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# 春汇/夏浇灌溉制度对盐碱土壤水盐运移及向日葵水分利用的影响

赵一波[1]，杨 威[1]，屈忠义[1,2*]，王丽萍[1]，高晓瑜[1]，张如鑫[1]，任恩良[2]
（1.内蒙古农业大学，呼和浩特 010000；2.内蒙古科技大学，内蒙古 包头 014010）

摘 要：【目的】确定河套灌区向日葵适宜的节水控盐春汇—夏浇灌溉制度，提高灌区农业灌溉水资源利用效率。【方法】设置非生育期畦灌（春汇 S，灌溉定额 135、95 mm）和作物生育期滴灌（夏浇 W，灌溉定额 135、100、68 mm）田间小区试验，研究了不同春汇/夏浇条件下的向日葵农田土壤水盐分布规律、盐分淋洗效果、作物生长特征及水分利用效率。【结果】S135W135 处理下的整个生育期内平均土壤含水率较高，为 17.10%，为饱和含水率的 75.53%；S95W135 处理下的土壤含水率变异系数最小，为 22.40%。S135、S95 处理下的土壤脱盐率分别介于 50.50%~32.64%、38.87%~21.87%，春汇后 S135 和 S95 处理下的 0~80 cm 土层的土壤盐分量无显著差异；S135W100、S95W135 处理下的灌溉水淋洗深度较高，脱盐效果较好，土壤脱盐率均显著高于除 S135W135 处理以外的其他处理，0~80 cm 土层脱盐率为 40.77%和 33.37%，较 S135W135 处理分别提高 68.39%、37.86%。S95W135、S135W100 处理下的地上部干物质量显著大于其他处理，相比 S135W135 处理增加 10.55%和 9.94%。S135W100 处理的作物水分利用效率最高（21.59%），较 S135W135 处理显著增加 13.03%。【结论】常规春汇水量减少 30%（95 mm）与夏浇滴灌（135 mm）是河套灌区向日葵农田适宜的灌溉制度。

关 键 词：河套灌区；节水灌溉；水盐运移；水分利用效率；脱盐率
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## 0 引 言

【研究意义】农业灌溉用水量占全球淡水资源消耗总量的 90%，内蒙古河套灌区的灌溉面积达 57 万 $hm^2$[1]，其中 50%的灌溉土地受到土壤盐渍化影响。灌区地下微咸水资源丰富，微咸水灌溉是解决淡水资源供需矛盾的有效手段。对有限的水资源进行合理分配以科学调控土壤水盐、提高水资源利用效率对灌区农业的可持续发展至关重要。【研究进展】以往研究主要集中于作物生育期淡水/微咸水交替灌溉[2]、井渠双灌的灌水量及方式研究等[3-4]。合理的咸淡水联合灌溉在稳产的前提下可有效节约淡水资源。河套灌区土壤易发生盐碱化，仅依靠作物生育期进行灌溉难以控制土壤盐分，在非生育期通过地面灌溉集中淋洗（春汇、秋浇）是灌区有效的水盐管理制度[5]。杨鹏年等[6]对新疆不同盐渍化程度的农田开展春灌定额研究，结果表明，中、重度盐渍化土壤的适宜定额为 1 800~2 250 $m^3/hm^2$，无法直接指导河套灌区的科学灌溉。李金刚等[7]在河套灌区盐碱地利用微咸水膜下滴灌的研究发现，春汇灌溉 225 mm 黄河水后各土层盐分量会降低 21.46%。Liu 等[8]发现，生育期使用微咸水进行膜下滴灌，非生育期采用 150 mm 灌溉定额淋洗，土壤盐分可以淋洗到 60 cm 以下土层。Phocaides 等[9]、明广辉等[10]推荐在作物收获后对盐分进行集中淋洗。Pang 等[11]研究表明，使用塑料薄膜覆盖土壤表面可以减少蒸发量和浅层土壤盐分量，提高水资源利用效率。【切入点】河套灌区灌溉制度及节水控盐机理的研究集中在作物类型[12]、生育期滴灌[13]、秋浇[14]等方面，生育期膜下滴灌协同春汇的灌水环节相互独立，土壤盐分分布的机制及盐分平衡规律仍不清楚。【拟解决的关键问题】鉴于此，本研究聚焦于不同春汇/夏浇灌溉制度下的土壤水盐分布和盐分平衡，以寻求作物高产、灌水利用效率提高的河套灌区科学合理的向日葵春汇/夏浇协同灌溉制度。

