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# Novel root zone soil water retention improves production with half the water in arid sands

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**Abstract**

Urbanization and industrial competition continue to reduce both farmland and available water for food production. Therefore, a new root zone soil water retention technology was modified to transform highly permeable soils into sustainable agriculture. This long-term drought avoidance technology was tested in two arid regions of Iraq, an arid country with declining irrigation water supplies. Manually installed U-shaped impermeable membrane troughs were compared with manually installed thin layers of partially decomposed organic matter. Tomato (*Solanum lycopersicum* L.) variety Dafnis (Syngenta Sweden) and spicy pepper (*Capsicum solanaceae* L.) crops were spring planted at Najaf and Diyala field sites during a 2-yr study. Soil water, temperature, and salinity were measured hourly, and compared to crop growth parameters, yields, and irrigation water use efficiency. Combined weights of four tomato and spicy pepper harvests were ($P$ = .05) 15 and 25% greater on sand soils equipped with root zone soil water retaining technology (SWRT) membranes and required 61% less irrigation water than crops grown on locally practiced organic matter-lined and no water retaining control soils. Spicy pepper production on SWRT membranes ($P$ = .05) increased 30% with concomitant ($P$ = .05) 125% greater irrigation water use efficiency (IWUE) than organic matter-layered and control soils at Diyala.

## 1 | INTRODUCTION

Diminishing agricultural lands are alluring farmers onto highly permeable soils planted with drought-resilient cultivars requiring excessive irrigation. More than half a century has passed since creative soil water conservation technologies were field tested to convert highly permeable soils into extended-term sustainable agriculture. Erickson et al. (1968) initiated these first attempts for row crops in the United States Garrity and Vejpas (1992) incorporated impermeable polymer liners into sands to maintain flooded rice (*Oryza sativa* L.) conditions between rainfall events in Indonesia.

Expanding global population and water conservation in upland soils are demanding more food with less water. Using HYDRUS 2D soil hydrology models, Guber et al. (2015) demonstrated how engineered subsurface water retention (SWRT) membranes improved root zone water storage for corn production on coarse-textured soils. Simultaneous large greenhouse lysimeter research by Smucker et al. (2016) announced significant production increases by corn (*Zea mays* L.), soybean [*Glycine max,* Merr.], and tomato

**Abbreviations:** EC, electrical conductivity; IWUE, irrigation water-use efficiency; NT, non-tilled controlled soil; SWRT, soil water retention technology; TCS, tilled control soil; TOM, tilled organic matter.

(*Solanum lycopersicum,* L.) production on sands equipped with root zone water retainers of irrigated sands. Kavdir et al. (2014) reported mechanical installation of new soil water retention technology (SWRT) membranes increased production and improved soil water conservation on sands in Michigan. Annually improved corn production by mechanically installed SWRT membranes, reported by Kavdir et al. (2014) was transported to Texas, where Van Pelt and Zobeck (2015) reported mechanically installed SWRT membranes provided drought mitigation, increasing Texas dryland cotton (*Gossypium hirsutum* L.) fibers 504%. Smucker et al. (2018). Reported membrane-transformed field sands doubled soil water contents of irrigated vegetable root zones, increasing crop production that enabled total payment of membrane installation costs within 2–3 yr.

Crop production in Middle Eastern arid sandy regions are among the most vulnerable to climate change and continue to experience irreversible water shortages (Elasha, 2010) causing substantial production losses (Al-Weshah, 2008; Fereres & Soriano, 2007). Dramatic declines in agricultural production by Iraq farmers, near the Tigris and Euphrates Rivers, exemplify how large river dams, constructed by neighboring countries of Turkey and Syria have substantially reduced agricultural production in arid regions of Iraq (Zakaria *et al.*, 2012). This project was developed to compare the successful soil-tilled SWRT membrane water conservation technology with a manually installed local farm water conservation technology of burring an expensive partially decomposed tilled organic matter (TOM) layer. The primary goal for this study was to compare irrigation water-use efficiency (IWUE) and yield improvements by two crops grown on buried SWRT membrane and organic matter layer retainers below plant root zones.

**Core Ideas**

- All marginal sands need new long-term technologies that retain more water in root zones.
- Novel ideas are needed for optimizing soil water, nutrients, and oxygen in root zones.
- Crop production on sands are increased with less than half the water.
- Transforming sand soils in arid regions into sustainable production.

