when salts reach groundwater (Rengasamy, 2006; Wang *et al.*, 2015). Thus, soil salinization is another pending problem for arid areas in the world. Excessive salt accumulation in the soil not only causes physiological limitations to crop (Wang and Li, 2013; Nicolás *et al*., 2016; Huang *et al*., 2019) but also brings salt into the soil and causes potential hazards to the soil environment (Rodrigues *et al*., 2014; Li JS *et al*., 2019).

The impact of brackish water irrigation on the soil environment primarily occurs through the alteration of soil physical and chemical properties (Feng *et al*., 2014). The use of brackish water for crop irrigation introduces salts into the soil, posing potential hazards to crop growth and soil health. This can affect crops and the soil environment in various ways, such as through water relations, ion toxicity, and the balance of nutrients and energy (Guo *et al*., 2022). Brackish water irrigation alters the redistribution of soil moisture through the profile, thereby affecting water spatial variability (Cheng *et al*., 2021). Soil moisture, acting as the carrier for various biological substances in soil, can affect the entire root zone microenvironment of crops (Bhattacharyya *et al*., 2022; Chen *et al*., 2022). Compared to freshwater irrigation, brackish water irrigation leads to soil salinity accumulation, especially if continuously used for irrigation, resulting in a substantial accumulation of salts in soil (Zhang YH *et al*., 2022). During the process of brackish water irrigation, salts move and fluctuate with water, and changes in salt concentration also alter the effectiveness of soil moisture (Cheng *et al*., 2021). Changes in soil water and salt do not occur in isolation but are often accompanied by a series of soil physical and chemical reactions. For instance, brackish water irrigation affects the absorption and utilization of soil nutrients by crops (Li *et al*., 2022); the accumulation of soil salts within a certain range can influence the function and activity of soil microorganisms (Hussain *et al*., 2020; Otlewska *et al*., 2020; Haj-Amor *et al*., 2022); and the accumulation of salts from brackish water irrigation also impacts the synthesis of enzymes in soil (Yavuz *et al*., 2022). The effects of brackish water irrigation on soil salinity distribution and nutrient status are complex and whether it will cause secondary salinization hazards to crops and soil is related to the quality of irrigation water, crop salt tolerance, and irrigation management practices (Yamada *et al*., 2015; Haj-Amor *et al*., 2016; Ozturk *et al*., 2018). In fact, establishing appropriate brackish water irrigation regimes are therefore necessary and important to ensure sustainability of soils and crop production (Aparicio *et al*., 2019; Lu *et al*., 2019).

Drip and flood irrigation are commonly used in agricultural production in arid land (Li CJ *et al*., 2020). However, flood irrigation is known to consume a significant amount of water, with substantial infiltration into deeper soil layers, leading to severe loss of soil nutrients (Mitchell *et al*., 1993). The uniformity of water distribution across a field is typically poor with this method, and the large amount of evaporation from the soil surface can cause soil compaction and secondary salinization (Jangir *et al*., 2011). Prolonged use of flood irrigation exacerbates these issues, intensifying soil secondary salinization and nutrient loss, in turn lowering water efficiency and crop yield (Hondebrink *et al*., 2017). Drip irrigation, however, provides more uniform water distribution and inhibits deep penetration of water, thus, enhancing water use efficiency and crop yield by precisely delivering water and nutrients to the roots (Umair *et al*., 2019; Wang *et al*., 2019; Piri and Naserin, 2020). This also helps to retain soil aggregate structure, reduce water loss, and lower the risk of soil salinization and degradation (Wang *et al*., 2011). Drip irrigation can save 25-60% of irrigation water compared to flood irrigation (Evans and Zaitchik, 2008). In cotton production, drip irrigation has been shown to increase yield by around 25% and save around 50% of water, compared to flood irrigation (Ward and Pulido-Velazquez, 2008).

The effects of drip irrigation on soil salinity are complex. Drip irrigation can effectively reduce the salt content in the crop root zone, providing a favorable water and salt environment for growth (Liu *et al*. 2012; Valentin *et al*. 2020). The beneficial effects of drip irrigation are primarily related to its ability to move salts to the margins of the wetted bulb. When using brackish water for drip irrigation, the leaching effect of drip irrigation tends to accumulate soil salts at the margins of the wetted bulb, thereby reduces the soil salinity directly below the drip emitter. This is beneficial for the normal growth of crops when crop root zone near the drip emitter (Guan *et al*., 2019). In fact, there is growing concern over soil salinization caused by drip irrigation. Soil salinization affects plant nutrient absorption and is an essential indicator of soil health (Abiala *et al*., 2018). Research indicates that drip irrigation can flush salt into deeper soil layers, reducing soil salinity accumulation in the area surrounding the dripper tape (Wang *et al*., 2013; Li FY *et al*., 2020). In contrast, drip irrigation may retain salts within the root zone when irrigation volumes are not sufficiently high (Wang *et al*., 2019). Nevertheless, understanding of salt accumulation under different irrigation regimes remains limited, particularly in extremely arid and salinized regions.

