ACCSCIENCE PUBLISHING

Asian Journal of Water, Environment and Pollution

ORIGINAL RESEARCH ARTICLE

Integrated effects of controlled traffic farming and irrigation scheduling on water productivity and yield of pumpkin under semi-arid sprinkler irrigation

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Citation: Atiyah AH, Ati AS, AL-Halfi KM, Dawod SS, Mouhamad RS. Integrated effects of controlled traffic farming and irrigation scheduling on water productivity and yield of pumpkin under semi-arid sprinkler irrigation. *Asian J Water Environ Pollut.* 2026;23(4):026200145. doi: 10.36922/AJWEP026200145

Received: May 12, 2026

Revised: May 29, 2026

Accepted: June 10, 2026

Published online: July 9, 2026

Abstract

Water-use efficiency in semi-arid agriculture is strongly influenced by irrigation management and soil structural conditions within the crop root zone. Repeated machinery traffic can degrade soil pore continuity and hydraulic conductivity, reducing infiltration efficiency and limiting productive water use under sprinkler irrigation systems. This study evaluated the combined effects of controlled traffic farming (CTF) and irrigation depletion regimes on seasonal crop evapotranspiration (ETc), growth, yield, and water productivity of pumpkin (*Cucurbita pepo* L.) under semi-arid field conditions in Kirkuk Governorate, Iraq, during the 2024 growing season. A split-plot randomized complete block design was used with three irrigation depletion levels (30%, 45%, and 60% of available soil water) as main plots and two traffic systems (CTF and random traffic farming [RTF]) as subplots. Seasonal ETc was higher under RTF (445–455 mm) compared to CTF (350–375 mm), indicating reduced water loss under controlled traffic. The highest yield (28 Mg ha^{-1}) and water productivity (0.95 kg m^{-3}) were achieved under the combination of CTF and 45% depletion. Severe depletion (60%) reduced growth and yield due to excessive water stress, while 30% depletion likely caused over-irrigation, reducing aeration and increasing non-productive water use. Overall, CTF improved soil hydraulic behavior and enhanced irrigation efficiency by minimizing traffic-induced compaction. Regression analysis revealed strong relationships among ETc, irrigation depletion, traffic system, and water productivity ($R^2 = 0.91$). The results suggest that integrating controlled traffic farming with moderate irrigation depletion optimizes soil water availability and root-zone aeration, thereby improving productive water use in semi-arid irrigated agriculture.

Keywords: Controlled traffic farming; Deficit irrigation; Evapotranspiration; Sprinkler irrigation; Soil compaction; Water productivity

1. Introduction

Agricultural production in semi-arid environments is increasingly constrained by declining water availability, rising evaporative demand, and progressive degradation of soil physical quality.[1-3] Under irrigated conditions, improving water productivity depends not only on the quantity of water applied but also on the soil's physical condition controlling infiltration, aeration, and root-water uptake. In mechanized agricultural systems, repeated machinery traffic frequently disrupts soil structural continuity by reducing pore volume and macropore connectivity through compaction. These changes can restrict root penetration, reduce saturated hydraulic conductivity, limit gaseous diffusion, and modify the storage and movement of water within the active root zone. The influence of traffic-induced compaction is significant in the context of sprinkler irrigation, as it interacts with irrigation-induced soil wetting, surface loads, and structural damage. Reduced soil infiltration and poor pore continuity could lead to higher surface evaporation rates and reduced water retention effectiveness within the cultivated soil horizon. Hence, under compaction, a higher irrigation volume will be needed to sustain optimal soil moisture. The review evidence summarized by Antille *et al.*[4] and Nawaz *et al.*[5] indicates that unmanaged machinery traffic can degrade soil physical properties and reduce crop productivity through soil-structure deterioration. Controlled traffic farming (CTF) represents a new management approach that can reduce machine impact on soil structure by limiting traffic to permanent tracks. Spatial restriction of soil disturbance caused by wheel traffic helps maintain the physical quality of cultivated soil and limit its repetitive compaction. Previous studies have reported improvements in infiltration, pore continuity, and structural stability under CTF compared to traditional random traffic farming (RTF).[6-10] Better structural continuity under CTF conditions is likely to promote more efficient root-zone water storage and distribution, thereby enhancing irrigation efficiency in water-limited situations. Another source of complexity is irrigation scheduling and the need to balance crop water requirements and root-zone aeration. Low depletion leads to excessively wet soils that can limit oxygen diffusivity, resulting in evaporation and leaching losses. High water depletion increases stress and stomatal closure, limiting the expansion of crop canopy and reproductive development. Thus, moderate soil depletion might be a more favorable condition than high or low depletion for irrigation management purposes.[11,12] Pumpkin (*Cucurbita pepo* L.) is an economically valuable vegetable crop with a high level of vegetative growth and requires considerable irrigation.[13] Crop productivity is highly sensitive to root-zone moisture conditions and irrigation management practices. Although deficit irrigation strategies for pumpkin production have been investigated previously, limited information is available regarding the interaction between traffic farming systems and irrigation depletion regimes under sprinkler irrigation conditions in semi-arid Iraqi environments. Most regional studies have evaluated irrigation scheduling or traffic management independently, whereas the combined influence of traffic-induced structural modification and depletion-based irrigation management on seasonal evapotranspiration (ETc) and productive water use remains insufficiently quantified. The present study was therefore conducted to evaluate the interaction between irrigation depletion levels and traffic farming systems on seasonal crop ETc, growth characteristics, yield response, and water productivity of pumpkin cultivated under semi-arid sprinkler irrigation conditions. It was hypothesized that restricting machinery traffic to permanent lanes would improve root-zone physical conditions sufficiently to reduce seasonal crop water consumption and enhance productive water use under moderate irrigation depletion compared with conventional random-traffic systems.