## 2 | MATERIALS AND METHODS

Two separate land sites in Iraq, located in arid tropical climates, identified as Koopen–Gieger Zone Bwh, were used to compare manual installations of the Michigan State University SWRT water-impermeable membrane contributions to crop resiliencies by doubling soil water-holding capacities in crop root zones in the irrigated arid climates of Iraq. The first location was a vegetable production region, 20 km North of Bagdad, at latitude 33˚38′58.4″ North and altitude 44º24′17.7″ East and 33 m above sea level. This location's soil is classified as a lower saline sandy loam Typic Torrifluevent. This field location is identified as the Diyala site. The second location was on the Date Palm Tissue Culture Research Station at the Holly Najaf Governorate, 180 km South of Baghdad, at latitude 32º07′37.8″ North and latitude 24º19′44.7″ East and 31 m above sea level. This second location's soil is classified as a more saline sandy loam Typic Torrifluevent. This field location is identified as the Najaf site.

Statistical analyses for this report were completed using SAS/STAT (SAS 9.4, SAS Institute, 2002) for the replicates of the randomized complete block design (RCBD) to determine Fishers LSD .05 among samples of plant and soil parameters.

### 2.1 | Soil physical and chemical properties for both field sites

Disturbed field soils were sampled from 0-to-30=, 30-to-60-, and, 60-to-90-cm layers with four replications (Table 1). Soil samples from each layer were air dried, mixed thoroughly, and passed through a 2-mm sieve. Randomly selected subsamples were analyzed for physical (Table 2) and chemical (Table 3) properties.

Soil physical properties: Soil particle size analysis, were completed by the pipette method. Soil bulk density was measured by core method. Soil moisture characteristic curves were determined using cindered glass funnels for suctions, 1–9 kPa, and membrane pressures between 10 and 1,500 kPa.

**TABLE 1** Irrigation water, containing these chemical properties were added daily to all treatments located at both field sites for the duration of this project

| Field sites | Chemical properties of irrigation | |
|---|---|---|
| **Najaf** | **Diyala** | |
| 812 | 501 | Total dissolved solids, mg $L^{-1}$ |
| 2.14 | 1.50 | Ca, mg $L^{-1}$ |
| 2.05 | 1.63 | Mg, mg $L^{-1}$ |
| 2.60 | 1.95 | Na, mg $L^{-1}$ |
| 0.085 | 0.091 | K, mg $L^{-1}$ |
| 260 | 90 | Cl, mg $L^{-1}$ |
| 525 | 240 | $SO_4$, mg $L^{-1}$ |
| – | 0.049 | $CO_3$, mg $L^{-1}$ |
| 3.20 | 2.62 | $HCO_3$, mg $L^{-1}$ |
| 0.05 | 0.04 | $NO_3$, mg $L^{-1}$ |
| 1.796 | 1.558 | Sodium absorption ratio, mg $L^{-1}$ |

**TABLE 2** Physical properties at soil depths for Diyala and Najaf field sites

| Location<br>Soil physical properties | Diyala site | | Najaf site | |
|---|---|---|---|---|
| | Soil layer depth, cm | | | |
| | 0–30 | 30–60 | 0–30 | 30–60 |
| Sand % | 74.4 | 59.9 | 68.6 | 74.6 |
| Silt % | 13.2 | 25.2 | 24.0 | 22.8 |
| Clay % | 12.4 | 14.9 | 7.4 | 2.6 |
| Soil texture | Sandy loam | Sandy loam | Sandy loam | Loamy sand |
| Bulk density, g $cc^{-1}$ | 1.48 | 1.51 | 1.59 | 1.65 |
| Particle density, g $cc^{-1}$ | 2.61 | 2.65 | 2.71 | 2.71 |
| Total porosity, % | 43.5 | 43.0 | 41.3 | 39.2 |
| Void ratio | 0.77 | – | 0.70 | – |
| Water content at 33 kPa, $cm^3cm^{-3}$ | 0.201 | – | 0.298 | – |
| Water content at 1,500 kPa, $cm^3$ $cm^{-3}$ | 0.038 | – | 0.101 | – |
| Available water, $cm^3cm^{-3}$ | 0.163 | – | 0.197 | – |
| Capillary rise, cm | 66.2 | – | 57.1 | – |