The Qaidam Basin in northwestern China is environmentally vulnerable due to desertification (Wang *et al*., 2018). Global warming exacerbates aridification and soil salinization, affecting 42.5% of agricultural land in the Qaidam area (Li YH *et al*., 2019). Precipitation is scarce, but brackish water is abundant and crucial for irrigation (Xiao *et al*., 2017). The use of brackish water resources needs to be optimized to alleviate water shortage crises and ensure the agricultural industry's sustainability. *Lycium ruthenicum*, also known as black Chinese wolfberry, is a perennial deciduous shrub with high drought and salt tolerance. It plays a vital role in restoring the desert ecosystem and alleviating soil salinity and alkalinity in China (Liu *et al*., 2018). While studies on *L. ruthenicum* have focused on its medicinal properties, few have investigated the soil status in various layers where *L. ruthenicum* grows. In the Qaidam area, *L. ruthenicum* is the dominant economic tree species, and flood irrigation is widespread. However, due to insufficient water resources, drip irrigation is necessary for cultivating *L. ruthenicum*. Limited knowledge exists regarding the effects of different irrigation regimes (drip and flood irrigation) on soil salt ion and nutrient status in the Qaidam Basin.

Our hypothesis is that flood and drip irrigation regimes have different impacts on soil salt accumulation and nutrient status, and that drip irrigation may provide a more conducive growth environment (with lower soil salinity accumulation but higher soil fertility) for *L. ruthenicum* compared to traditional flood irrigation. To test this hypothesis, we conducted a comparative study to investigate changes in soil salt ions and status in various soil layers used to cultivate *L. ruthenicum* under different irrigation regimes. This study aims to evaluate the effects of flood and drip irrigation regimes on soil salt accumulation and nutrient status, providing a foundation for drip irrigation technology and ensuring the sustainability of brackish water irrigation and reducing soil salinization for irrigated *L. ruthenicum* in arid regions.

Materials and Methods

Study area

The study area is located in Nomuhong Farm (36°20′-36°30′N, 96°15′-96°35′E), Qaidam area, Qinghai Province, China. It covers a total area of 91.3 km^2 and is the largest original wild *L. ruthenicum* community forest belt in China, with a planting area exceeding 400 hm^2. The area has a typical plateau continental climate at an altitude of 2790 m and belongs to an arid desert zone. The average annual rainfall is 43.5 mm, and potential evaporation is 2849.7 mm. The groundwater table depth ranges within 3-10 m, and its recharge mainly comes from snow melt of the Kunlun Mountains. The study area experiences an average annual temperature of 4.9°C with significant temperature differences between day and night. The average temperature is 35.8°C in January and -31°C in July. Strong solar radiation prevails in the area, with a total annual hour of sunlight of more than 3100 h (Zhang *et al*., 2019). The soil layer in the study area is thicker compared to that under natural vegetation and is characterized by surface soil predominantly composed of saline desert soil containing 5-10% soluble salt content. The natural vegetation is sparse and simple in structure, consisting mainly of shrubs, subshrubs, and herbs adapted to drought, salt, and alkali conditions (Dang *et al*., 2021).

Field experimental design

To evaluate soil salt ion distribution and nutrient status under different irrigation regimes, field experiments were conducted on *L. ruthenicum* irrigated with brackish water at the Nomuhong Farm. The brackish water had pH 7.76 and a total salt content of 0.36 g L^{-1}. Seedlings were cultivated in 2012 and trees were planted in 2013. From May 2019 to September 2020, a randomized block design with three replicates was established for two treatments: flood and drip irrigation. Irrigation was conducted during the *L. ruthenicum* growing season of June-August. Flood irrigation was done twice a month (on the 5th and 20th of every month) using a PVC pipe (100 mm in diameter), following a local irrigation schedule, with water amounts of 350 m^3 ha^{-1}. Drip irrigation, however, was performed using a drip tape (16 mm in diameter, 0.3 mm in wall thickness). Two emitters were installed on one *L. ruthenicum* plant, respectively located at the plant's east and west sides. The emitters had a 40 cm spacing, while the spacing between two adjacent drip tapes was 100 cm, and row width was 150 cm. Water drippers supplied *L. ruthenicum* plants with water at a flow rate of 2.2 L h^{-1} and a pressure of 0.1 MPa. In this study, each irrigation quota was 350 m^3 ha^{-1}, given twice a month (on the 5th and 20th of every month), corresponding to the average local irrigation schedule for *L. ruthenicum*. Urea and phosphoric acid were used as fertilizer for both flood and drip irrigation treatments. The fertilization regime consisted of two separate times: the first fertilization (basal fertilizer, 200 kg ha^{-1} N and 100 kg ha^{-1} P_2O_5) before the first irrigation in each year and the second fertilization three months later (top-dressing fertilizer, 100 kg ha^{-1} N and 50 kg ha^{-1} P_2O_5). The first fertilization was carried out on May 20, 2019 and 2020, while the second fertilization was on August 20, 2019 and 2020. Weeds were removed mainly manually and using rotary cultivator.

