

Effect of alternating canal and marginal groundwater irrigation on banana yield, water use efficiency, and soil salinity under furrow plantation

Nazar Gul^{a,b}, Hafiz Abdul Salam^{a,b}, Muhammad Ashraf^{b,c}, Majid Taie Semiromi^{d,*}

^a Drainage and Reclamation Institute of Pakistan (DRIP), Tando Jam, Sindh, Pakistan

^b Pakistan Council of Research in Water Resources, Islamabad, Pakistan

^c International Water Management Institute, Pakistan

^d Hydrogeology Group, Freie Universität Berlin, Malteserstr 74-100, 12249 Berlin, Germany

ARTICLE INFO

Handling Editor - J.E. Fernández

Keywords:

Banana production
Soil moisture depletion
Water use efficiency
Furrow
Water saving
Pakistan

ABSTRACT

Banana is one of the most important cash crops in Sindh, Pakistan; however, its production is increasingly compromised due to declining freshwater availability. Currently, banana is cultivated using conventional flat basin irrigation, which results in low water use efficiency (WUE). Groundwater in the region is predominantly marginal to saline in quality but could potentially supplement limited freshwater resources. Therefore, it is essential to evaluate the conjunctive use of marginal-quality groundwater and canal water to address freshwater shortages without compromising crop yields. In this study, the Dwarf Cavendish banana variety (locally known as Basrai) was cultivated over a four-year period (October 2015–June 2019) on furrows (0.90 m furrow width, 1.20 m bed width, and 0.23 m bed height). Alternate irrigation using canal and marginal groundwater was applied at three levels of available soil moisture depletion (ASMD): 50 %, 40 %, and 30 %. Traditional farmer irrigation practices were also monitored for comparison. At ASMD levels of 50 %, 40 %, and 30 %, annual water applications were 1228 mm, 1403 mm, and 1592 mm, respectively. In contrast, farmers applied 2866 mm of water annually. Irrigation at 50 % ASMD resulted in 12–23 % higher yield and 23–41 % higher WUE compared to 30 % and 40 % ASMD treatments. Compared to the 50 % ASMD treatment, farmer practices produced 24 % lower yield and 67 % lower WUE. Importantly, soil salinity remained within acceptable threshold limits across all treatments. These results suggest that banana can be successfully cultivated on furrows using alternate irrigation with canal and marginal groundwater at 50 % ASMD. This strategy offers substantial water savings while improving yield and WUE, making it a viable and sustainable solution for banana production in water-scarce regions.

1. Introduction

Banana is a cash crop with the highest global annual production (127.3 million tonnes), and ranked fourth in terms of agricultural commodity value (63.6 billion US\$) after rice, wheat, and milk (Ploetz et al., 2015; FAOSTAT, 2018). It employs millions of people and is a significant source of foreign earnings for many countries (Panigrahi et al., 2021). Due to its high economic return, banana crop is extensively grown in the Sindh province of Pakistan (Irfana et al., 2015). Its water requirement is high, reflected in evapotranspiration (ET) of 2000 mm during the first year of cropping and 3500 mm during the second to fifth years of cropping (Gul et al., 2023). However, farmers normally apply

more than 5000 mm of water annually mainly due to conventional irrigation system (flat basins) and lack of knowledge about irrigation scheduling (i.e. when and how much water to apply). Freshwater is increasingly becoming scarce in Pakistan in general and Sindh in particular. Moreover, groundwater in Sindh is either saline or of marginal water quality. This has resulted in a reduction in cropped area and yield. As a result of the water stress, Panigrahi et al., (2021) reported yield losses of up to 65 % due to loss in bunch weight. It therefore becomes imperative to manage the irrigation water judiciously for growing banana using practices that can save water, increase crop yield and water use efficiency (WUE) and can have high economic return per unit of water used (Capra et al., 2008; Gul et al., 2023).

* Corresponding author.

E-mail addresses: nazargul43@gmail.com (N. Gul), hasmemon@gmail.com (H.A. Salam), m.ashraf@cgiar.org (M. Ashraf), majid.taie@fu-berlin.de (M. Taie Semiromi).

¹ <https://orcid.org/0000-0003-4339-4217>

<https://doi.org/10.1016/j.agwat.2025.109603>

Received 29 October 2024; Received in revised form 2 June 2025; Accepted 8 June 2025

Available online 24 June 2025

0378-3774/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Several irrigation methods have been tried throughout the world for saving irrigation water and increasing WUE (Zhang et al., 2021). For instance, Bassoi et al. (2004) cultivated banana (Pacovan variety) under micro sprinkler irrigation in Brazil, and Khalifa (2012) cultivated banana (Grand Nain variety) under drip irrigation system in Gezira, Sudan and found better yields with significant water saving. These methods have distinct advantages over conventional methods in reducing the irrigation water use, regulating the salts through reduced evaporation and utilizing the irrigation water precisely playing an important role in agricultural production (Amayreh and Al-Abed, 2005; Wang et al., 2011; El-Shafei and Mattar, 2022). However, these methods are cost extensive and require a high level of skills for their operation, repair and maintenance. Moreover, frequent irrigation is applied to the crop under drip and micro sprinkler system to meet the crop ET. However, irrigation water allocation in Sindh is based on warabandi, a rotational irrigation system. A farmer gets its allocated water with an interval of 15–21 days, making micro sprinkler and drip irrigation highly unlikely to be adopted.

Moreover, the marginal to saline groundwater could be utilized beneficially in agricultural sector (Machado and Serralheiro, 2017) to bring more area under crop cultivation (Sheikh and Ashraf, 2009). However, the ability of a plant to withstand against the toxic effects of the saline water will determine the degree of success and the production of economic yield (Ahmad et al., 2017; Kaleem et al., 2018). Soil and water salinity above the threshold limit is one of the most limiting factors to the expansion of cultivated areas of banana, as the banana production declines with a high salinity (Al-Harhi and Al-Yahyai, 2009; Almeida et al., 2016). The impact of continuous application of varying groundwater qualities has been assessed for different banana genotypes over different time spans in the past around different regions of the world. Under a greenhouse experiment for a period of 120 days, and adapting an irrigation scheduling of 24 h intervals keeping the soil at field capacity, Almeida et al., (2016) found 14 % reduction in shoot dry mass of banana with an EC of 1.50 dS/m as compared to 0.50 dS/m. Under the open field conditions with deep groundwater-table conditions in a rotational warabandi system, Akbar et al., (2014) found no change in yield when groundwater with an EC of 0.75 – 2.25 dS/m was used for cultivation of banana in district Lasbela of Balochistan, Pakistan. However, Al-Harhi and Al-Yahyai (2009) found that frequent saline irrigation water application (at 10–12 kPa) with 3.0 dS/m EC could cause a 15 % reduction of leaf area index of banana when it is grown for a period of 9 months in polyethylene bags. Leaf area index further declines with increasing EC, and even at 9.0 dS/m, it is reduced by 44 %. Under the field conditions, banana yield response is subject to the extent of irrigation water salinity and it should not exceed 2.25 dS/m; otherwise, the growth parameters and yield of banana could be compromised.

The studies mentioned above were conducted under controlled conditions for a short period, with frequent saline irrigation (applied daily and at 10–12 kPa soil moisture tension, i.e., near-saturation). As a result, the banana plants did not reach the fruiting stage, and the effect of salinity on fruit production could not be observed. Irrigating with saline water frequently almost on daily basis is likely to lead to more significant and rapid negative impacts on plant growth compared to irrigating with saline water applied less frequently with a proper irrigation scheduling. Daily saline irrigation leads to continuous salt accumulation in the root zone, increasing the osmotic pressure and making it harder for plants to uptake water and nutrients. Moreover, these studies did not account for proper irrigation scheduling, nor did they assess the impact on soil properties and crop yield. Another major aspect which has not been considered in these studies is the use of marginal saline groundwater in conjunction with fresh canal water. Therefore, using marginal groundwater in conjunction with canal water through a furrow irrigation system can offer significant potential to expand banana cultivation, enhance yield, and improve WUE without compromising crop productivity.