2. Materials and methods

2.1. Experimental site and climatic conditions

The field study was conducted during the 2024 growing season on a privately owned agricultural plot in Daquq district, Kirkuk Governorate, Iraq (35°16'04" N, 44°39'26" E; Figure 1). This area has a semi-arid climate with warm summers, low precipitation, and relatively high atmospheric evaporative demand during the cropping period. In such conditions, proper management of the irrigation system is crucial to achieving maximum crop production and optimal water use.[11,12] Pumpkin (*C. pepo* L.) was selected as the test plant species because of its economic importance and its sensitivity to water availability in the root region.[13] Seeds were planted on August 20, 2024, and harvested on November 25, 2024.

2.2. Soil physical and chemical properties

Composite soil samples were collected from the experimental field before planting to characterize selected physical and chemical soil properties. Particle-size distribution analysis indicated that the soil was classified as sandy loam according to the United States Department of Agriculture textural classification system, containing 580, 240, and 180 g kg^{-1} of sand, silt, and clay, respectively.[14,15] Sandy loam soils under semi-arid irrigation conditions are generally characterized by relatively rapid infiltration and moderate water-holding capacity, making them responsive to changes in soil structural continuity and traffic-induced compaction.[16,17]

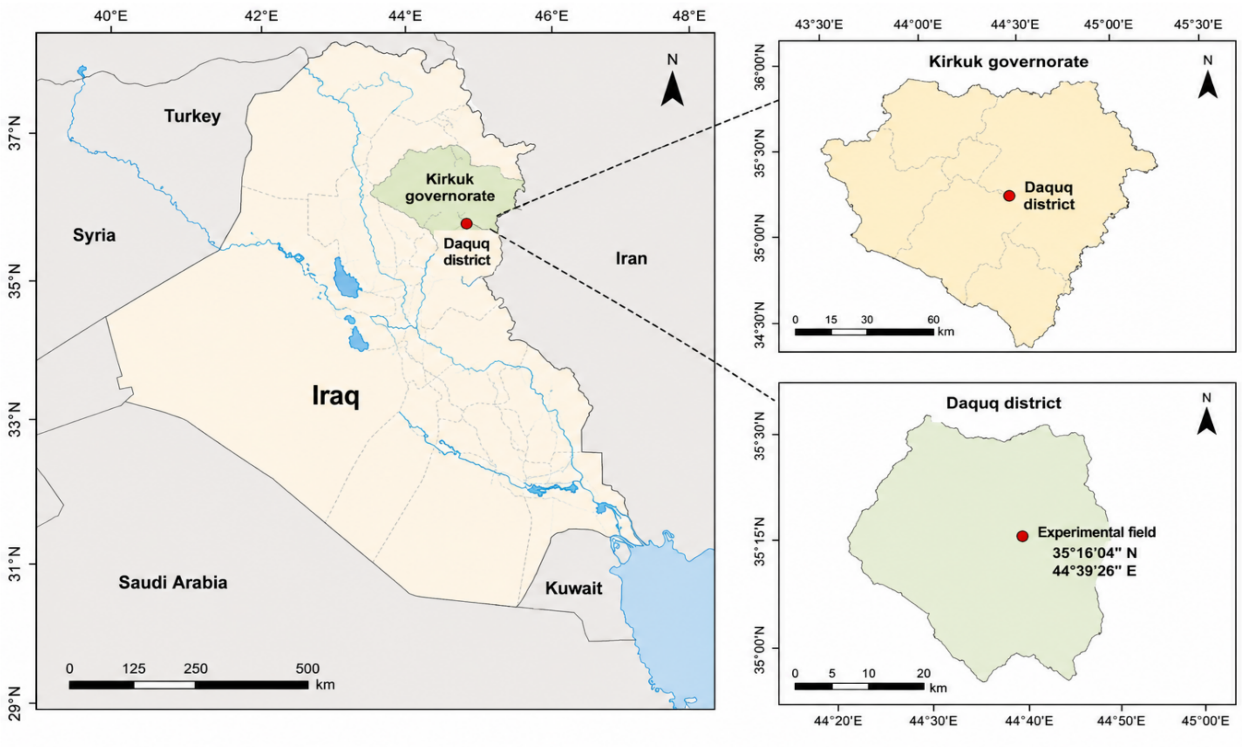

Figure 1. Experimental site location in Daquq district, Kirkuk Governorate, Iraq

Volumetric water content at field capacity (θfc) and permanent wilting point (θwp) were determined using pressure plate extraction at matric potentials of 33 and 1,500 kPa, respectively. Soil electrical conductivity and pH were measured in a 1:1 soil–water suspension. Organic matter content, calcium carbonate concentration, and available nutrients were determined according to standard laboratory procedures.[16-18]

2.3. Experimental design and traffic farming systems

The experiment was arranged as a split-plot within a randomized complete block design (RCBD) with three replications. Irrigation depletion treatments were assigned to the main plots because irrigation application under sprinkler systems required larger operational units to minimize hydraulic interference among treatments. Traffic farming systems were assigned to the subplots.

Three irrigation depletion levels based on depletion of available soil water were evaluated:

- 30% depletion of available soil water
- 45% depletion of available soil water
- 60% depletion of available soil water

Two traffic farming systems were investigated:

- RTF
- CTF

Therefore, the experiment consisted of six treatment combinations distributed across eighteen experimental units.