Soil sampling and analysis

In September 2020, we selected *L. ruthenicum* plants that grew relatively uniformly in the study plot under flood and drip irrigation treatments, respectively. Soil samples were collected near *L. ruthenicum* after irrigation during the growth period of *L. ruthenicum* at depths of 0-5, 5-10, 10-20, 20-40, 40-60, 60-80, and 80-100 cm by soil auger. Five subsamples at the same depth were collected for each plot and thoroughly mixed as one composite sample. The composite samples were passed through a 2-mm mesh sieve (to remove larger particle materials such as stones, roots, and plant residues from soil) and divided into two parts. One part was used to measure soil water content (SWC), while the other part was air-dried and used for analysis of salt ion and nutrient contents. Salt ion analysis included Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, HCO_3^-, CO_3^{2-}, and SO_4^{2-}. Nutrient analysis included soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), total potassium (TK), available nitrogen (AN), available phosphorus (AP), and available potassium (AK).

The SWC was determined using the gravimetric method. Soil salt ion content was analyzed using a 1:5 soil:water suspension (Abdi *et al*., 2012). The cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}) were measured by atomic absorption spectrometry, and the anions (Cl^-, HCO_3^-, CO_3^{2-}, and SO_4^{2-}) were evaluated by the titration method (Wang *et al*., 2022). Soil nutrient content analyses were standardized according to ISSCAS (1978). The SOC levels were determined by the wet oxidation method with $K_2Cr_2O_7$; TN and AN were evaluated using semi-micro Kjeldahl and $KMnO_4$ oxidation methods, respectively. The TP was digested with H_2SO_4-$HClO_4$ and measured by ascorbic acid method; AP was extracted with $NaHCO_3$ and determined by Mo-Sb colorimetry; and TK and AK were assessed using HF-$HClO_4$ and NH_4OAc flame photometer methods, respectively.

Statistical analysis

The results were expressed as the mean ± standard deviation (SD). Statistical analysis was conducted using SPSS 20.0 (SPSS Inc., Chicago, IL, USA), with ANOVA to evaluate the effects of irrigation regime and soil depth on SWC, soil salt ion content, and soil nutrient content. Two-way ANOVA was applied, and one-way ANOVA was used to test differences in soil parameters at different depths for each irrigation regime. Differences were compared using Duncan's test at $p<0.05$.

Results

Soil water content

The SWC was significantly influenced by the irrigation regime and soil depth ($p<0.001$, Table 1). Flood irrigation resulted in higher SWC levels at each soil depth, except for 0-5 cm, compared with drip irrigation (Table 1). Further analysis indicated that SWC significantly increased from shallow to deep layers, particularly within the depth range of 40-100 cm. The SWC reached 12.55%,

Table 1. The effects of irrigation regime, soil depth, and their interaction on soil water content of *L. ruthenicum*.

	Soil water content
Irrigation regime	773.14***
Soil depth	92.92 ***
Irrigation regime × Soil depth	98.61 ***

Data are F-values; ***$p<0.001$ using Duncan's test.

16.43%, and 18.41% in 40-60, 60-80 and 80-100 cm, respectively, notably higher than the various soil layers within the 0-40 cm depth ($p<0.05$, Figure 1). However, under drip irrigation, SWC initially increased and then decreased with greater soil depth. Compared to other soil layers, soil at depth of 20-40 cm had significantly ($p<0.05$) higher SWC than the other layers, reaching 5.13% (Figure 1).