Furrow irrigated with raised beds is an improved form of surface

irrigation, in which most of the crops are grown either on edge or top of the bed. It offers several advantages such as better crop root growth, reduction in deep percolation, and a higher WUE (Benjamin et al., 1994; Kang et al., 2000; Xu and Li, 2007; El-Shafei and Mattar, 2022, Ejaz and Ashraf, 2023). This method is easy to adopt, less expensive, and does not require much technical skill and knowledge. A properly designed furrow and bed size facilitates growing banana with significant water saving compared to traditional flat basins. However, a comprehensive review of literature shows that planting bananas on furrow irrigation has not been studied anywhere in the world.

Therefore, this study was conducted to answer the following questions: 1) Does growing banana on furrows with alternate irrigation using canal and marginal groundwater at different levels of available soil moisture depletion (ASMD) significantly reduce irrigation water use, while improving crop yield and water use efficiency (WUE) compared to conventional farmer practices?; 2) Can furrow planting combined with the use of marginal-quality groundwater increase banana yield?; 3) Does transplanting banana on furrows with alternate irrigation of canal and marginal groundwater affect soil salinity?

2. Materials and methods

2.1. Site description and experimental design

The experiment was conducted at the research and demonstration farm of Drainage and Reclamation Institute of Pakistan located at Tando Jam ($25^{\circ} 25' 10.6''$, $68^{\circ} 31' 35.2''$), Sindh. Fig. 1 shows the location of the experimental site. The experiment was setup as Randomized Complete Block Design with four treatments. These treatments included irrigation application when the available water in the crop effective root zone depletes by 50 % (T1), 40 % (T2), 30 % (T3), and farmer practices (T4). Farmers usually apply 80 mm weekly in summer from April – October, fortnightly in winter from November – March, and 167 mm after hoeing practices. Each treatment was replicated thrice. An area of 990 m² was occupied by each plot (length: 30 m, width: 33 m). Overall, an area of 2970 m² (90 m long and 33 m wide) was used for each treatment.

2.2. Preparation of land and transplantation of corms

The land was prepared using disc harrow followed by cultivator and was leveled using laser land leveler. After plowing, a raised bed maker was used to make furrows and raised beds. Initially, the furrow and raised bed widths were maintained at 0.60 m and 1.50 m, respectively (Fig. 2a). However, after 5–6 months, the furrow width was manually increased to 0.90 m using a spade, resulting in a reduction of the raised bed width to 1.20 m (Fig. 2b). The furrow width was increased to avoid the reduction in flow of water in furrows due to the sucker germination and to keep suckers population within the furrow. The height of the raised bed was maintained at 0.23 m. The pits (length = 0.61 m, width = 0.61 m and depth = 0.61 m) were dug manually using a spade for the transplantation of banana corms. The farmyard manure (0.50 kg/pit) was mixed with the soils obtained from the pits. One healthy banana corm was transplanted in each pit and the pit was refilled with the soil. The corms were transplanted on the edge of the furrows. The field was irrigated immediately after transplanting the corm. The plants and rows spacing were kept the same for each treatment i.e. 2.13 m × 2.13 m.

The suckers germinated within 10–15 days after the transplantation of corms. However, the number of suckers germinated from the corm varied. Initially, only one sucker was left to become the mother plant. Five months after corm transplantation, two suckers each with a five-month interval (Robinson and Nel, 1986) were left to grow with the mother plant (1st sucker) as a follower for the 1st ratoon crop. To obtain uniform cropping, the same package of sucker selection was followed for the 2nd and 3rd ratoons. The mother plant and its sucker are commonly called a mat. Each mat consisted of one mother plant and two suckers.

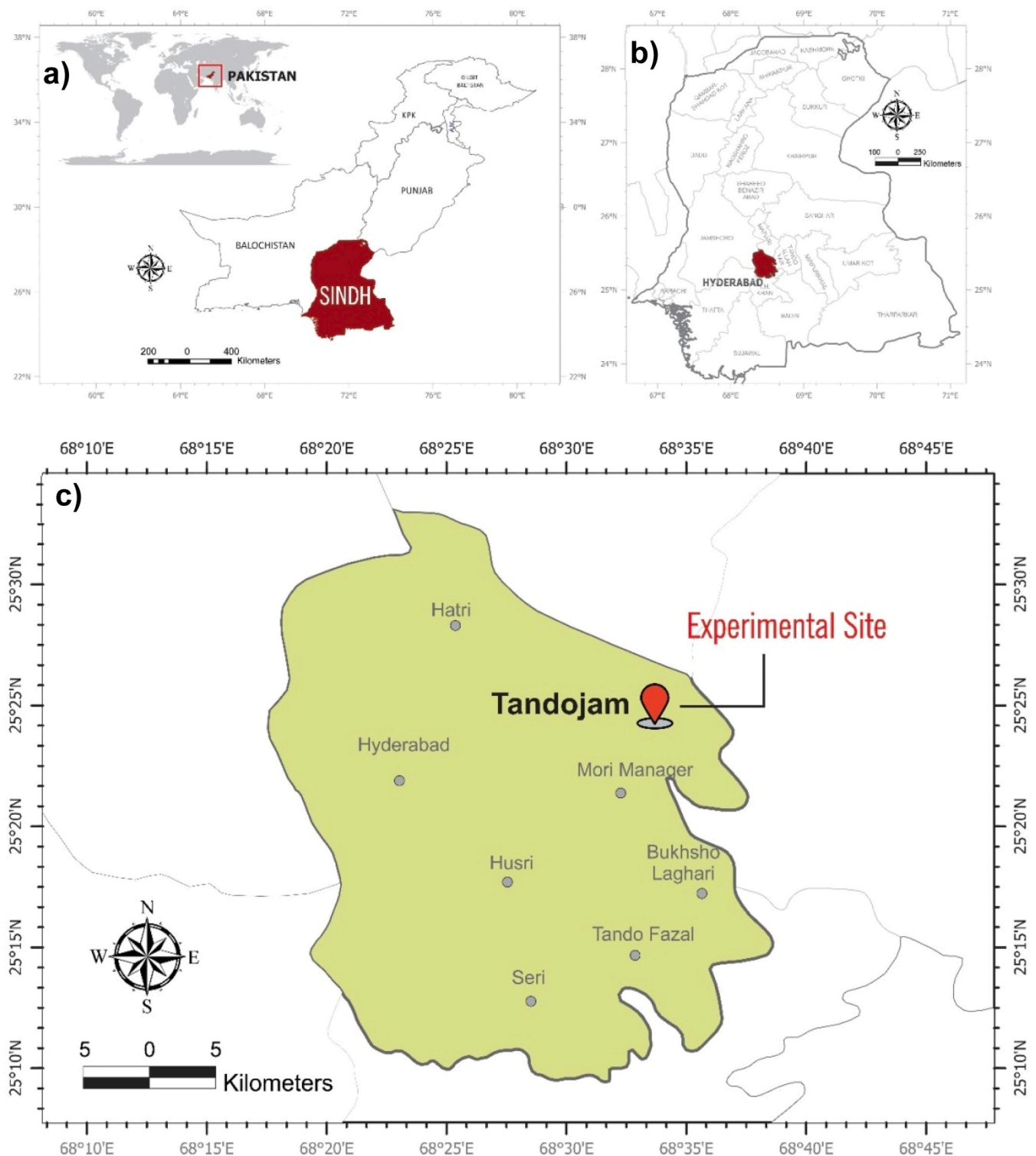


Fig. 1. a) The position of Pakistan on the global map; b) The location of Tandojam in the Sindh province; and c) The location of the experimental site.

2.3. Hoeing, fertilization and de-suckering practices

The hoeing practices were carried out with an interval of two months in each treatment, till the crop attained full canopy (12 months after corm transplantation). Thereafter, hoeing was carried out on a quarterly basis. The fertilizer was applied at the rate of 544 – 227 – 494 kg/ha/year NPK (Memon et al., 2010). The N was applied in the form of Nitrophous (NP), P in the form of Di-ammonium Phosphate (DAP), and K

in the form of Sulphate of Potash (SOP). The NPK fertilizers were applied after every two months followed by irrigation. To remove the unwanted suckers and to maintain the 1:2 banana mother plant and sucker's ratio, the de-suckering practices were carried out on quarterly basis. Plant partial and complete dry leaves were cut on quarterly basis. The leaves and the plant stem (after harvesting) were spread over the bed as organic mulching. This was done to improve soil fertility, conserve soil moisture and avoid evaporation, thus reducing the risk of salt accumulation.