**TABLE 3** Chemical properties at three soil depths for Diyala and Najaf field sites

| Chemical characteristics | Location and depth | | | | | |
|---|---|---|---|---|---|---|
| | Najaf site | | | Dayala site | | |
| | 60–90 cm | 30–60 cm | 0–30 cm | 60–90 cm | 30–60 cm | 0–30 cm |
| 7.44 | 7.35 | 7.51 | 7.53 | 7.17 | 7.32 | pH |
| 3.20 | 3.36 | 2.86 | 0.84 | 1.47 | 1.14 | ECe, $dSm^{-1}$ |
| 5.72 | 7.55 | 2.09 | 2.09 | 2.64 | 2.34 | Ca, $mmol_c$ $L^{-1}$ |
| 4.11 | 3.63 | 0.61 | 0.61 | 2.12 | 2.00 | Mg, $mmol_c$ $L^{-1}$ |
| 17.22 | 20.31 | 5.14 | 5.14 | 6.65 | 6.22 | Na, $mmol_c$ $L^{-1}$ |
| 0.13 | 0.21 | 0.03 | 0.03 | 0.04 | 0.07 | K, $mmol_c$ $L^{-1}$ |
| 5.53 | 6.42 | 1.24 | 1.24 | 1.31 | 2.42 | $SO_4$, $mmol_c$ $L^{-1}$ |
| 12.53 | 13.79 | 5.10 | 5.10 | 5.98 | 6.80 | Cl, $mmol_c$ $L^{-1}$ |
| 2.18 | 2.59 | 0.69 | 0.69 | 2.03 | 1.47 | $HCO_3$, $mmol_c$ $L^{-1}$ |
| 0.27 | 0.14 | 0.08 | 0.08 | 0.07 | 0.05 | $NO_3$, $mmol_c$ $L^{-1}$ |
| 0.31 | 0.21 | 0.10 | 0.10 | 0.10 | 0.10 | $PO_4$, $mmol_c$ $L^{-1}$ |
| 5.60 | 6.19 | 6.63 | 1.80 | 4.29 | 3.46 | SAR, $mmol_c$ $L^{-1}$ |
| 13.6 | 14.0 | 14.7 | 12.0 | 12.7 | 12.3 | CEC, mol $kg^{-1}$ |
| 11.1 | 9.4 | 8.21 | 8.21 | 7.1 | 6.0 | OM |
| 2.27 | 2.34 | 0.85 | 0.85 | 0.71 | 0.62 | Gypsum |
| 191 | 210 | 120 | 120 | 134 | 118 | $CaCO_3$ |

These data were fitted to the van Genuchten equation and reported in Figure 1.

Textures of both field sites were at the soil textural borders of loamy sand and sandy loam, depending on soil depth, clay content was somewhat higher at all three soil depths in the Diyala site. Total porosities and bulk densities, reported in (Table 2), were similar for both soils. Soil volumetric water ($cm^3$ $cm^{-3}$) retention capacities by the Diyala soil diminished somewhat at soil water tensions greater than −10 KPa, (Figure 1, Table 2). These data demonstrate some variability which should not interfere with combining results from both sites to comprehensively define specific improvements of IWUE and crop production across the four field treatments of this report.

### 2.1.1 Soil chemical properties

Soil salinity was determined by the electrical conductivity (EC) method. Soil pH was measured by electrodes in

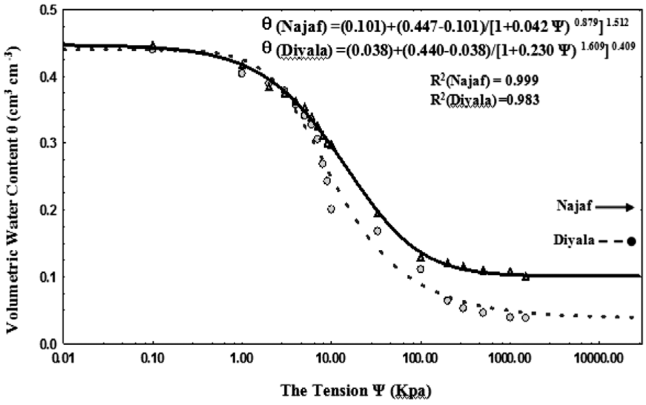


**FIGURE 1** Volumetric soil water contents retained at different soil water tensions using 0-to-30-cm samples of sands at both Diyala and Najaf field sites