Soil salt ion content

The contents of salt ions in different soil layers differed significantly ($p<0.001$). Irrigation regimes had a significant impact on the contents of Na^+, K^+, HCO^{3-}, and SO_4^{2-} ($p<0.05$), but not Ca^{2+}, Mg^{2+}, Cl^-, and CO_3^{2-} (Table 2). Soil salt ion content was higher under flood compared to drip irrigation at every soil depth. For 0-5/5-10/10-20 cm soil depths, the Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^-, CO_3^{2-}, and SO_4^{2-} contents were higher by 13.08/16.22/22.64%, 16.44/12.28/12.96%, 15.13/10.49/2.22%, 7.95/2.44/5.41%, 9.80/7.55/1.44%, 5.18/4.58/6.69%, 15.09/12.37/6.45%, and 16.92/10.93/23.75% under flood compared to drip irrigation, respectively (Table 2). Additionally, the soil salt ion content decreased significantly with greater soil depth under flood irrigation. Specifically, the Na^+ content was significantly reduced by 12.24%, 11.56%, 38.10%, 44.22%, 44.22%, and 45.58% at 5-10, 10-20, 20-40, 40-60, 60-80, and 80-100 cm soil depths, respectively, compared to 0-5 cm ($p < 0.05$, Figure 2a). Similarly, the K^+ content was considerably decreased by 24.71%, 28.24%, 55.29%, 74.12%, 77.65%, and 77.65% at 5-10, 10-20, 20-40, 40-60, 60-80, and 80- 100 cm depths compared to 0-5 cm ($p<0.05$, Figure 2b). In addition, the responses of Mg^{2+}, Ca^{2+}, Cl^-, CO_3^{2-}, HCO_3^-, and SO_4^{2-} to soil depth were consistent with those of Na^+ and K^+. Under drip irrigation, soil salt ion contents exhibited similar patterns of response to flood irrigation as soil depth increased. From shallow to deep layers, the Na^+ content notably decreased by 14.62%, 18.46%, 27.69%, 33.85%, 37.69%, and 38.46% at 5-10, 10-20, 20-40, 40-60, 60-80, and 80-100 cm depths, respectively, compared to 0-5 cm ($p<0.05$, Figure 2a). Similarly, K^+ content reached its lowest level at a depth of 80-100 cm and was considerably reduced by 69.86% compared to 0-5 cm ($p<0.05$, Figure 2b).

Soil nutrient content

Most of the soil nutrient content of *L. ruthenicum* was significantly affected by irrigation regime, soil depth, and their interaction ($p<0.05$), except for SOC and AN, which were not affected by irrigation regime ($p>0.05$, Table 3). Furthermore, SOC, TK, and AN had no significant response to the irrigation regime and soil depth interaction ($p>0.05$, Table 3). Compared to flood irrigation, drip irrigation promoted higher soil nutrient contents. For 0-5/5-10/10-20 cm soil depth, the contents of SOC, TN, TP, TK, AN, AP, and AK were higher by 2.67/1.67/4.47%, 4.35/7.50/23.84%, 12.81/25.76/6.49%, 7.74/7.07/9.39%, 1.20/1.21/8.39%, 12.65/9.50/34.79%, and 9.41/8.02/7.73% under drip irrigation compared to flood irrigation, respectively (Table 3). Moreover, as soil depth increased, contents of SOC, TN, TP, TK, AN, AP, and AK remarkably decreased under both irrigation types. The SOC content remarkably decreased by 2.93%, 29.79%, 46.09%, 46.97%, 61.60%, and 62.13% under flood irrigation, and significantly decreased by 3.86%, 28.56%, 43.69%, 41.63%, 65.02%, and 64.11% under drip irrigation at soil depths of 5-10, 10-20, 20-

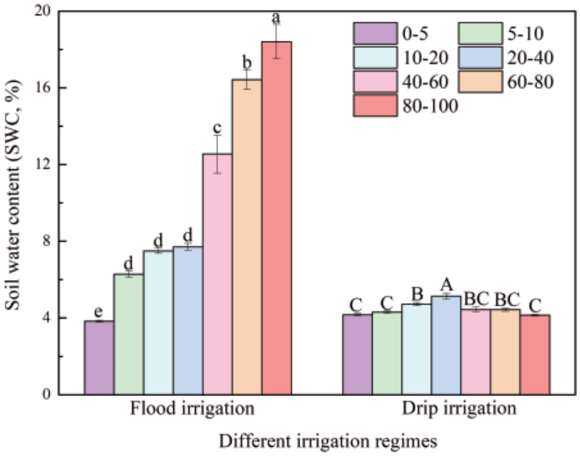

Figure 1. Different irrigation regimes.