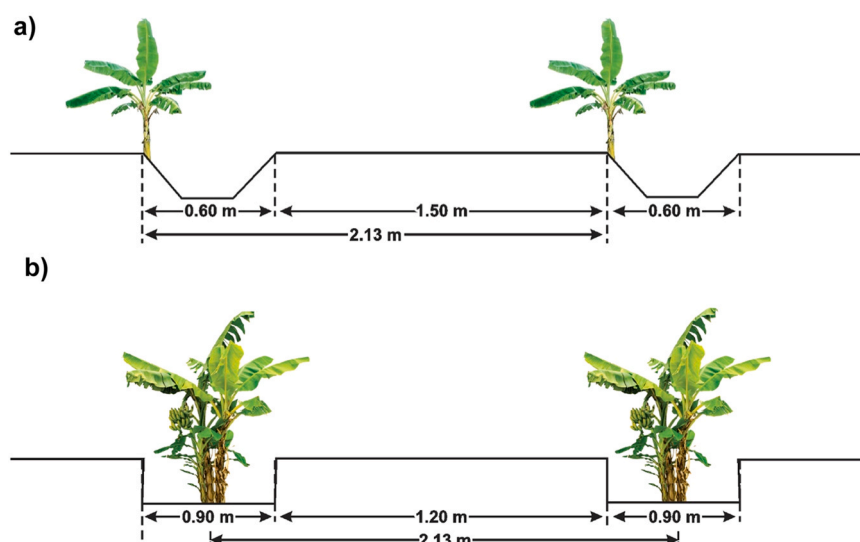


Fig. 2. a) Schematic diagram of furrow planation of banana, showing the initial configuration with a furrow width of 0.60 m and raised bed width of 1.50 m; b) the same as Fig. 2a but showing changes after 5–6 months: furrow width increased to 0.90 m, and raised bed width reduced to 1.20 m.

2.4. Irrigation application

Available soil moisture is the difference of soil moisture between field capacity and wilting point. Available soil moisture in the crop effective root zone depletes continuously with an uptake of water by plants to meet its evaporative demand. When a certain portion of available water is removed from the soil, it is termed available soil moisture depletion (ASMD). In other words, ASMD is the amount of available water that is removed from the soil (by plant uptake and evaporation) since the last time the soil was at field capacity level. The ASMD level varies with crop type and growth stages, soil properties, and weather conditions. Different crops have different levels to withstand against the soil moisture deficit. Therefore, it is important to have proper knowledge and information about the effects of different ASMD levels on banana yield, yield traits and WUE. This information is needed for adopting proper irrigation scheduling. Many studies have shown that irrigation scheduling based on optimum soil moisture depletion levels increases yield and improves WUE (Geerts and Dirk, 2009; Mahamed et al., 2011).

Irrigation to the banana crop was applied as per the designed treatments i.e. when the available soil moisture in the crop – effective root zone was depleted by 50 % (T1), 40 % (T2) and 30 % (T3). The banana effective root depth is 0.40 m from planting to 286 days after planting with 89–95 % of the whole root system (Basso et al., 2004). Farmer practices were followed as control (T4). Available soil water is the difference between field capacity and permanent wilting point. Soil of the experimental site is of the Sultanpur soil series (silt loam texture), one of the dominant soil series of the Lower Indus. The soil of the experimental site was silt loam textured with different proportions of soil separates. The proportions included 22.8 – 26.8 % of sand, 51.2 % of silt and 22–26 % of clay. The field capacity and permanent wilting point (on volume basis) for this soil type is 37.8 % and 7 % with dry bulk density 1.4 g/cm³, respectively. Hence, available water becomes 30.8 %. When 50 %, 40 % and 30 % of the available water was depleted from the effective root zone (moisture contents in the soil were at 15 %, 18 % and 22 %), the next irrigation was applied.

The available soil moisture was determined through gravimetric technique. For this purpose, soil samples were collected from the furrows around the banana plants at 0–0.15 m, 0.15–0.30 m, and 0.30–0.45 m depths. The sampling started after 4–5 days of irrigation application when soil moisture dropped below the field capacity level. The sampling continued until the next irrigation was due. The results of

these samples were averaged and checked to determine whether the soil moisture reached the required level. Accordingly, the irrigation was applied.

Since the plant population was maintained within the furrows, irrigation was applied directly to the furrows. Water was applied until the furrows were filled to three-fourths of their height, and the time required to fill the furrows for each plot was recorded. A cutthroat flume, operating under free-flow conditions, was installed at the center of the field channel to measure the discharge rate. The dimensions of each experimental plot were predetermined. Using the measured field channel discharge (Q), the time taken to fill the furrows (T), and the area of the plot (A), the depth of water applied (D) was calculated using Eq. 1:

$$D = \frac{Q \times T}{A} \quad (1)$$

Where D is the depth of water applied in the furrows (m), Q is the discharge of the field channel (m³/s), T is the time taken to fill the furrows up to three-fourths of their height (s), and A is the area occupied by each treatment (m²). In addition, precipitation during the growing period was recorded using a rain gauge installed at the Agro-Meteorological Observatory of the DRIP Campus, Tandojam. The recorded rainfall was then used to calculate effective rainfall with the help of FAO CROPWAT software, and the effective rainfall values were incorporated into the water balance for each treatment.

2.5. Quality of irrigation water

Alternative irrigation of canal and marginal GW was applied over a period of four years (October 2015 – June 2019). DRIP research and demonstration farm uptake canal water from R.D 18.05 Pipe Water Course, i.e., Qaiser Minor, Khesana Mori, Tajpur Sub-Division, Rohri Canal Circle. The data on water quality parameters for both sources is

Table 1
Quality of irrigation water used for banana irrigation.

Water quality parameters	Water sources	
	Canal water	Groundwater
EC (dS/m)	0.40	1.50
pH	8.40	7.40
Sodium Adsorption Ratio (SAR)	0.96	5.31
Residual Sodium Carbonate (RSC)	0.00	3.90

given in Table 1. Residual Sodium Carbonate (RSC) is a parameter that estimates the capacity of water to alkalize the irrigated soil. The RSC was above the threshold limit. The RSC of ≤ 1.25 is considered to be low sodium hazardous, medium hazardous when RSC is $1.25 - 2.50$, and high sodium hazardous if RSC is ≥ 2.5 . However, irrigation water with $RSC > 5$ is not recommended to use for plant irrigation (Rawat et al., 2018). A high RSC of water can be reduced by adopting strategies like dilution of high RSC water with low salt water and addition of calcium-based amendments, along with organic manures (Murtaza et al., 2021). The pH of canal water is higher than that of groundwater mainly due to the dumping of waste in the canal (Panhwar et al., 2022).

2.6. Yield, yield parameters and WUE

The fresh harvested yield of banana crops was measured under different treatments. The harvesting of banana yield was started in May 2017. Initially, the yield was measured for each replication and converted to kilograms per hectare (kg/ha). Furthermore, WUE was calculated to measure how effectively irrigation water was used for crop production (kg/m^3). To assess the effect of alternative irrigation of canal and marginal GW on banana yield at different ASDM under furrow plantation, twelve banana plants were selected from each treatment (four from each replication). The yield parameters such as bunch weight (kg), bunch length (cm), bunch width (cm), length of longest finger in 3rd hand (cm), width of longest finger in 3rd hand (cm), number of hands/bunch (Nos.), and stem girth (cm) were also measured.

2.7. Soil chemical properties

Farmers believe planting crops on furrows and raised beds leave certain areas fallow. The salinity can decrease in furrows and at the bed edges and increases towards the bed center. Moreover, the adaptation of alternative irrigation could further increase the soil salinity on the center of the raised beds. To test this hypothesis, soil samples were collected from center of the furrow with an increasing distance of 0.15 m up to the center of the bed (Fig. 3). The sampling depth was kept at 0–0.15 m, 0.15–0.30 m, and 0.30–0.45 m. Overall, nine samples were collected from the center of the furrow to the center of the bed and were given captions as sampling point P1 to P9. Initially, in October 2015, soil samples were collected from the bare soil, before preparation of the furrows and raised beds. However, above-mentioned sampling strategy was adapted during the period of 2016–2018. The last sampling was carried out by the end of December 2018. These soil samples were analyzed for the determination of EC, pH, SAR and ESP. All analysis was carried out at the Soil and Water Analysis Laboratory, DRIP, PCRWR, Tando Jam.