equilibrium solutions of 10 g sand in 25-ml distilled water. Soil organic matter was determined by the chromate and sulfuric acid Wikelly–Black method. Soil cations and anions were quantified in 1:1 soil to water-extracted solutions. Cations were measured by the cation exchange capacities measurement, using the total soil carbonates method. Soluble K was estimated by the method of Knudsen et al. (1982). Soluble soil P was identified by the rapid field soil malachite green methods of Olsen and available N by method of Nelson and Sommers (1982). Soil chemical properties of the Najaf site are more saline, higher EC, than Diyala, including greater quantities of Na, $SO_4$, and Cl while mostly similar among the remaining chemical characteristics of both field sites, as reported in Table 3.

## 2.2 | Experimental design

Metal framed walls 25 m long and 12 m wide, and the 3 m ceiling were covered by 200-μm polyethylene film and oriented in the North–East direction. Both ends of this high ceiling hot house remained open without forced-air ventilation nor heating systems. Four main lines of plots, subdivided into four 4 m randomly spaced total of 16 treatments plots. Three treatments were manually excavated to soil depths of 60 cm and widths of 30 cm. The SWRT membranes consisted of linear, low-density, polyethylene (LLDPE) films, 3-mil thick, formed into U-shaped, 3:1 aspect ratio, troughs 30 cm wide and 10-cm deep (Guber et al., 2015), and 4 m lengths at 60 cm and refilled to 10 cm above the original soil surface, to compensate for soil settling. Hakkarainen et al. (2004) also reported zero water permeability of LLDPE film when buried in soils adjusted to pH ranges from 4.0 to 8.3 and microbial populations fivefold natural populations for 17 yr, without deterioration. Tilled organic matter soil treatments were excavated to 60-cm depths and partially back-filled to 35 cm. Installations of approximately 3-cm thick flat layers of commercially available partially decomposed organic material were refilled to 10 cm above the original soil surface. Tilled control soil (TCS) treatments were excavated to 60 cm and refilled to 10 cm above the original soil surface, without adding water retention material. The no-tilled (NT) soil remained in a natural condition. Four replications of these four soil treatments were distributed in a randomized complete block design with four replications of the four treatments among the 16 separate plots placed at 1 m spacings between and at 3 m distances from each end of the high-ceiling hot house. Pre-planting surface soil applications of one-half the granular NPK followed by five separate fertigations, via the buried irrigation drip tape, for a total of 250, 100, and 250 kg ha$^{-1}$ of NPK at both locations.

Subsurface drip irrigation (SDI) network (John Deere) installed at 35-cm soil depth, were periodically connected to a fertigation source designed to maximize IWUE measurements while maintaining optimal plant nutrients for the duration of experiments at both field sites for 2 yr. Single row of SDI drip tape, 1.6 cm in diameter, with emitters spaced at 30-cm intervals to discharge rates irrigation and fertigation at rates of 1.35 L h$^{-1}$ were connected to field pipes having diameters of 4 cm and operated at 100 kPa pressure for best application of prescriptively replacing daily soil water losses monitored by 5TE probes (Metric) engineered to measure soil water, temperature, and salinity changes during the previous 24 h irrigation water in each of the 16 plots. Soil monitoring probes were installed at 15-, 30-, and 45-cm depths and recorded hourly by connected EM50 data loggers.

## 2.3 | Planting, irrigating, sampling, and analyses

Seedlings of tomato and spicy pepper were spring planted in two rows at 50 cm row spacing and 40 cm within rows during the 1st year at both Najaf and Diyala field sites. Seedlings of chili pepper (*Capsicum solanaceae* L.) were spring planted in the same plots and row spacings during the 2nd year, at both field sites. All 16 plots at both sites periodically received 20% of the total 250 kg N ha$^{-1}$ and 100 kg K ha$^{-1}$ added by separate fertigation events, via irrigation drip tapes, during five separate afternoons during both years. Water loss recoveries could be replaced by days or weeks. Daily soil water replacements were established during early forenoon, to avoid multiple root death rates and whole plant metabolic suffering reported for crops during prolonged drought stress reported by Yildirim et al. (2009) . To best accommodate this irrigation study, 24 h water replacements were scheduled to accurately evaluate daily crop water uptake and deep leaching and minimizing whole plant water drought stresses. Therefore, daily morning irrigations were employed to bring soil water volumes up to 0.25 cm$^3$ cm$^{-3}$ (25%) within the 0-to-30-cm soil