Table 2. The effects of irrigation regime, soil depth, and their interaction on soil salt ion content of *L. ruthenicum.*

	Soil salt ion content (g kg^{-1})							
	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	HCO_3^-	CO_3^{2-}	SO_4^{2-}
Irrigation regime	12.507*	7.489*	4.083	3.435	0.885	29.109***	4.210	8.238*
Soil depth	69.208***	290.392***	30.617***	147.351***	83.051***	195.150***	64.888***	44.403***
Irrigation regime × soil depth	4.215 ***	5.235***	1.113	1.427	0.943	0.329	1.051	2.949

Data are F-values; *p<0.05, ***$p<0.001$, using Duncan's test.

40, 40-60, 60-80, and 80-100 cm, respectively, in contrast with 0-5 cm ($p<0.05$, Figure 3). The other soil nutrient contents showed similar trends.

Discussion

Effects of irrigation regimes on SWC

The SWC is a critical factor influencing *L. ruthenicum* growth and serves as a crucial indicator for evaluating water balance in arid and semiarid regions (Guo *et al*., 2016). Our studies showed that SWC at each soil depth was generally higher under flood than drip irrigation, except for 0-5 cm (Table 1). Furthermore, there were variations in SWC between flood and drip irrigation in the soil vertical direction, related to the different effects of irrigation methods on the distribution of soil moisture. Changes in irrigation methods are often accompanied by changes in the distribution of moisture. In drip-irrigated crops, the moisture is primarily distributed in the soil around the roots, with water infiltration being slow and even, and the moisture is retained in the main root zone (Mitchell *et al*., 1993). Meanwhile, the solutes are also expected to remain in that zone, which potentially lead to localized accumulation of salts. In contrast, flood irrigation shows a significant phenomenon of water seeping into deeper layers, with soil moisture often retained in deeper areas, resulting in a poorer uniformity of overall moisture distribution (Jangir *et al*., 2011). Thus, the solutes should be leached to deeper soil layers, which can contribute to groundwater salinization over time. In the case of drip irrigation, water in the soil zone was distributed more around the drip tape,