2.8. Statistical analysis

All the data were processed through Statistix software version 8.1. For the analysis purpose, linear model was selected and data were processed with 2-way interaction of the least significant difference (LSD) at alpha values of 0.05, i.e. confidence level of 95 %.

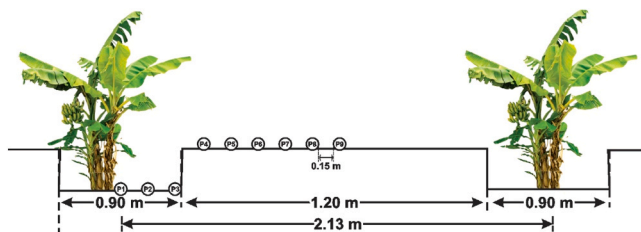


Fig. 3. Schematic diagram for soil sampling from center of the furrow with an increasing distance of 0.15 m up to the center of the bed with sampling caption P1 to P9.

3. Results and discussion

3.1. Irrigation water use

Fig. 4 shows the water used by banana grown in furrows under different ASDM and farmer practices. Banana used 1228 mm, 1403 mm, 1592 mm and 2866 mm of water/year (including effective rainfall) at 50 %, 40 %, 30 % ASDM and under farmer practices, respectively. Gul et al. (2023) found evapotranspiration of fully grown banana ranging between 2430 and 3023 mm. However, in literature we have not found any study where banana has been grown on furrows and irrigated at different ASDM. However, Abd El-Kader et al. (2006) found banana water use as 1475 mm and 1435 mm at 40 % and 60 % ASDM levels, respectively. These values are 2 %–17 % higher than those found in current study at 50 % and 40 % ASDM levels. This difference in banana water use may be due to the varietal changes. William variety was cultivated by Abd El-Kader et al. (2006), whereas the Dwarf Cavendish variety was cultivated in the current study. William variety comparatively has longer (2.00 m–2.09 m) and broader leaves (0.71 m–0.74 m), attains maximum height (2.23 m–2.24 m) and its roots penetrates to deeper depths (Abd El-Kader et al., 2006). This it may uptake more water increasing the crop water use.

The banana cultivated on furrows at 50 % ASDM used 7 %–26 % lower water than that reported by Rao et al., (2019) with 50 % ASDM under controlled condition of lysimeters in the same environmental condition with the same planting density at 1.50 m–2.50 m water table depths (WTDs). This difference may be attributed to the irrigation of a larger surface area in lysimeters compared to furrow plantations.

Banana used 12 % and 23 % less water in furrows at 50 % ASDM over 40 % ASDM and 30 % ASDM, respectively. Compared to the farmer practices, banana used 57 % less water on furrows at 50 % ASDM. This is due to the frequency of irrigation that was higher at 30 % and 40 % ASDM, respectively. Resultantly, the number of irrigations applied to banana was higher, thus leading to higher water application at 30 % and 40 % ASDM. Abd El-Kader et al. (2006) also found a similar trend for banana at 40 % and 60 % ASDM levels. There are significant differences ($R^2 = 0.78$) in the water application at different ASDM levels and farmer practices (Fig. 2b). The trend line shows an increase in water application with a decrease in ASDM from 50 % to 30 %. The highest water was applied under farmer practices.

3.2. Yield and water use efficiency

Table 2 shows the yield and WUE of banana at different ASDM and farmer practices. Banana produced both i.e., productive and non-productive yield on furrow plantation. A productive yield may be referred to the marketable yield, while non-productive yield is the banana bunches that do not have a market value. Banana bunches and leaves are increasingly being utilized for bio-compost production. However, one limitation of furrow planting in banana cultivation is that suckers tend to emerge not only along the edge of the furrow but also in the center of the raised bed. The central part of the bed typically contains

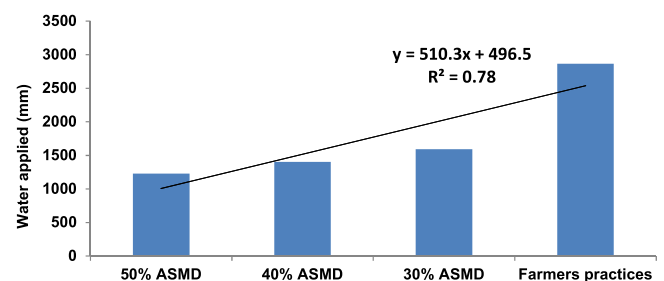


Fig. 4. Water applied to banana under different soil moisture depletions with furrow plantation and under the farmer practices.

Table 2
Banana yield and WUE.

Treatments	yield (kg/ha)			WUE (kg/m ³)
	Productive yield	Non – productive yield	Total yield	
50 % ASMD	43867 a	7904	51771 a	3.57 a
40 % ASMD	38532 b	7706	46238 b	2.75 b
30 % ASMD	33592c	6916	40508c	2.11c
Conventional	33493c	-	33493 d	1.17 d

Means followed by the same letter don not differ significantly ($p \leq 0.05$)

comparatively loose soil. Under such conditions, when a sucker develops into a mother plant and produces fruit, it often fails to remain upright and instead bends over, leading to the formation of a non-productive bunch. Additionally, banana plants growing at the center of the bed may have reduced access to nutrients, as nutrient availability is generally higher in the furrow zone. In contrast, banana plants grown along the furrow edges benefit from enhanced nutrient uptake due to their proximity to the irrigation zone, resulting in improved growth and the production of healthier bunches.

This is because fertilizer and irrigation water are applied in the furrows. The non – productive yield was 15 %–17 % of the total banana yield at 30 %, 40 % and 50 % ASMD levels, respectively.

The highest productive yield of bananas was observed at 50 % ASMD, with yield decreasing as the ASMD level was reduced. This trend may be attributed to the higher frequency of irrigation required at 30 % ASMD. Under this condition, marginal-quality groundwater should be applied more frequently than at 40 % or 50 % ASMD, increasing the exposure of banana plants to saline water. As a result, the plants at 30 % ASMD are more adversely affected by the use of marginal-quality groundwater, leading to a reduction in yield. These findings are consistent with the results reported by Almeida et al. (2016) and Mahmoud et al. (2020), who observed that salt ion toxicity significantly reduced banana bunch yield. Similarly, Al-Harthi and Al-Yahyai (2009), as well as Almeida et al. (2016), found that banana growth declined when the salinity of irrigation water exceeded 1.0 dS/m. In the present study, banana yields ranged from 33,592 kg/ha to 43,867 kg/ha at 30 % and 50 % ASMD, respectively. In contrast, Abd El-Kader et al. (2006) reported yields of 31,230 kg/ha at 40 % ASMD and 31,770 kg/ha at 60 % ASMD. Thus, the yields obtained in the current study at 30 %–50 % ASMD are approximately 7 %–29 % higher than those reported by Abd El-Kader et al. (2006). This difference may be attributed to: (i) Varietal differences, as Abd El-Kader et al. (2006) cultivated the William variety, whereas a different variety was used in the current study; and (ii) Planting density, with 2200 plants/ha used in this study compared to 815 plants/ha in Abd El-Kader et al. (2006). A higher planting density, combined with proper plant spacing, likely contributed to increased yields. However, the banana yield in the present study was lower than that reported by Rao et al. (2019), who observed yields of 63,372–72,496 kg/ha at 50 % ASMD under controlled lysimeter conditions, using the same planting density and within the same environmental setting. This substantial yield difference — 31 %–40 % higher — may be explained by the use of high-quality irrigation water in the study by Rao et al. (2019).

The WUE of banana is the productive yield divided by the total water applied. The WUE of banana increased with an increase in ASMD. It was 23 % and 41 % higher at 50 % ASMD over 40 % and 30 % ASMD levels. This is due to the (i) less water used at 50 % ASMD level, and (ii) a higher yield obtained. An increase in ASMD led to decrease in irrigation frequency, thereby resulting in reduced water applied. Abd El-Kader et al. (2006) found WUE of banana as 2.12 kg/m³ and 2.22 kg/m³ under 40 % and 60 % ASMD, respectively. The WUE of banana in the current study is 23 %–41 % higher than that of obtained by Abd El-Kader et al. (2006). The WUE achieved in the current research is 7 %–26 % higher than that obtained by Rao et al. (2019) under controlled lysimeter conditions with

50 % ASMD, using the same environmental conditions and planting density. While banana yield reported by Rao et al., (2019) is 31 %–40 % higher, WUE was found to be the lower due to substantially higher amount of water used (2094–2584 mm). In contrast, the water use of banana on furrow plantation at 50 % ASMD level was 1228 mm, giving a better WUE.