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作者简介：赵一波（1999-），女。博士研究生，主要从事盐碱地改良与水资源高效利用研究。E-mail: 1352236820@qq.com
通信作者：屈忠义（1969-），男。教授，博士生导师，主要从事节水理论与农田水土环境效应研究。E-mail: quzhongyi@imau.edu.cn

表 2　2022 年生育期 0~40 cm 土层的土壤含水率

Tab.2　Soil moisture content of 0-40 cm soil layer during crop growth period in 2022　　%

| 处理 | S135W135 | S135W100 | S135W68 | S95W135 | S95W100 | S95W68 |
| --- | --- | --- | --- | --- | --- | --- |
| 范围 | 9.41~23.63 | 8.05~20.80 | 6.84~21.16 | 7.70~18.96 | 7.11~20.54 | 6.16~17.32 |
| 平均值 | 17.06 | 15.67 | 13.80 | 14.89 | 13.72 | 12.74 |
| 中位数 | 17.62 | 16.47 | 13.53 | 16.00 | 15.26 | 13.09 |

## 2.2 春汇/夏浇灌溉制度对土壤盐分的影响

### 2.2.1 春汇/夏浇灌溉制度对土壤盐分的影响

图 3 为不同春汇/夏浇灌溉制度下土壤盐分量剖面分布。春季气温回升，冻土层通融，土壤表层反盐，春汇前土壤盐分有明显的积聚现象，平均含盐量为 5.74 g/kg；试验区春汇较周边农田稍晚，被淋洗到地下水中的盐分随地下水位上升被带回深层土壤，因此土壤盐分随着土层深度的增加先降低后增加，在 40 cm 土层出现极小值。春汇后，0~40 cm 土层含盐量明显降低，S135、S95 处理下的含盐量分别达到 2.65 g/kg 和 3.72 g/kg；40~80 cm 土层淋洗效果减弱，S135、S95 处理下的含盐量分别为 4.12 g/kg 和 4.50 g/kg，各处理无显著差异。

夏浇后土壤含盐量均较春汇后出现了不同程度的增加。0~40 cm 土壤含盐量增加了 0.68 g/kg，40~80 cm 土壤含盐量增加了 0.35 g/kg，盐分呈向上迁移趋势。夏浇后，S95W135 处理平均含盐量显著小于其他处理，为 2.59~3.78 g/kg；0~80 cm 土层土壤盐分移动最为缓慢。

图 3　春汇和夏浇制度下土壤盐分剖面分布

Fig.3　Spatial and temporal distribution of soil salinity profiles under spring and summer watering systems

### 2.2.2 不同灌溉制度对土壤脱盐率的影响

脱盐率可直观表述土壤脱盐效果，评价灌溉脱盐的有效性。表 3 为不同春汇/夏浇灌溉制度下的向日葵全生育周期不同土层脱盐率。春汇后，0~80 cm 土层土壤脱盐率与灌水量呈正相关，135、95 mm 灌溉定额下土壤脱盐率分别为 50.50%~32.64%、38.87%~21.87%。各处理全年平均脱盐率受春汇、夏浇的共同影响，由大到小依次为 S135W100、S95W135、S95W100、S135W135、S135W68、S95W68 处理；春汇将盐分淋洗至深层土壤后使用微咸水滴灌，生育期各次灌溉后土壤积盐率如表 3 所示。滴灌水量为 100 mm 时积盐率最小，土壤反盐抑制效果最好；S95W68 处理下的春汇淋洗不充分，滴灌对较高盐分的淋洗作用不明显，土壤含盐量居高不下，使滴灌积盐率趋近于 0。土层深度与土壤脱盐率呈负相关，0~20 cm 土壤脱盐率最高，为 39.71%；20~40 cm 土壤脱盐率为 27.71%；40~80 cm 土壤脱盐率为 21.35%。S135W100、S95W135 处理下的淋洗深度较深，脱盐效果较好，0~80 cm 土层的土壤脱盐率分别介于 48.84%~34.68%、49.51%~18.24%。