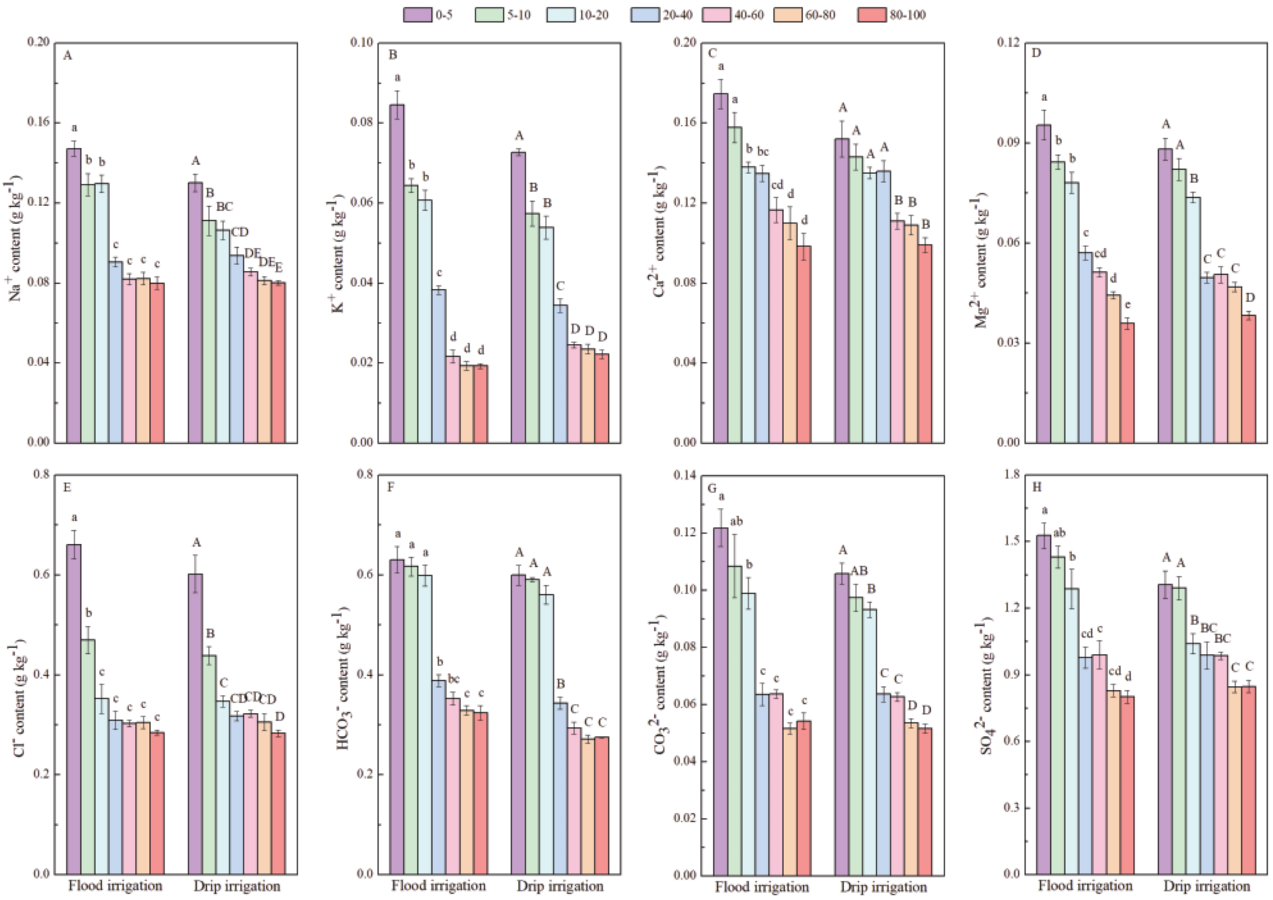

Figure 2. Content of salt ions in different soil layers.

Table 3. The effects of irrigation regime, soil depth, and their interaction on soil nutrient content of *L. ruthenicum*.

	Soil nutrient content						
	SOC	TN	TP	TK	AN	AP	AK
Irrigation regime	2.596	9.187*	25.853***	9.272*	1.583	39.949***	44.158***
Soil depth	232.787***	103.333***	118.349***	19.043***	124.492***	760.757***	2152.251***
Irrigation regime × Soil depth	0.823	2.917*	5.955***	0.726	0.801	9.563***	6.331***

Data are F-values; $^{*}p<0.05$, $^{***}p<0.001$, using Duncan's test.

and SWC remained high for a period of time, especially in the *L. ruthenicum* root zone. Although SWC below the roots decreased due to infiltration, the soil did not restrict plant growth and development (Reyes-Cabrera *et al*., 2016; Gao *et al*., 2021). Previous studies reported that short-term decreases in SWC are favorable for *L. ruthenicum* seedling growth (Guo *et al*., 2016). Therefore, drip irrigation not only ensures the water required for plant growth but also achieves water-saving irrigation. However, the low SWC in the soil surface layer with drip irrigation can be attributed to rapid evaporation caused by intense solar radiation (Wang *et al*., 2022). Unlike flood irrigation, during drip irrigation, the surface soil does not receive direct replenishment of water and therefore has a lower moisture content.

Effects of irrigation regimes on soil salt ion distribution

Soil salt ion distribution not only affects *L. ruthenicum* growth but is also affected by brackish water (Guo *et al*., 2019; Qin *et al*., 2022). According to Jalali and Ranjbar (2009), irrigation with brackish water supplies salt ions to the soil. In our study, soil salt ion content (Na^+, K^+, HCO_3^-, and SO_4^{2-}) was higher under flood than drip irrigation at the different soil depths (Table 2). The difference in salt content under the two irrigation systems may be due to the larger amount of salt supplied to the soil by flood irrigation. Wang *et al*. (2011) studied the impact of drip irrigation on salt distribution under different irrigation systems in Xinjiang and found that leaching of salts under drip irrigation was distinct from other irrigation methods. Chen *et al*. (2014) used flood and drip irrigation methods to investigate the characteristics of soil salt transport during winter irrigation of saline-alkali land in northern Xinjiang. They showed that drip irrigation not only facilitates the control of water quotas, with even water infiltration and improved water use efficiency, but also allows for uniform leaching of salts. The differences in irrigation systems lead to variations in the patterns of soil water and salt transport, which in turn affect the distribution of soil salts. Moreover, our results showed that soil salt ions were mainly distributed in the topsoil layer (0-40 cm), and salt ion accumulation significantly declined with the increase of soil depth under both flood and drip irrigation (Figure 2, $p<0.05$), consistent with previous research. Although different irrigation methods may have varying impacts on soil salinity at different soil depths, irrigation with slightly saline water can lead to increased salt accumulation in the 0-100 cm soil layer (Wang *et al*., 2016; Zhang YH *et al*., 2022). For soils with high salinity (the study area in question is part of the Qinghai-Tibet Plateau's cold saline-alkali region with relatively high soil salinity content), the salts predominantly accumulate in the topsoil layer within 0-20 cm (Yang *et al*., 2008). The accumulation of salt ions in this layer is due to high evaporation rates. The salt content within the 0-40 cm layer increased during the growing season (June-August) of *L. ruthenicum* with brackish