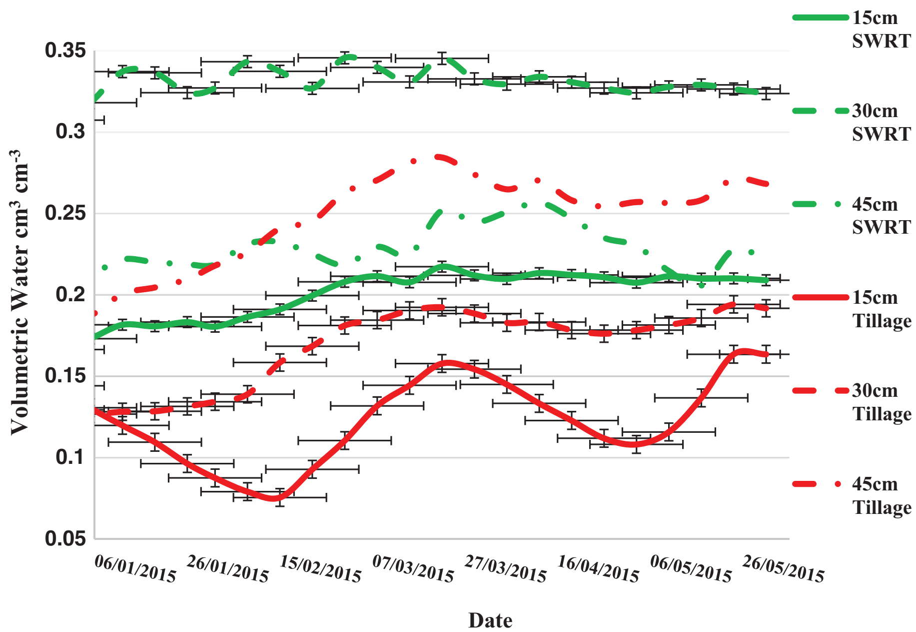


FIGURE 2 Greater volumetric soil water contents retained in crop root zones by soil water retention technology (SWRT) membranes during the 5-mo season for peppers at Diyala site. Standard error bars are applied to 15-cm soil depths (solid) and 30-cm soil depths (dashed) lines for both SWRT and tilled control soil (TCS)

depths, approximating the 50% available plant-available soil water contents, outlined in Figure 1. This recovery of soil water measured by the soil water probes at 15- and 30-cm soil depths, equilibrates root zone water levels most accurately as defined by Figure 1 and Table 2. Total daily water replacement volumes removed from the root zone by crop uptake and deep soil leaching best approximates soil water losses by highly permeable soils. Certainly, if more drought stress would have been implemented in this study, there would be even greater improvements in crop production on SWRT transformed sands, illustrated by the 504% Texas cotton fiber gains by SWRT membrane retention of limited rainfed water vs. acute crop drought stress on control sands without crop root zone water retention, reported by Van Pelt and Zobeck (2015).

## 2.4 | Soil water retention and salinity distributions

The SWRT membrane retention of 62% more plant available water in 15- and 30-cm soil depths nearly doubled soil water contents beyond tilled control soils (TCS) (Figure 2, 3).

Although Diyala soils had lower salt concentrations in their natural soil profile (Table 3) greater soil retention of irrigation water, above SWRT membranes (Figure 2) combined with plant uptake resulted in decreased salt concentrations in the 15- and 30-cm regions of the root zone (Figure 3). Lower salts in the presence of optimal soil water, reduced root zone soil salinity nearly 50% for a majority of crop growth at Diyala sands (Figure 3). The lower electrical conductivity in membrane retained soil water, d above the SWRT membranes, demonstrates a previously unknown benefit of the SWRT membrane disruption of upward solute flow. This new observation adds to the growing number of environmental improvements by SWRT membranes outlined by Kavdir et al. (2014). Higher native soil salinity at the Najaf site (Table 3) appeared to reduce IWUE of tomatoes all treatments except when soil root zones were improved by SWRT membranes (Figure 4).