## 2.3 不同春汇/夏浇灌溉制度对向日葵生长及水分利用效率的影响

### 2.3.1 向日葵叶面积指数

叶片是作物进行光合作用的主要场所，是决定作物干物质累积和产量的关键因素之一，作物群体的叶面积大小通常使用 *LAI* 表示。图 4 为向日葵各生育期

不同灌水制度下的 *LAI*，各处理向日葵 *LAI* 迅速增长后稳定下降，呈单峰曲线变化。营养生长阶段向日葵叶片生长较快，现蕾期 S135W100、S135W68、S95W135、S95W100、S95W68 处理下的 *LAI* 增长率分别为 297.60%、276.67%、157.99%、197.90%、213.52%、225.55%；开花后期 *LAI* 达到最大，S135W100、S95W135 处理分别为 10.19、9.78，较 S135W135 处理显著增加 7.94、3.54%。开花末期，向日葵由营养生长转为生殖生长阶段，叶片生长速率逐渐转为负值，*LAI* 趋于稳定并开始缓慢下降。灌浆期结束时 S135W100、S95W135 处理下的 *LAI* 显著高于其他处理。

表 3 春汇/夏浇灌溉制度下 0~80 cm 土层的土壤脱盐率

Tab.3 Soil desalting rate in 0-80 cm soil layer under spring sink/summer irrigation system

| 处理 | 土层/cm | 春汇脱盐率/% | 生育期各次夏浇脱盐率/% | | | | | 全年脱盐率/% |
|---|---|---|---|---|---|---|---|---|
| | | | 幼苗期 | 现蕾期 | 开花期 | 灌浆期 | 平均值 | |
| S135W135 | 0~20 | 51.29 | -48.33 | 18.44 | -36.16 | 17.75 | -12.07 | 39.50 |
| | 20~40 | 24.72 | -23.12 | 8.41 | -12.24 | -2.56 | -7.38 | 12.28 |
| | 40~60 | 38.49 | 12.44 | -4.07 | -5.50 | 5.25 | 2.03 | 20.82 |
| | 60~80 | 42.90 | 26.50 | -10.26 | 1.57 | -6.90 | 2.73 | 24.24 |
| | 平均值 | 39.35 | -8.13 | 3.13 | -13.08 | 3.38 | -3.67 | 24.21ab |
| S135W100 | 0~20 | 54.10 | -7.31 | 1.42 | -15.75 | 14.95 | -1.67 | 48.84 |
| | 20~40 | 69.70 | -32.32 | 7.00 | 12.24 | -8.94 | -5.50 | 43.12 |
| | 40~60 | 31.76 | 16.20 | 3.11 | 3.89 | -14.24 | 2.24 | 36.42 |
| | 60~80 | 46.42 | 18.95 | 3.73 | -2.39 | -33.12 | -3.21 | 34.68 |
| | 平均值 | 50.50 | -1.12 | 3.82 | -0.50 | -10.33 | -2.04 | 40.77a |
| S135W68 | 0 ~ 20 | 51.35 | -25.72 | 6.49 | -5.99 | -4.80 | -7.50 | 35.81 |
| | 20 ~ 40 | 53.95 | -31.66 | 21.24 | -9.68 | -14.11 | -8.55 | 13.56 |
| | 40 ~ 60 | 2.42 | 2.58 | -9.99 | 1.02 | -25.32 | -7.93 | 14.71 |
| | 60 ~ 80 | 22.85 | 4.14 | -19.40 | 4.63 | -29.80 | -10.11 | 13.01 |
| | 平均值 | 32.64 | -12.66 | -0.41 | -2.50 | -18.51 | -8.52 | 19.27b |
| S95W135 | 0~20 | 52.81 | -22.27 | 40.25 | 11.09 | -66.18 | -9.27 | 49.51 |
| | 20~40 | 41.64 | -73.15 | 1.71 | 20.28 | -12.44 | -15.90 | 40.13 |
| | 40~60 | 28.20 | -25.15 | 19.67 | 14.33 | -48.90 | -10.01 | 25.60 |
| | 60~80 | 22.69 | 8.82 | 13.37 | -19.22 | -30.78 | -6.95 | 18.24 |
| | 平均值 | 36.34 | -27.93 | 18.75 | 6.62 | -39.57 | -10.53 | 33.37ab |
| S95W100 | 0~20 | 49.58 | 11.52 | -26.37 | 18.90 | -3.00 | 0.26 | 41.69 |
| | 20~40 | 49.06 | 32.54 | -47.99 | 20.06 | 1.23 | 1.46 | 35.80 |
| | 40~60 | 49.63 | 41.53 | -65.27 | 18.76 | -6.16 | -2.78 | 28.80 |
| | 60~80 | 7.23 | 25.15 | -24.92 | 11.73 | -13.98 | -0.50 | 8.37 |
| | 平均值 | 38.87 | 27.68 | -41.14 | 17.36 | -5.48 | -0.39 | 28.66ab |
| S95W68 | 0~20 | 25.88 | -10.90 | -11.42 | 12.02 | -5.09 | -3.85 | 22.93 |
| | 20~40 | 21.70 | 10.88 | -9.24 | 27.31 | -29.08 | -0.03 | 21.38 |
| | 40~60 | 14.49 | 14.64 | -11.35 | 9.00 | -2.52 | 2.44 | 26.47 |
| | 60~80 | 25.39 | 32.57 | -18.72 | 11.19 | -24.93 | 0.03 | 4.88 |
| | 平均值 | 21.87 | 11.80 | -12.68 | 14.88 | -15.41 | -0.35 | 18.91b |