Each experimental unit measured 20 m × 4 m (80 m^2) and consisted of two cultivated beds, each 1.25 m wide. A 1 m buffer zone was maintained between adjacent plots to reduce hydraulic and operational interference among treatments. Additional operational space was allocated before each plot to allow agricultural machinery to reach stable operating conditions during field activities.

Under the RTF system, machinery traffic occurred randomly across the cultivated surface during tillage and crop-management operations. In contrast, machinery movement under the CTF system was restricted to permanent traffic lanes throughout the growing season to minimize repeated loading within the cultivated root zone.[6-10] Although axle load and tire-pressure measurements were not directly monitored during the experiment, the traffic treatments were designed to represent practical field-scale differences between uncontrolled and spatially confined machinery movement under local agricultural conditions.

2.4. Land preparation and crop establishment

The experimental field was initially leveled and subsequently tilled using disc plowing to a depth of approximately 25 cm. Pumpkin seeds were manually planted according to local agronomic recommendations. Following seedling establishment, plants were thinned to one healthy plant per hill to maintain uniform plant density across treatments.

All agronomic practices, including fertilization, weed management, and pest control, were uniformly applied to all experimental units during the growing season to minimize non-treatment variability.

2.5. Irrigation system and irrigation scheduling

A solid-set sprinkler irrigation system equipped with oscillating sprinklers was used throughout the experimental period. The sprinkler discharge rate was approximately 1,000 L h^{-1}. A preliminary system evaluation was conducted at different operating pressures to identify the pressure level that produced the most stable irrigation performance. An operating pressure of 175 kPa was subsequently adopted for all irrigation treatments (the selected pressure provided the most even distribution of water over the experimental area during the preliminary evaluation of the system). The available soil water within the effective root zone was calculated using **Equation 1**:

$$AW = \theta fc - \theta wp \quad (1)$$

where:

- AW: Available soil water ($cm^3\ cm^{-3}$)
- θfc: Volumetric water content at field capacity
- θwp: Volumetric water content at permanent wilting point

The irrigation depth was determined using **Equation 2:**[19]

$$d = (\theta fc - \theta w) \times D \quad (2)$$

where:

- d: Irrigation depth (mm)
- θw: Volumetric soil water content before irrigation
- D: Effective root-zone depth (300 mm)