## 2.5 | Aboveground and belowground plant responses to soil water conservation

Although several aboveground plant components were measured at harvest, the four soil treatments had little impact on aboveground plant growth parameters.

Total roots identified in the 0-to-50-cm soil depths for both crops at both field sites were generally ($P$ = .05) greater in sands improved by SWRT improved soils compared to control and TOM soils (Table 4). More saline Najaf soils (Table 3) tended to reduce root quantities of both crops (Table 4). Higher soil water contents, retained by SWRT membranes, at the same 10-to-20-cm and 20-to-30-cm soil depths, averaged 19 and 32 g cc$^{-1}$ more roots than other soil treatments. Statistically significant, 42 and 113% greater quantities of soil water retained in plant root zones above SWRT membranes appear promote root survival by avoiding frequent drought stresses that kill roots in soils with lower soil water contents in the TCS treatments. Greater root numbers in the 0-to-50-cm soil depths above water-retaining SWRT treatment,

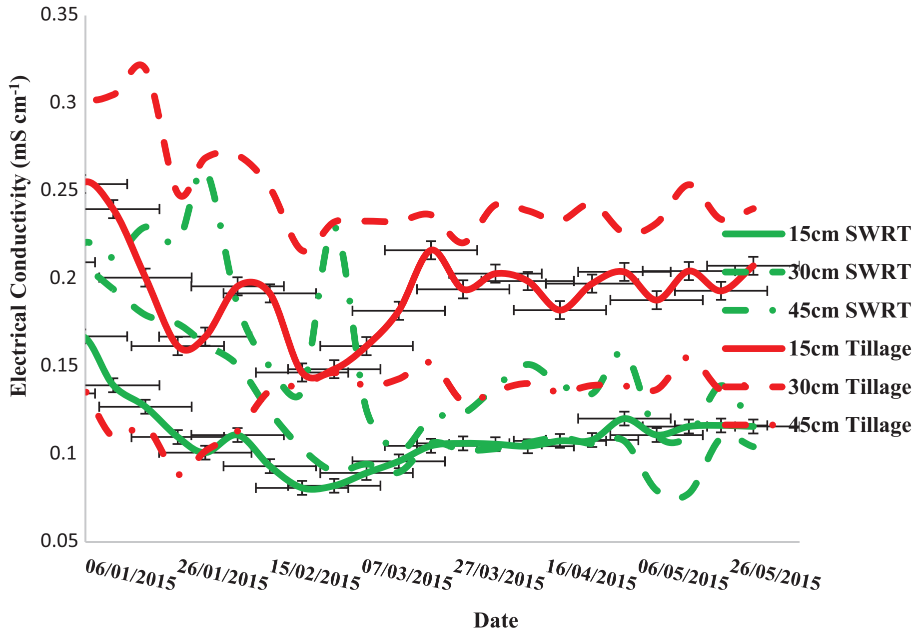


FIGURE 3 Soil salinity reductions in soil root zones, by soil water retention technology (SWRT) membranes, during the 5-mo season for peppers at Diyala site. Standard error bars are applied to solid 15-cm soil depths for SWRT and tilled control soil (TCS)

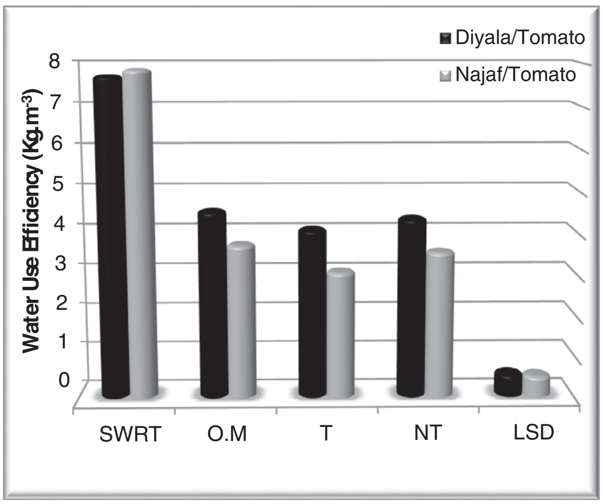


FIGURE 4 Highest irrigation water-use efficiency (IWUE) by tomato grown on soil water retention technology (SWRT) water retention membranes. Greater salinity of Najaf soil, significantly reduced IWUE in sands without SWRT water retaining membranes

avoid drought-related root death similar to the tremendous crop root losses during frequent droughts (Smucker & Aiken, 1992 ). Soil salinity also caused lower yields in TOM, TCS, and NT treatments, but not in SWRT ( Table 5). These results suggest SWRT water conservation and salt mitigation have unlimited global impacts.