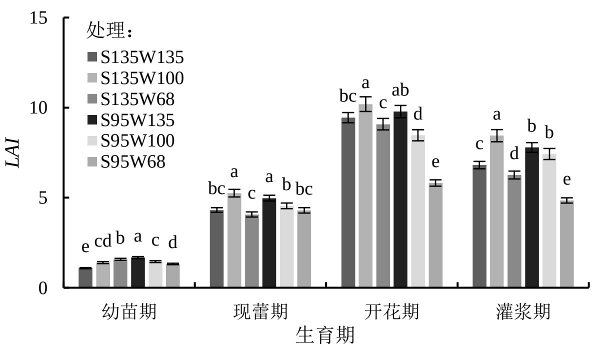


图 4 春汇/夏浇灌溉制度下向日葵 *LAI* 响应差异

Fig.4 Response difference of sunflower leaf area index under spring/summer irrigation system

### 2.3.2 向日葵产量和水分利用效率

表 4 为不同春汇/夏浇灌水制度下的向日葵产量与水分利用效率。S95W135、S135W100 处理下的向日葵地上部干物质量、产量显著大于其他处理，地上部干物质量相较于 S135W135 处理增大了 10.55%和 9.94%；S95W135 处理向日葵产量分别较 S135W135、S135W100、S135W68、S95W100、S95W68 处理增加 16.12%、2.25%、33.47%、25.18%、56.53%；S95W68 处理下的产量仅为 4 251.30 kg/hm$^2$。

S135W100 处理下的水分利用效率最高，为 21.59 kg/（mm·hm$^2$），水分利用效率由大到小依次为 S135W100、S95W135、S95W100、S135W135、S135W68、S95W68 处理，其中 S135W100、S95W135 处理相对较高，分别相比 S135W135 处理增加了 11.96%和 7.86%。

表 4 向日葵产量、耗水量与水分利用效率

Tab.4 Yield, water consumption and water use efficiency of sunflower

| 处理 | 百粒质量/g | 地上部干物质量/(kg·hm$^{-2}$) | 产量/(kg·hm$^{-2}$) | 耗水量/mm | 水分利用效率/(kg· mm$^{-1}$·hm$^{-2}$) |
|---|---|---|---|---|---|
| S135W135 | 18.86a | 1 335.80b | 5 731.14b | 300.08b | 19.10b |
| S135W100 | 19.47a | 1 468.64a | 6 508.35a | 301.49b | 21.59a |
| S135W68 | 17.37b | 1 103.46d | 4 986.02d | 295.81b | 16.86c |
| S95W135 | 19.89a | 1 476.72a | 6 654.77a | 327.27a | 20.33a |
| S95W100 | 19.09a | 1 241.44c | 5 316.25c | 253.26c | 20.99a |
| S95W68 | 17.13b | 642.36e | 4 251.30e | 212.65d | 10.52d |