The ETc was calculated using a simple soil–water balance method (**Equation 3**):

$$ETc = I + P \pm \Delta S \quad (3)$$

where ETc refers to seasonal crop evapotranspiration/crop water consumption (mm), estimated using the soil–water balance method, *I* is irrigation water applied (mm), *P* is effective rainfall (mm), and *ΔS* is the change in soil water storage within the effective root zone. The water balance calculation did not include surface runoff, which was negligible under the experimental conditions, and deep percolation below the effective root zone, which was assumed to be small. Irrigation events were triggered if the soil water deficit in the effective root zone reached the pre-defined treatment thresholds of 30%, 45%, or 60% of available soil water. The quantity of soil water depleted was calculated from periodic gravimetric soil-moisture measurements taken in the root zone prior to irrigation. The calculated depletion level was then used to determine when and how much to irrigate for each treatment. Uniform irrigations were applied to all treatments during crop establishment. Differential irrigation scheduling was initiated from the fifth irrigation onward according to the designated depletion levels. Soil moisture content within the root zone was monitored periodically using gravimetric sampling (soil samples were collected from the 0–30 cm root-zone layer prior to each scheduled irrigation) and oven drying. Although continuous soil water monitoring was unavailable, periodic measurements were used to maintain consistent irrigation scheduling across treatments throughout the growing season.

2.6. Growth parameters and yield determination

Plant height (cm) was measured at physiological maturity using a measuring tape from the soil surface to the apical meristem (Measurements were obtained from five randomly selected plants within each experimental unit). The number of branches per plant was determined from randomly selected plants within each experimental unit. Total yield (Mg ha^{-1}) was calculated from the cumulative fruit weight harvested from each plot and converted to a hectare basis.

Water productivity was calculated according to Allen *et al.*[19] as **Equation 4**:

$$WP = \frac{Y}{WA} \quad (4)$$

where:

- WP: Water productivity (kg m^{-3})
- Yield: Total yield (kg ha^{-1})
- Water applied: Total irrigation water applied ($m^3\ ha^{-1}$)

2.7. Regression modeling

Regression analysis was conducted to evaluate the relationships among water productivity, seasonal crop ETc, irrigation depletion level, and traffic farming system.[19] The predictive model was expressed as **Equation 5**:

$$WP = a + bETc + cID + dTS \quad (5)$$

where:

- WP: Water productivity (kg m^{-3})
- ETc: Seasonal crop evapotranspiration (mm)
- ID: Irrigation depletion level (%)
- TS: Traffic system factor

Traffic-system coding was defined as RTF = 0 and CTF = 1. A secondary regression model was developed to estimate yield response (**Equation 6**):

$$Y = \beta 0 + \beta 1 WP + \beta 2 TS - \beta 3 ETc \quad (6)$$

where:

- Y: Total yield (Mg ha^{-1})
- WP: Water productivity (kg m^{-3})
- TS: Traffic system factor
- ETc: Seasonal crop evapotranspiration (mm)
- β0: Intercept
- β1, β2, β3: Regression coefficients

Model performance was evaluated using the coefficient of determination (R^2), root mean square error (RMSE), and p-values. Because several hydrological variables were partially interrelated, regression outputs were interpreted cautiously to avoid overestimating the predictive independence of the variables.

2.8. Statistical analysis

Experimental data were analyzed using Statistical Analysis System software (Version 9.4, SAS Institute Inc., USA). Analysis of variance appropriate for split-plot arrangements within RCBD was performed to evaluate the effects of irrigation depletion level, traffic farming system, and their interaction on the measured variables. Treatment means were separated using the least significant difference test at the 0.05 probability level. Regression analyses were additionally conducted to quantify the relationships among seasonal crop ETc, irrigation depletion level, traffic management, yield, and water productivity. Residual behavior and model significance were evaluated during regression analysis to improve the reliability of statistical interpretation. Graphical analyses and figure preparation were performed using SigmaPlot software (Version 14.0, Systat Software Inc., USA).

3. Results and discussion

3.1. Soil physical responses to traffic farming systems

Traffic farming systems significantly influenced soil physical properties after harvest (Table 1). CTF consistently improved soil structural conditions compared with RTF. Soil bulk density under CTF decreased to 1.36 Mg m^{-3} compared with 1.54 Mg m^{-3} under RTF, whereas total porosity increased from 41.9% under RTF to 48.7% under CTF. Similarly, soil penetration resistance under CTF decreased by approximately 34.9% compared to RTF, indicating lower mechanical impedance in the cultivated root zone. In contrast, infiltration rate under CTF increased markedly and reached 19.4 mm h^{-1} compared with 11.6 mm h^{-1} under RTF. The changes in soil physical properties under CTF could be attributed to restricted entry of farm machinery into traffic lanes only, which reduced soil compaction in the root zone. The observed reductions in bulk density and penetration resistance suggest improved soil physical functioning and infiltration capacity under CTF. Such responses in soil physical properties under CTF practices have been consistently reported in previous studies.[6-10] Relative to RTF, CTF reduced bulk density by 11.7% and penetration resistance by 34.9%, but increased total porosity by 16.2% and infiltration rate by 67.2%.