3.3. Yield traits

Table 3 shows yield traits of banana grown on furrows and irrigated alternatively with canal and marginal groundwater under different ASMDs. All yield traits of banana, including bunch weight, bunch length, bunch width, length of longest finger in 3rd hand, width of longest finger in 3rd hand, number of hands per bunch, and stem girth are significantly higher ($p < 0.05$) at 50 % ASMD compared to 40 % and 30 % ASMD and under farmer practices. However, Abd El-Kader et al. (2006) found yield traits of banana to be the highest at 60 % ASMD followed by 40 % ASMD. Moreover, the banana yield traits that they found are much higher than those found in the current study mainly because of varietal changes and good quality water used for irrigation purposes. However, they found the same trend as stem girth has the highest values at maximum ASMD level.

3.4. Soil properties

Fig. 5 illustrates the variation in soil electrical conductivity (EC) across different years under varying ASMD levels and farmer practices. In the first year of the study (2015), soil EC ranged from 1.89 to 2.26 dS/m. In 2016, soil EC decreased within the furrows but gradually increased with distance from the furrow, particularly at sampling points P5 to P9. This pattern is likely due to irrigation water being applied directly within the furrows, which facilitated the leaching of salts downward. In contrast, evaporation from the raised beds caused salts to accumulate toward the wetting front, i.e., the sides and center of the raised beds.

In 2017, soil EC further declined, even at the center of the beds (sampling points P5 to P9), primarily due to a significant rainfall event on August 30, 2017, which delivered 86 mm of precipitation. This rainfall submerged both furrows and raised beds, promoting salt leaching across the profile. As rainfall was minimal in 2018, all water demands of the banana crop were met through irrigation. Consequently, salt accumulation was observed on the raised beds, especially at sampling points P7 to P9.

A similar trend was reported by Devkota et al. (2015) for cotton cultivation on raised beds, where furrow irrigation led to increased salt concentration at the sides and center of the beds. Despite these variations, the soil EC in the current study remained within the safe threshold of 4.00 dS/m, indicating that furrow planting of banana combined with alternate use of canal and marginal groundwater did not adversely affect soil health.

Under farmer practices, soil EC increased during the second year of banana cultivation (2016), decreased in 2017, and reached its lowest level in 2018. This may be attributed to the leaching of salts during farmer irrigation cycles, where all available canal water is typically applied during scheduled turns.

Fig. 6 illustrates the soil pH in different years with variegated ASMD and farmer practices. The soil pH during the 1st year was between 8.07 and 8.1. However, it decreased during 2016 within the furrows. The decrease in pH was less with an increase in the distance from the furrow, particularly at the sampling points P7 to P9. It increased in 2017 within furrows and, even at the center of the raised bed at sampling point P7 to P9. It further decreased in 2018 following the same pattern of 2017. Since urea chemical fertilizers had been applied to the furrows, it led to a reduction of the soil pH. It has been reported that the use of the urea fertilizer decreases soil pH because of nitrification and acidification processes and the release of H⁺ by plant roots (Benbi and Brar, 2009; Czarnecki and During, 2015; Liang et al., 2012).

Table 3

Yield traits of banana under different treatments.

Treatments	Bunch weight (kg)	Bunch length (cm)	Bunch width (cm)	Length of longest finger in 3 rd hand (cm)	Width of longest finger in 3 rd hand (cm)	No. of hands/bunch	Stem girth (cm)
50 % ASMD	21.92 a	63.60 a	34.50 a	12.50 a	2.80 a	10.60 a	67.10 a
40 % ASMD	19.25 b	62.60 b	33.30 b	12.30 b	2.60 b	9.30 b	63.60 b
30 % ASMD	16.80c	57.40c	32.70 b	11.00c	2.33c	9.10 bc	56.20c
Farmer practices	16.75c	52.10 d	31.00c	10.80 d	2.30c	8.00c	50.10 d
LSD	0.2359	0.1155	0.3127	0.0816	0.0449	0.4714	0.4082

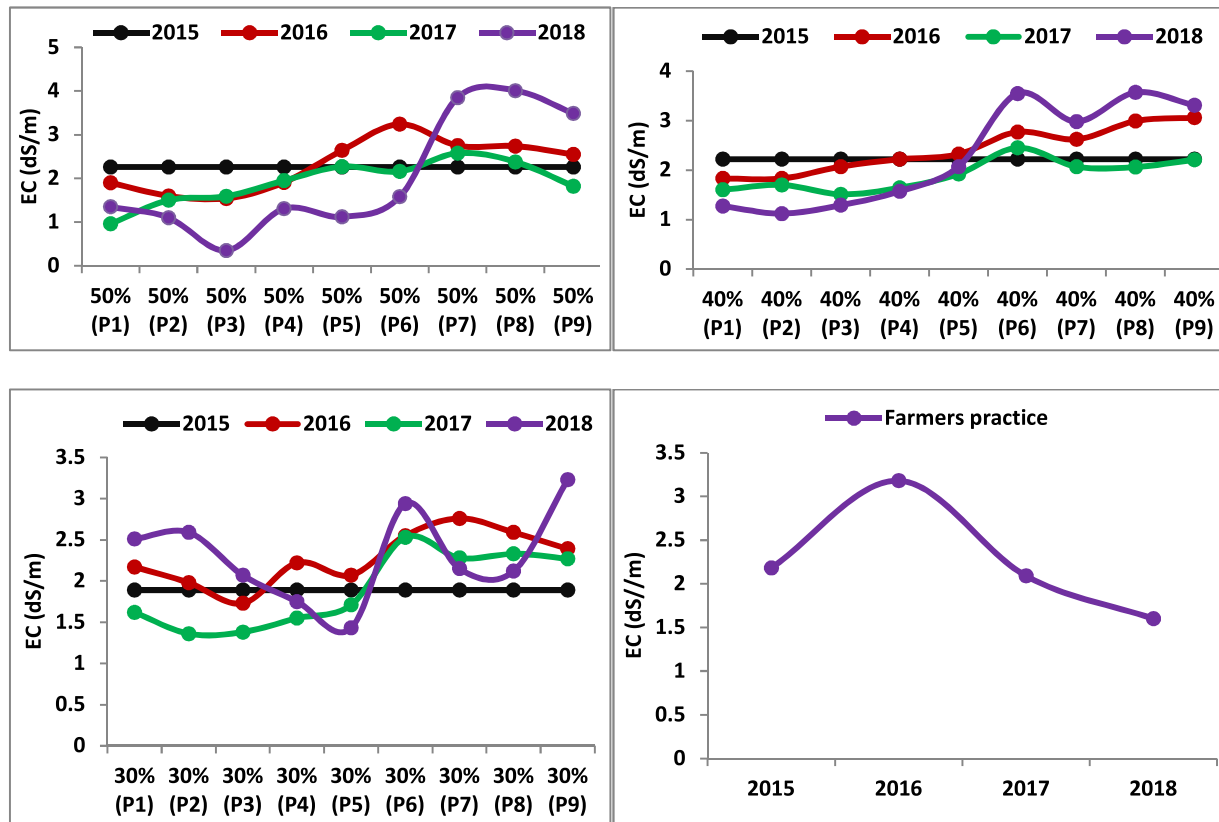


Fig. 5. Soil EC over different years at different ASMD. Note that P1–P9 denote soil sampling points at depths P1 (0–0.15 m), P2 (0.15–0.30 m), P3 (0.30–0.45 m), P4 (0.45–0.60 m), P5 (0.60–0.75 m), P6 (0.75–0.90 m), P7 (0.90–1.05 m), P8 (1.05–1.20 m), and P9 (1.20–1.35 m).