## 3 讨 论

盐分淋滤效率可以评价灌溉制度的优劣[19]。春汇灌溉定额越大，盐分向下迁移的效果越好，根层（0~40 cm）土壤脱盐率大于深层（40~80 cm）；春汇后土壤盐分随水分蒸发小幅度上升，但相较于春汇前仍处于脱盐状态。夏浇滴灌水量较小，淋洗效果有限，导致土壤盐分量增加[20]，结合春汇对盐分的淋洗作用，土壤仍处于脱盐状态。研究表明，滴灌定额较大且矿化度较低（0.4 g/L）时不会出现土壤次生盐渍化[21]；同时灌溉水量和次数的增加，土壤离子组成朝着良性方向发展[5]。农田本身是质地不同的层状土壤，盐分的运移因阻滞作用滞留在黏土夹层中[22]。本研究表明，135、100 mm 滴灌定额可使土壤盐分维持在较低水平。

土壤水盐运移与灌溉水量及灌水次数直接相关。膜下滴灌淋洗深度有限，0~40 cm 土层盐分变化幅度大，深层土壤盐分变化缓慢；表层土壤在生育后期产生盐分累积。灌水量较大、灌水次数多的处理下的土壤含水率基本高于灌水量较小、灌水次数较少的处理，水分携带盐分在土壤蒸发和灌溉的共同作用下运移，灌水量较大、灌水次数较多的处理土壤盐分在较稳定水平。在向日葵生育前期，灌溉次数相同，灌水量越大，土壤盐分下移距离和范围越广，盐分积累也越慢[23]。灌溉结束后，S95W135 处理下的土壤含水率较高，抑制土壤返盐效果显著。

S135W100 处理可以显著提高向日葵叶面积指数，向日葵苗期受低盐胁迫，作物自身调节促使根系发育较好[24-25]，生长期微咸水滴灌反而可产生一定的促进作用[26]；当灌溉定额到达一定水平后，增加灌溉水量对叶面积指数影响不大甚至有负向影响[27]。S135W100、S95W135 处理下的叶片凋萎速率低于其他处理，有利于作物干物质累积、增加籽粒产量。生育期滴灌频繁、水量过大会延长作物成熟进程，从而影响产量[28]；滴灌至充分供水有利于向日葵苗期同化物向叶片的分配转移，对作物地上部生物量累积、产量补偿显著[29]。

## 4 结 论

1）S135W100、S95W135 处理下的淋洗深度较深，脱盐效果较好，0~80 cm 土层土壤脱盐率为 31.60%和 29.28%，分别较 S135W135 处理提高了 30.53、20.96%。

2）春灌和夏浇协同改善了土壤水盐环境，轻度缺水灌溉不会使向日葵产量明显下降，且会提高水分利用效率。

3）综合考虑水分高效利用、节水控盐及作物稳产，春汇灌水定额 95 mm，夏浇滴灌定额 135 mm，向日葵全生育期灌水 6 次的灌溉制度是河套灌区适宜的向日葵灌溉制度。

（作者声明本文无实际或潜在利益冲突）

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# The effect of dual spring-summer irrigations on water and salt transport in saline- alkali soil and water use of sunflower in Hetao Irrigation District

ZHAO Yibo[1], YANG Wei[1], QU Zhongyi[1,2*], WANG Liping[1], GAO Xiaoyu[1], ZHANG Ruxin[1], REN Enliang[2]

(1. Inner Mongolia Agricultural University, Hohhot 010000, China;