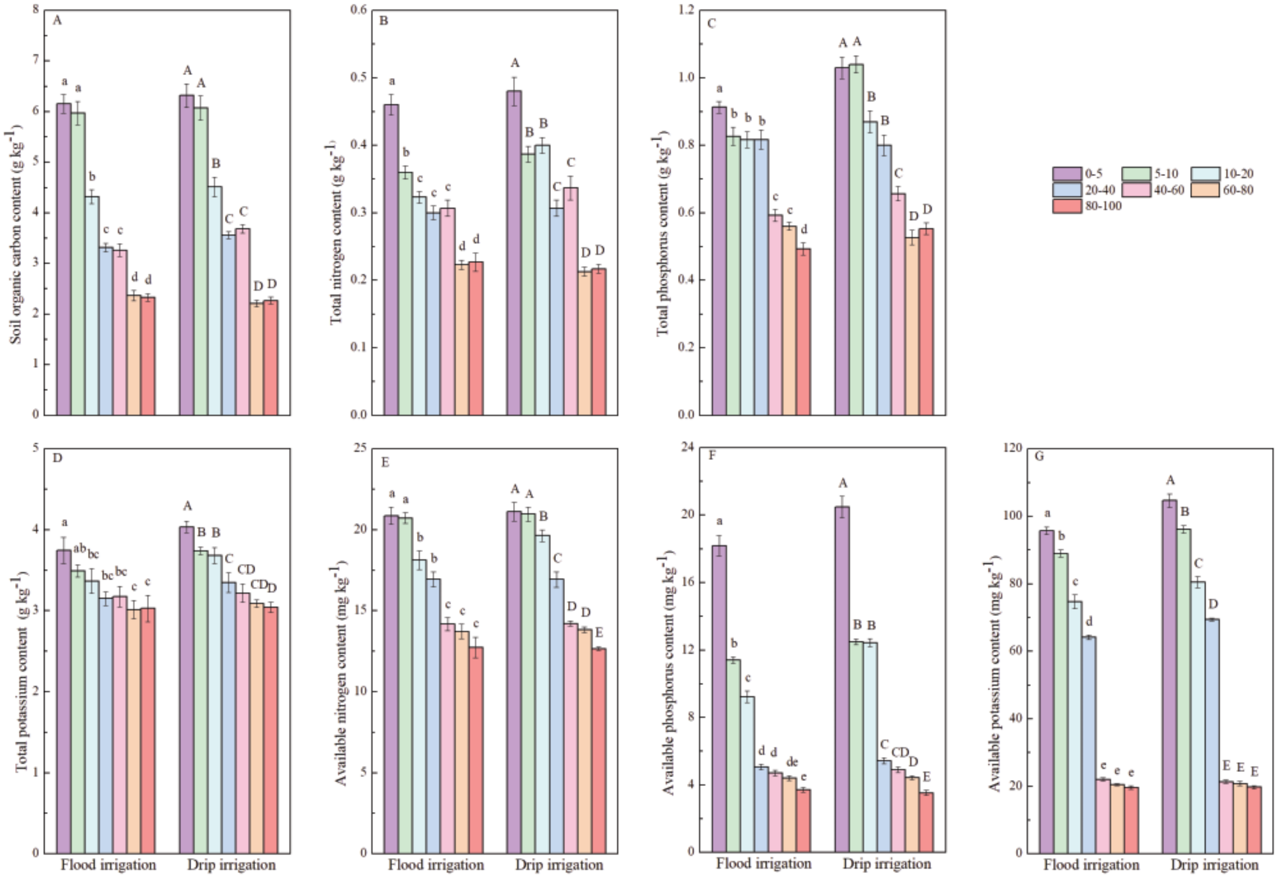

Figure 3. Soil nutrient content in soil depth under flood and drip irrigation.

water irrigation, where mean annual evaporation can reach 2849.7 mm at the study site, while the mean annual precipitation is only 43.5 mm (Zhang *et al*., 2019). The low precipitation and high evaporation primarily affect the topsoil by increasing soil water evaporation and decreasing salt leaching by rain, leading to accumulation of salt ions in the topsoil layer (Pang *et al*., 2010). However, soil at deeper depths may be less impacted by high evaporation, which is supported by our results showing significantly lower SWC in the topsoil layer than at other soil depths (Figure 1). Notably, significant evaporation occurs only after the supplementation of water from deep soil (or even groundwater) to the surface layer of the soil column, causing rapid salt accumulation at the surface due to the migration of salt ions in the same direction as water movement after the evaporation of water (Zhang X *et al*., 2022). The relatively lower accumulation of salt ions in deeper soil may be attributed to the salt-washing effect of flood irrigation, whereby salt ions can be leached to deeper soil layers (Li *et al*., 2022). Moreover, the lower accumulation of salt ions in deeper soil may also be affected by less evaporation, with greater evaporation tending to increase salt accumulation (Huang *et al*., 2016). In contrast, for drip irrigation, limited irrigation water near the *L. ruthenicum* root zone causes salt ions to concentrate in the area surrounding the drip tape and topsoil layer with evaporation, which is unlikely to bring salt ions into deep soil (>40 cm).