Similarly, Fig. 7 indicates sodium adsorption ratio (SAR) across different years, ASMD levels and under farmer practices. The soil SAR during the first year was 4.10–4.68. A slight increase in soil SAR was observed within the furrows, while a more pronounced increase occurred with greater distance from the furrows, particularly at sampling points P5 to P9. It was reported that when irrigation water has a high residual sodium carbonate (RSC), the calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions tend to precipitate, leading to an increase in soil sodium adsorption ratio (SAR) (Prasad et al., 2001). As the residual sodium carbonate (RSC) of the groundwater used ($\text{RSC} = 3.90$) exceeded the acceptable threshold, salt accumulation led to an increase in soil SAR. Prolonged use of this irrigation water with its elevated RSC, increased soil sodium concentrations, thereby further raising the SAR (Murtaza et al., 2021). Such types of soil could be managed by applying the excess irrigation with good quality water and adopting appropriate cropping patterns (Ashraf and Saeed, 2006). High rainfall can also help manage the soil salinity. For example, due to a high rainfall on August 30, 2017 (86 mm), the furrows and raised beds were submerged, resulting in salt leaching and declining in the soil SAR in 2017, even at the center of the raised beds. On contrary, during 2018, owing to drought

condition, entire water requirement of banana was met through irrigation, leading to salt accumulation on the raised beds, particularly at sampling points P7 to P9. The soil SAR remained within the safe limit of ≤ 13 . This shows that the adaptation of banana furrow plantation with alternative irrigation of canal and marginal groundwater may not deteriorate the soil health.

A comparison between the Exchangeable Sodium Percentage (ESP) of soil under different ASMD and farmer practices is shown in Fig. 8. The values of the soil ESP during the first year of banana cropping ranged from 4.56 to 5.35. However, a slight increase in the soil ESP values was observed within furrows in 2016, while it increased considerably at sampling points P5 to P9. Choudhary et al., (2019) adopting alternative irrigation of canal with sodic water ($\text{EC}: 1.40 \text{ dS/m}$, $\text{SAR}: 14.9$ and $\text{RSC}: 10.1$) over a period of 16 years under wheat-cotton cropping cycle found an increase in the soil ESP from 3.4 to 10.6. This huge increase in ESP may be due to the facts that they collected and analyzed soil samples just from the top layer, i.e. at 0–15 m, where the maximum salts deposition occurred, leading to higher ESP. However, in the current study, the soil samples were analyzed up to 0.45 m depths. Moreover, the irrigation water they used had higher SAR and RSC values than that used in the

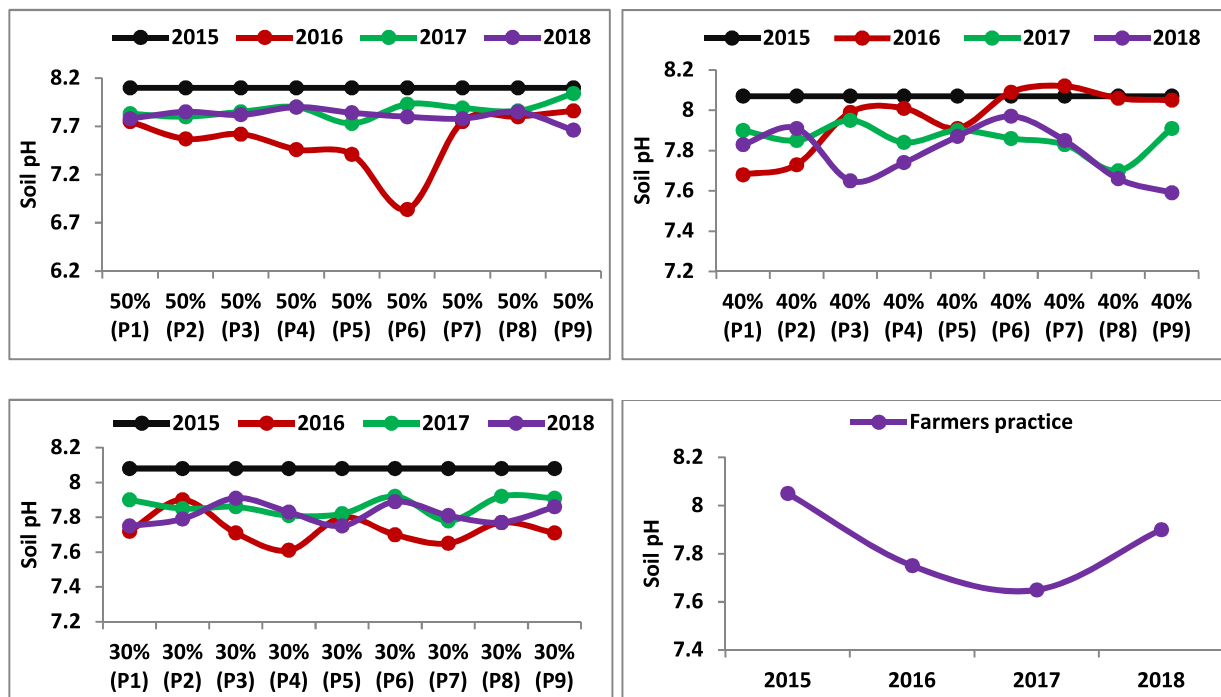


Fig. 6. Soil pH over different years at different ASMD. Note that P1-P9 denote soil sampling points at depths P1 (0–0.15 m), P2 (0.15–0.30 m), P3 (0.30–0.45 m), P4 (0.45–0.60 m), P5 (0.60–0.75 m), P6 (0.75–0.90 m), P7 (0.90–1.05 m), P8 (1.05–1.20 m), P9 (1.20–1.35 m).

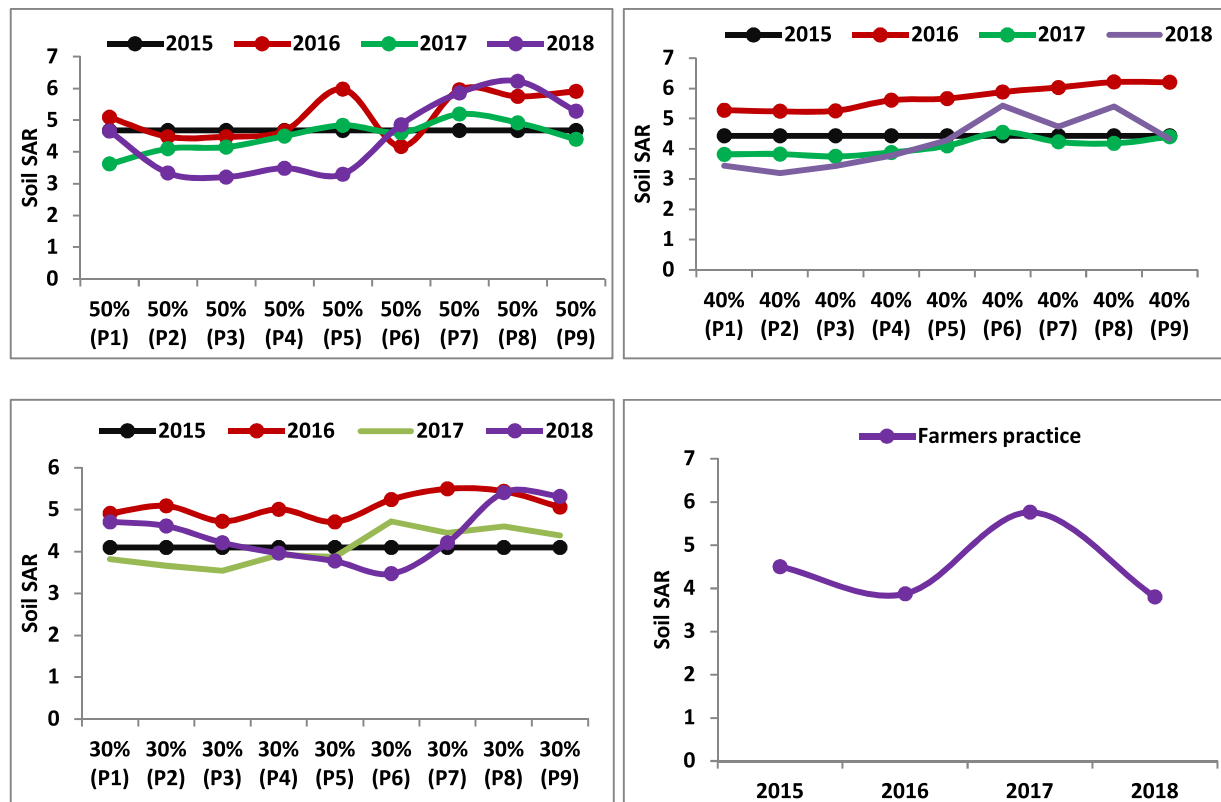


Fig. 7. Soil SAR over different years at different ASMD. Note that P1-P9 denote soil sampling points at depths P1 (0–0.15 m), P2 (0.15–0.30 m), P3 (0.30–0.45 m), P4 (0.45–0.60 m), P5 (0.60–0.75 m), P6 (0.75–0.90 m), P7 (0.90–1.05 m), P8 (1.05–1.20 m), and P9 (1.20–1.35 m).