## 2.6 | Crop yield and IWUE responses to soil water conservation

Tomato production and IWUE in the TOM treatments at Diyala were not increased when compared to TCS control.

Although tomato production on TOM was greater than TCS in Najaf, irrigation totals and IWUE were similar. Although total irrigation dropped, pepper production on TOM treatments at the Diyala site did not increase beyond neither TCS or NT controls (Table 5). The majority of measured aboveground plant parameters of SWRT crops were ($P$ = .05) greater than TOM, NT, and TCS treatments for both crops and locations, TOM had 22% lower yields than SWRT improved soils and failed to produce significantly greater yields than TCS and NT controls (Table 5). Our results showed TOM demonstrated no significant production beyond TCS and NT controls (Table 5). However, SWRT distinctly different results of increased tomato yields 15% at Diyala and 48% at Najaf. These findings were attributed to improved water use efficiency (Table 5).

This improved IWUE, beyond TCS, offers farmers a new technology that conserves a calculated 15,870 $m^3$ reduction of irrigation water per hectare annually.

The remarkable 135% greater IWUE for plants growing in SWRT membrane-improved water-holding capacity (Table 5) appears to be constant throughout the crop season, enabling plants to avoid fewer brief water deficits (Figure 2).

**TABLE 4** Average root totals within 10-cm intervals of soils from 0 to 50 cm, at harvest

| Treatments | | Tomato | | Pepper | |
|---|---|---|---|---|---|
| Soil water retentions | depthlayer | Distribution of roots | | Distribution of roots | |
| | | Diyala | Najaf | Diyala | Najaf |
| | cm | g cm$^{-3}$ | | | |
| Tilled soil membranes (SWRT) | 0–10 | 4.82 | 3.70 | 4.93 | 3.07 |
| | 10–20 | 9.07 | 8.69 | 6.72 | 5.85 |
| | 20–30 | 7.27 | 7.04 | 7.06 | 6.54 |
| | 30–40 | 2.35 | 3.66 | 3.45 | 3.98 |
| | 40–50 | 0.86 | 0.94 | 0.87 | 0.64 |
| Total SWRT roots | – | 24.36a | 24.03a | 23.04b | 20.08a |
| TOM layer at 35 cm | 0–10 | 2.78 | 3.49 | 3.90 | 4.00 |
| | 10–20 | 7.63 | 6.34 | 7.76 | 6.28 |
| | 20–30 | 9.05 | 7.40 | 8.06 | 6.64 |
| | 30–40 | 2.70 | 3.22 | 3.10 | 3.41 |
| | 40–50 | 0.24 | 0.26 | 0.37 | 0.37 |
| Total TOM roots | – | 22.40b | 20.71b | 23.18b | 19.70ab |
| NT no membranes | 0–10 | 2.93 | 2.99 | 3.49 | 4.43 |
| | 10–20 | 5.86 | 5.75 | 5.35 | 6.52 |
| | 20–30 | 6.51 | 6.63 | 6.53 | 6.61 |
| | 30–40 | 1.94 | 1.86 | 1.99 | 2.30 |
| | 40–50 | 0.49 | 0.16 | 0.88 | 0.22 |
| Total NT roots | – | 17.70c | 17.38c | 18.24c | 20.27a |
| TCS no membranes | 0–10 | 3.98 | 3.26 | 4.15 | 3.74 |
| | 10–20 | 8.48 | 5.94 | 7.70 | 4.70 |
| | 20–30 | 7.41 | 7.48 | 8.28 | 4.66 |
| | 30–40 | 1.51 | 1.22 | 2.65 | 1.61 |
| | 40–50 | 0.61 | 0.60 | 0.89 | 0.41 |
| Total TCS Roots | – | 21.98b | 18.49c | 23.76a | 15.52c |
| LSD .05 for root totals in four soil water retainers | | 0.77 | 0.67 | 0.53 | 0.61 |

*Note*. SWRT, soil water retention technology; TOM, tilled organic matter; NT, non-tilled controlled soil; TCS, tilled control soil.