Effects of irrigation regimes on soil nutrient status

Our study showed that irrigation regimes affected soil nutrient content, with drip irrigation promoted higher content at greater soil depth than did flood irrigation (Table 3). This indicates that drip irrigation using brackish water may result in less deterioration of soil properties than flood irrigation. This is consistent with the results of Li FY *et al*. (2020), who reported that SOC content was notably higher under drip than under flood irrigation in jujube. In fact, distinct irrigation methods exhibit differential impacts on soil nutrient dynamics. Under flood irrigation conditions, soil moisture quickly becomes saturated or supersaturated over a short period, generating a large amount of gravitational water, and the soil aggregate structure is easily damaged (Gao *et al*., 2013), which is highly detrimental to the maintenance of nutrients in the soil. During flood irrigation events, low molecular-weight nutrients are prone to leaching losses through surface runoff and deep percolation pathways (Nachimuthu *et al*., 2018). In contrast, drip irrigation is a form of localized irrigation in which water enters the soil from a point source and gradually spreads outward. It is characterized by a small amount of water applied, a small wetted area, and a shallow wetted depth (Goldberg *et al*., 1976; Wang *et al*., 2014; Hondebrink *et al*., 2017), this approach effectively mitigates soil nutrient loss risks through lower deep percolation (compared to flood irrigation), no surface runoff and even reduced inter-row evaporation (Hondebrink *et al*., 2017). Moreover, our results showed that soil nutrient content remarkably decreased with increased soil depth under flood and drip irrigation (Figure 3, $p < 0.05$), which is related to the movement of water in the soil, which is the basis for the transport and accumulation of salts and nutrients. Soluble nutrients migrate in the same direction (with salt-washing effect by flood irrigation and the evaporation of water), which may lead to the decrease of soil nutrients with increased soil depth under flood and drip irrigation (Zhang YH *et al*., 2022). On the one hand, nutrients are transported downward with the infiltration of irrigation water into deeper soil layers (>1 m) or into the groundwater (in this study area, the groundwater level is >3 m) and are lost. On the other hand, nutrients are drawn into the surface soil layer with the intense evaporation of water.

Conclusions

We compared SWC, soil salt ion distribution, and soil status at various soil depths for *L. ruthenicum* under flood and drip irrigation regimes using brackish water. The SWC levels were higher at each soil depth under flood compared to drip irrigation, except for 0-5 cm depth. Flood irrigation caused a significant increase in SWC with greater soil depth, whereas drip irrigation initially resulted in an increase, followed by a decrease in SWC with soil depth. Soil salt ion content was higher under flood than drip irrigation at each soil depth. However, soil nutrient content was higher under drip irrigation, and both salt ion and nutrient contents decreased significantly with greater soil depth for both irrigation regimes. Our findings suggest that flood irrigation with brackish water worsens soil salinization and nutrient depletion. In contrast, drip irrigation is more beneficial. Drip irrigation delivers water directly to the plant's root zone, resulting in controlled water application and reducing evaporation and runoff. This efficient water delivery method helps maintain desired soil moisture levels. Additionally, drip irrigation promotes the redistribution of salts within the soil profile. The gradual and localized release of water ensures a more uniform distribution of salts, minimizing their concentration near the plant roots. Consequently, this minimizes the negative effects of salt accumulation in the root zone. Furthermore, drip irrigation enhances the availability and uptake of nutrients in the soil. By effectively reducing soil salinity through brackish water irrigation, it diminishes the competition between salt ions and essential nutrients for plant root absorption. Consequently, this improves nutrient availability and uptake, leading to healthier plant growth. For preserving irrigation water resources, reducing secondary soil salinization, and preventing soil nutrient loss, drip irrigation appears to be the better irrigation method. Moreover, the impact of soil salinity and nutrient content on soil microorganisms and enzymes, which are essential for soil fertility, should be further investigated by analyzing the variation in soil microbial community diversity and soil enzyme activities for *L. ruthenicum* irrigated with brackish water under different irrigation regimes.

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