current study. During 2018, due to drought, entire water requirement of banana was met through irrigation, leading to salt accumulation on the raised beds, particularly at sampling points P7 to P9. However, the ESP

did not exceed the permissible limit ($ESP \leq 15$). The soil ESP values under farmer practices declined 19 % in 2018 as compared to the initial value of 2015. This may be attributed to a higher amount of canal water

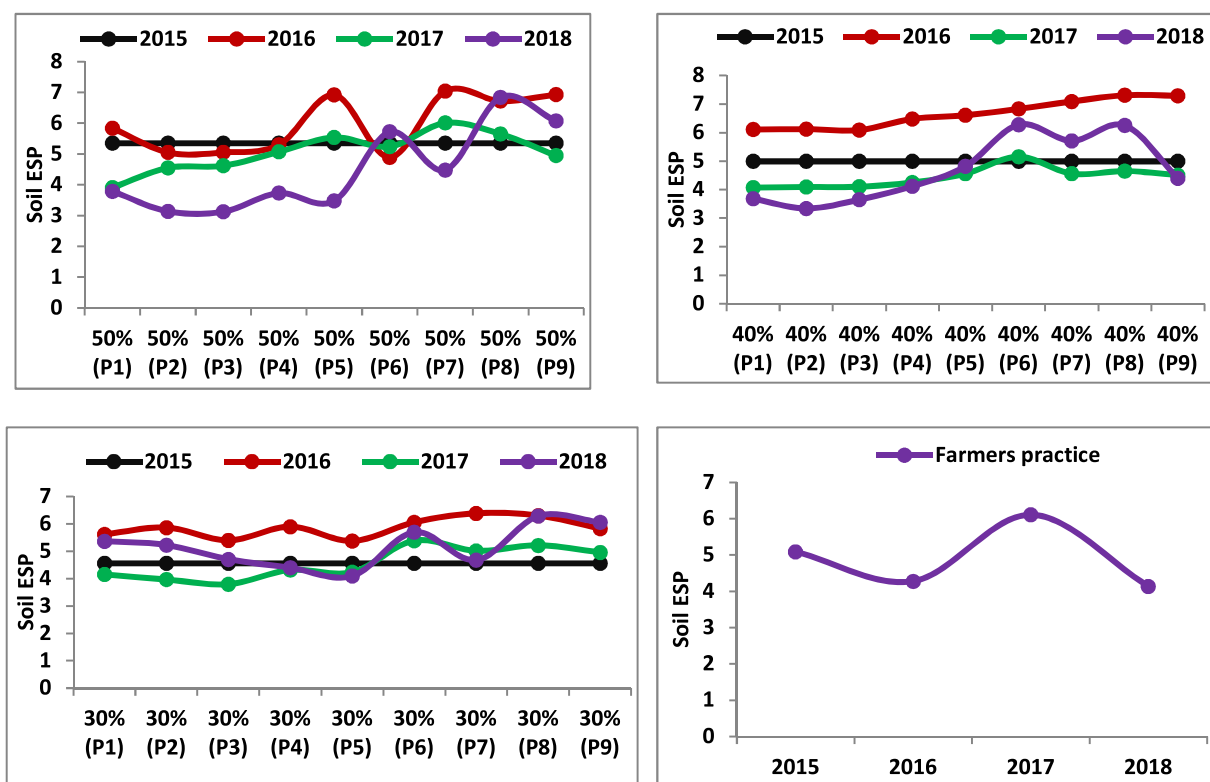


Fig. 8. Soil ESP over different years at different ASDM. Note that P1-P9 denote soil sampling points at depths P1 (0–0.15 m), P2 (0.15–0.30 m), P3 (0.30–0.45 m), P4 (0.45–0.60 m), P5 (0.60–0.75 m), P6 (0.75–0.90 m), P7 (0.90–1.05 m), P8 (1.05–1.20 m), and P9 (1.20–1.35 m).

application.

4. Conclusions

Furrow planting and different levels of available soil moisture depletion (ASMD) had a significant impact on water application, yield, yield components, and water use efficiency (WUE) in banana cultivation. A strong positive linear correlation ($R^2=0.78$) was observed between annual water application and yield, highlighting the potential of varying ASMD levels for optimizing banana production under furrow planting. Under water-scarce conditions, banana can be successfully cultivated on furrows, achieving substantial water savings of up to 57 % compared to conventional farmer practices. Additionally, irrigation scheduling at 50 % ASMD saved 12–23 % more water compared to 30 % and 40 % ASMD levels. However, transplanting banana corms on the edge of furrows often results in suckers emerging at the top of the raised beds, which may lead to non-productive yields in the range of 15–17 %. Therefore, sucker selection for the next mother plant should be done carefully to avoid further sucker development for ratoon crops on the top of the raised bed. Although the use of marginal groundwater in combination with canal water under furrow planting conditions led to a slight increase in soil salinity, it did not exceed the critical threshold. Banana yield traits were negatively affected by lower ASMD levels, whereas 50 % ASMD effectively mitigated the adverse effects of conjunctive irrigation and improved both yield and yield-related traits. Overall, cultivating bananas on furrows with alternate irrigation using canal and marginal groundwater at 50 % ASMD is an effective strategy to enhance water savings, increase productivity, and improve WUE, while maintaining soil salinity within safe limits. This approach presents a sustainable solution for banana production in water-scarce regions.

Funding

This research was supported by the International Center for

Agricultural Research in the Dry Areas (ICARDA) under Agreement No. 200058 and BUS No. 200157, with funding provided by the United States Department of Agriculture (USDA).

CRediT authorship contribution statement

Nazar Gul: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation. **Muhammad Ashraf:** Methodology, Formal analysis, Conceptualization. **Hafiz Abdul Salam:** Software, Formal analysis, Data curation. **Majid Taie Semiromi:** Writing – review & editing, Supervision.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to enhance the readability of the revised sections. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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.

Acknowledgements

The authors gratefully acknowledge the support of the International Center for Agricultural Research in the Dry Areas (ICARDA) for facilitating this research. We appreciate ICARDA's technical and administrative assistance throughout the project.

Data availability

Data will be made available on request.