2. Inner Mongolia University of Science and Technology, Baotou 014010, China)

**Abstract:**【Objective】A pre-planting border irrigation in spring coupled with a drip irrigation in summer during crops growth season is an irrigation technique to reduce soil salinity and safeguard crops growth in the salt-affected

soils in the Hetao Irrigation District in Inner Mongolia. This paper investigates the impact of different combinations of irrigation amounts in the dual irrigations on changes in soil water and salt, as well as the growth of sunflower. 【Method】The field experiment compared two spring (S) irrigation amounts: 95 mm and 135 mm, and three summer (W) irrigation amounts: 68, 100 mm and 135 mm. In each treatment, we measured the spatiotemporal changes in soil water and salt, as well as crop growth characteristics.【Result】① The soil water content in the S135W135 treatment was the highest among all treatments during the experimental period, with the average soil water content and saturation being 17.10% and 75.53%, respectively. The coefficient of variation of soil water content in the S95W135 treatment was 22.40%, the lowest among all treatments. ② Depending on the summer irrigation amount, the desalination rate of the 0-80 cm soil layer under S135 and S95 varied from 32.64% to 50.50% and 21.8% to 38.87%, respectively. Although the spring irrigation amounts did not significantly affect immediate post-irrigation salt content, the S135W100 and S95W135 combinations showed deeper leaching depths and higher desalination rates (40.77% and 33.37%, respectively) than other treatments. ③ Aboveground dry matter production was significantly higher in the S95W135 and S135W100 combinations than in other combinations, surpassing the S135W135 combination by 10.55% and 9.94%, respectively. The S135W100 combination achieved the highest water use efficiency at 21.59%, an increase of 13.03% compared to S135W135.【Conclusion】Reducing spring irrigation by 30% to 95 mm combined with a summer drip irrigation of 135 mm is the most efficient irrigation scheme for sunflower cultivation in the salt-affected soils in the Hetao Irrigation District.
**Key words:** Hetao Irrigation District; water-saving irrigation; water and salt transport; water use efficiency; desalinization rate

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# Effect of tillage and preceding crops on yield, water and fertilizer use efficiency of winter wheat

SHAO Yun[1], WANG Pengfei[1,2], AN Jiahui[1,2], MENG Ye[2], CHEN Haiqing[2], LIU Xuchen[2], LIU Zhandong[2], GAO Yang[2], MA Shoutian[2*]

(1. College of Life Sciences, Henan Normal University, Xinxiang 453000, China;

2. Institute of Farmland Irrigation, Chinese Academy of Agricultural Sciences, Xinxiang 453002, China)

**Abstract:**【Objective】Winter wheat in Northern China is often rotated with other crops which are expected to have a legacy effect. This paper aims to study the effect of different tillage and preceding crops on soil nutrients, yield and water use efficiency of the winter wheat.【Method】The field experiment consisted of a rotary tillage (RT) and a no-tillage (NT). The preceding crops for each tillage were corn (MW) or soybean (SW). During the experiment, we measured the changes in soil nutrients, soil water content, water and fertilizer use efficiency, and yield of the wheat. 【Result】For the same preceding crop, non-tillage increased soil water content compared to rotary tillage; under the same tillage, soil water content with maize as the preceding crop was higher than that with soybean as the preceding crop. In all treatments, soil nutrients decreased with soil depth. In the 0-50 cm soil layer, NTSW increased soil organic carbon, soil total nitrogen and nitrate nitrogen by 4.14%-13.54%, 35.51%-54.44% and 55.75%-112%, respectively, compared to the RTMW. RTMW had the highest available phosphorus and potassium in the 10-50 cm soil layer. The RTSW had the highest ammonium nitrogen in the 0-50 cm soil layer, 13.39%-20.64% more than that in the RTMW. The winter wheat in NTSW had the highest spike numbers, spikelet numbers, thousand-grain weight; and its grain yield was 16.62% higher than that of RTMW. The NTSW had the highest water use efficiency, 8.67% more than that of RTMW. The NTSW had the highest nitrogen, phosphorus and potassium use efficiency. 【Conclusion】The NTSW facilitated nutrient accumulation in the winter wheat field. It had the highest water and fertilizer use efficiency and increased grain yields the most as a result.
**Keywords:** rotary tillage; no-tillage; preceding crop; soil nutrient; water and fertilizer use efficiency; crop yield

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