The SWRT soil water conservation treatments at Najaf, enabled the production of 48% more tomato resulting in a 156% improved IWUE that conserves a calculated 16,688 m$^3$ less irrigation water per hectare, than required by TCS soils (Table 5).

These yield improvements, coupled with 156% improved IWUEs enables farmers to recover installation costs for SWRT membranes, within a few years.

The SWRT transformed sands improved yields by 30% requiring only 40% irrigation water required by TOM (Table 5). This 167% improved IWUE further promotes the need for Iraq and other Middle East arid countries to incorporate SWRT membrane technologies into all irrigated arid sands.

## 3 | RESULTS AND DISCUSSION

Distinctly proven higher production with less water by SWRT water-impermeable membranes have clearly demonstrated new opportunities for improving tomato and spicy pepper production 20–30% at both locations. Pepper production on SWRT improved sands ($P$ = .05) increased 30%, while using 60% less irrigation water, than TCS. Pepper IWUE on SWRT membranes, increased by a ($P$ = .05) statistically significant 167%, a 2.7-fold increase (Table 5). Crop production for each m$^{-3}$ irrigation water doubled for both crops at both locations in arid tropical sands of the Middle East. Impacts of SWRT and TOM contributions to crop yields and associated greater IWUE are dramatically different at each field site.

**TABLE 5** Total calculated crop yields per hectare by multiplying averages of four replicated yields in each treatment plot by 793.50. Irrigation water-use efficiency (IWUE) is calculated using average production and irrigation rates from replicated research plots for tomato at both sites. The IWUE and yields for the pepper crop at Najaf were omitted due to failures in daily irrigation scheduling

| Treatments | Tillage SWRT | Tillage TOM | NT | TCS | LSD .05 |
|---|---|---|---|---|---|
| **Tomato** | | | | | |
| Diyala site | | | | | |
| Calculated field crop yields, kg $h^{-1}$ | 196,071a | 182,183ab | 180,952bc | 169,980bc | 14,386 |
| Total irrigation for research plots, $m^3$ | 31.98b | 50.61a | 52.33a | 52.33a | 4.30 |
| IWUE by research plots, kg $m^{-3}$ | 7.73a | 4.54b | 4.36b | 4.09b | 0.54 |
| Najaf site | | | | | |
| Calculated field crop yields, kg $h^{-1}$ | 168,294a | 133,234b | 131,409b | 113,671c | 13,578 |
| Total irrigation for research plots, $m^3$ | 26.96b | 45.12a | 46.72a | 46.72a | 4.18 |
| IWUE by research plots, kg $m^{-3}$ | 7.87a | 3.73b | 3.55b | 3.07c | 0.49 |
| **Spicy pepper** | | | | | |
| Diyala site | | | | | |
| Calculated field crop yields, kg $h^{-1}$ | 542,216a | 453,889b | 472,847b | 416,708b | 53,917 |
| Total irrigation for research plots, $m^3$ | 41.03c | 70.72b | 84.20a | 84.20a | 8.81 |
| IWUE by research plots, kg $m^{-3}$ | 16.65a | 8.08b | 7.08c | 6.24c | 0.85 |

*Note*. SWRT, soil water retention technology; TOM, tilled organic matter; NT, non-tilled controlled soil; TCS, tilled control soil.

Although sands treated with TOM (decomposing organic matter layers) significantly increased IWUE by 30% for peppers at Diyala, without significantly increasing yields (Table 5). Therefore, we encourage farmers of sandy soils to save time and money by replacing less beneficial annual installations of costly materials with more reliable long-term engineered water retaining membranes that conserve water in crop root zones to maximum crop production with less water on irrigated arid sands.

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## AUTHOR CONTRIBUTIONS

M.I.A. conceived the manuscript and wrote the initial draft. A.J.M.S. and E.P.R. provided critical reviews, revisions, and English language additions, included in this final draft. The remaining co-authors, S.S.M., H.A.M, and F.H.A. are graduate students and research associates who directly contributed to the two-year field research project.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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