References

- Abd El-Kader, A.M., Saleh, M.M.S., Ali, M.A., 2006. Effect of soil moisture levels and some anti transpirants on vegetative growth, leaf mineral content, yield, and fruit quality of Williams banana plants. *J. Appl. Sci. Res.* 2 (12), 1248–1255.
- Ahmad, R., Jamil, S., Shahzad, M., Zorb, C., Irshad, U., Khan, N., Younas, M., Khan, S.A., 2017. Metabolic profiling to elucidate genetic elements due to salt stress. *Clean. Soil Air Water* 45, 1600574.
- Akbar, F., Khan, G.D., Akbar, F., Ullah, W., Khan, S., 2014. Characterization of Salinity and Sodicity Levels in Groundwater and Their Impact on the Yield of Banana (Musa Indicata) in District Lasbela. *J. Nat. Sci. Res.* 4 (7), 12–16.
- Al-Harthi, K., Al-Yahyai, R., 2009. Effect of NPK fertilizer on growth and yield of banana in Northern Oman. *J. Hortic. For.* 1 (8), 160–167.
- Almeida, A.M.M., Gomes, V.F.F., Filho, P.F.M., Lacerda, C.F., Freitas, E.D., 2016. Influence of salinity on the development of the banana colonised by arbuscular mycorrhizal fungi. *Rev. Cienc. Agron.* 47 (3), 421–428.
- Amayreh, J., Al-Abed, N., 2005. Developing crop coefficients for field-grown tomato (*Lycopersicon esculentum* Mill.) under drip irrigation with black plastic mulch. *Agric. Water Manag* 73, 247–254.
- Ashraf, M., Saeed, M.M., 2006. Effect of improved cultural practices on crop yield and soil salinity under relatively saline groundwater applications. *Irrig. Drain. Syst.* 20, 111–124.
- Basso, L.H., Teixeira, A.H.D.C., Filho, J.M.P.L., Silva, J.A.M.E., Silva, E.E.G.D., Ramos, C.M.C., Sediya, G.C., 2004. Guidelines for irrigation scheduling of banana crop in Sao Francisco valley, Brazil. *Rev. Bras. De Frutic. Jaboticabal* 26 (3), 464–467.
- Benbi, D.K., Brar, J.S., 2009. A 25-year record of carbon sequestration and soil properties in intensive agriculture. *Agron. Sustain. Dev.* 29 (1), 257–265.
- Benjamin, J.G., Havis, H.R., Ahuja, L.R., Alonso, C.V., 1994. Leaching and water flow patterns in every-furrow and alternate-furrow irrigation. *Soil Sci. Soc. Am. J.* 58, 1511–1517.
- Capra, A., Consoli, S., Sicolone, B., 2008. Water management strategies under deficit irrigation. *J. Agric. Eng.* (4), 27–34.
- Choudhary, O.P., Bhalla, M., Sharma, S., Sharda, R., Mavi, M.S., 2019. Long-term impact of cyclic use of sodic and canal water for irrigation on soil quality and wheat yield in cotton-wheat cropping system. *J. Indian Soc. Soil Sci.* 67 (1), 34–43.
- Czarnecki, S., During, R.A., 2015. Influence of long-term mineral fertilization on metal contents and properties of soil samples taken from different locations in Hesse, Germany. *J. Soil* 1, 23–33.
- Devkota, M., Gupta, R.K., Martius, C., Lamers, J.P.A., Devkota, K.P., Sayre, K.D., Vlek, P. L.G., 2015. Soil salinity management on raised beds with different furrow irrigation modes in salt-affected lands. *Agric. Water Manag.* 152, 243–250.
- Ejaz, K., Ashraf, M., 2023. Water Productivity and Economic Feasibility of Growing Rice and Wheat on Beds in Central Punjab, Pakistan. *Pakistan Council of Research in Water Resources (PCRWR)*, Islamabad, p. 53.
- El-Shafei, A.A., Mattar, M.A., 2022. Irrigation Scheduling and Production of Wheat with Different Water Quantities in Surface and Drip Irrigation: Field Experiments and Modelling Using CROPWAT and SALTMed. *Agronomy* 12 (7), 1488.
- FAOSTAT., 2018. Food and Agricultural Organization (FAO). Retrieved from: (<http://www.fao.org/faostat/en/#data>).
- Geerts, S., Dirk, R., 2009. Deficit irrigation as an on farm strategy to maximize crop productivity in dry area. *Agric. Water Manag.* 96, 1275–1284.
- Gul, N., Salam, H.A., Ashraf, M., 2023. Water requirements of banana and papaya under different water table depths and soil types in the Lower Indus Basin of Pakistan. *Irrig. Drain.* 1–18.
- Irfana, N.M., Sanaullah, N., Barkat, L.A., 2015. Economic Efficiency of Banana Production under Contract Farming in Sindh Pakistan. *J. Glob. Econ.* 3 (4), 1–5.
- Kaleem, F., Shabir, G., Aslam, K., Rasul, S., Manzoor, H., Shah, S.M., Khan, A.R., 2018. An overview of the genetics of plant response to salt stress: present status and the way forward. *Appl. Biochem. Biotechnol.* <https://doi.org/10.1007/s12010-018-2738-y>.
- Kang, S., Liang, Z., Pan, Y., Shi, P., Zhang, J., 2000. Alternate furrow irrigation for maize production in an arid area. *Agric. Water Manag* 45, 267–274.
- Khalifa, A.B.A., 2012. Comparison of surface and drip irrigation regimes for Banana (Musa AAA) cv. Grand Nain in Gezira, Sudan. A thesis submitted to the Sudan academy of sciences in fulfillment of the requirements for degree of master of science in agriculture (soil and water sciences).
- Liang, Q., Chen, H., Gong, Y., Fan, M., Yang, H., Lal, R., Kuzyakov, Y., 2012. Effects of 15 years of manure and inorganic fertilizers on soil organic carbon fractions in a wheat-maize system in the North China Plain. *Nutr. Cycle Agroecosyst* 92, 21–33.
- Machado, R.M.A., Serralheiro, R.P., 2017. Soil Salinity: Effect on Vegetable Crop Growth. Management Practices to Prevent and Mitigate Soil Salinization. *Horticulturae* 3 (2), 30.
- Mahamed, M.B., Sarobol, Ed, Hordof, T., Kaewrueng, S., Verawudh, K., 2011. Effects of Soil Moisture Depletion at Different Growth Stages on Yield and Water Use Efficiency of Bread Wheat Grown in Semi Arid Conditions in Ethiopia. *Kasetsart J. (Nat. Sci.)* 45, 201–208.
- Mahmoud, L.M., Dutt, M., Shalan, A.M., El-Kady, M.E., El-Boray, M.S., Shabana, Y.M., Grosse, J.W., 2020. Silicon nanoparticles mitigate oxidative stress of in vitro-derived banana (Musa acuminata ‘Grand Nain’) under simulated water deficit or salinity stress. *South Afr. J. Bot.* 132, 155–163.
- Memon, N., Memon, K.S., Anwar, R., Ahmad, S., Nafees, M., 2010. Status and response to improved NPK fertilization practices in banana. *Pak. J. Bot.* 42 (4), 2369–2381.
- Murtaza, G., Rehman, M.Z., Qadir, M., Shehzad, M.T., Zeeshan, N., Ahmad, H.R., Farooqi, Z.R., Naidu, R., 2021. High residual sodium carbonate water in the Indian subcontinent: concerns, challenges and remediation. *Int. J. Environ. Sci. Technol.* 18 (1), 1–16.
- Panhwar, M.Y., Panhwar, S., Keerio, H.A., Khokhar, N.H., Shah, S.A., Pathan, N., 2022. Water quality analysis of old and new Phuleli Canal for irrigation purpose in the vicinity of Hyderabad, Pakistan. *Water Pract. Technol.* 17 (2), 529–536.
- Panigrahi, N., Thompson, A.J., Zubezu, S., Knox, J.W., 2021. Identifying opportunities to improve management of water stress in banana production. *Sci. Hortic.* 276 (27), 109735.
- Ploetz, R.C., Kema, G.H., Ma, L.J., 2015. Impact of diseases on export and smallholder production of banana. *Annu. Rev. Phytopathol.* 53, 269–288.
- Prasad, A., Kumar, D., Singh, D.V., 2001. Effect of residual sodium carbonate in irrigation water on the soil sodication and yield of palmarosa (*Cymbopogon martinii*) and lemongrass (*Cymbopogon flexuosus*). *Agric. Water Manag.* 50 (3), 161–172.
- Rao, M.I., Salam, H.A., Gul, N., Ashraf, M., 2019. Water requirements of banana and papaya in Sindh. *Pak. Coun. Res. Water Resour. (PCRWR)* 68.
- Rawat, K.S., Singh, S.K., Gautam, S.K., 2018. Assessment of groundwater quality for irrigation use: a peninsular case study. *Applied Water. Science* 8, 233.
- Robinson, J.C., Nel, D.J., 1986. The influence of planting date, sucker selection, and density on yield and crop-timing of bananas (cultivar ‘Williams’) in the Eastern Transvaal. *Sci. Hortic.* 29 (4), 347–358.
- Sheikh, A.A., Ashraf, M., 2009. Use of low quality groundwater for sustainable crop production: agriculture with low quality groundwater. *LAP Lambert Acad. Publ.* 72.
- Wang, F.X., Wu, X.X., Shock, C.C., Chu, L.Y., Gu, X.X., Xue, X., 2011. Effects of drip irrigation regimes on potato tuber yield and quality under plastic mulch in arid Northwestern China. *Field Crops Res.* 122, 78–84.
- Xu, D., Li, Y., 2007. Review on advancements of study on precision surface irrigation system. *J. Hydraul. Eng.* 2007 (38), 529–537.
- Zhang, T., Zou, Y., Kisekka, I., Biswas, A., Cai, H., 2021. Comparison of different irrigation methods to synergistically improve maize's yield, water productivity and economic benefits in an arid irrigation area. *Agric. Water Manag* 243, 106497.