Table 1. Soil physical indicators (0–30 cm depth) under RTF and CTF systems after harvest

Traffic farming system	Bulk density (Mg m^{-3})	Total porosity (%)	Penetration resistance (MPa)	Infiltration rate (mm h^{-1})
RTF	1.54 ± 0.04	41.90 ± 1.20	2.18 ± 0.11	11.60 ± 1.50
CTF	1.36 ± 0.03	48.70 ± 1.00	1.42 ± 0.09	19.40 ± 1.80
LSD (0.05)	0.08	2.10	0.24	3.20

Abbreviations: CTF: Controlled traffic farming; LSD: Least significant difference; RTF: Random traffic farming.

3.2. Seasonal crop water consumption

Seasonal irrigation water application and crop ETc were strongly affected by both irrigation depletion level and traffic farming system (Table 2). Across all depletion treatments, CTF consistently reduced seasonal crop water consumption relative to RTF. Under the 30% depletion treatment, ETc under RTF was 455 mm $season^{-1}$, whereas under CTF it was reduced to 350 mm $season^{-1}$. The same pattern was evident when analyzing ETc at 45% and 60% depletion rates, where the value decreased from 449 mm $season^{-1}$ to 360 mm $season^{-1}$ and from 445 mm $season^{-1}$ to 375 mm $season^{-1}$, respectively. With reduced seasonal water use under CTF, the need for irrigation decreased, as did the number of irrigation events (Table 2). Improved infiltration behavior and preservation of soil structural continuity under CTF likely reduced non-productive

doi: 10.36922/AJWEP026200145

evaporative losses and increased the proportion of irrigation water available for productive transpiration.[3,9,10]

3.3. Growth characteristics, yield, and water productivity

Analysis of variance demonstrated significant effects of irrigation depletion level, traffic farming system, and their interaction on plant height, branch number, yield, and water productivity (Table 3). The interaction effect confirmed that crop response to irrigation depletion depended substantially on traffic-management conditions.[6,9-12]

The highest vegetative growth and productivity were obtained under the combination of CTF and 45% depletion (Table 4). Under this treatment, plant height reached 276 cm, branch number reached 12 branches plant^{-1}, and yield increased to 28 Mg ha^{-1} with a corresponding water productivity of 0.95 kg m^{-3}. Conversely, the lowest growth and productivity values were recorded under RTF combined with 60% depletion, where plant height decreased to 132 cm, branch number per plant to 5, and yield to 13 Mg ha^{-1}. In view of the better results obtained with the 45% depletion rate coupled with traffic management, it is likely that preservation of soil structural integrity enhanced the ratio of water availability to aeration in the root zone. Increased soil wetness under this depletion rate could have led to a loss of non-productive water and reduced oxygen movement through the rhizosphere.[3,11] In contrast, severe depletion at 60% likely imposed prolonged water stress sufficient to suppress vegetative development and reproductive growth.[11,12]

The relative improvement achieved under CTF compared with RTF is summarized in Table 5. Controlled traffic management increased water productivity by 52.9–93.9% across depletion levels, while yield improvement ranged from 23.1 to 47.4%. The greatest improvement occurred under the 45% depletion treatment, indicating that moderate soil water depletion, combined with reduced traffic-induced compaction, optimized productive water use under sprinkler irrigation conditions.

3.4. Correlation and regression analysis

Correlation analysis demonstrated strong relationships between soil physical properties and pumpkin productivity (Table 6). Soil bulk density and soil penetration resistance were negatively correlated with both yield and water productivity, whereas total porosity and infiltration rate

Table 2. Applied irrigation water, irrigation frequency, rainfall, and seasonal crop water evapotranspiration of pumpkin under traffic farming systems, and available water depletion levels

Available water depletion	Applied irrigation water under CTF (mm)	Applied irrigation water under RTF (mm)	Number of irrigations under CTF	Number of irrigations under RTF	Rainfall (mm)	Seasonal water consumption under CTF (mm season^{-1})	Seasonal water consumption under RTF (mm season^{-1})
30%	285	390	27	38	65	350	455
45%	295	384	20	25	65	360	449
60%	310	380	17	20	65	375	445
Mean	297	385	21	28	65	362	450

Abbreviations: CTF: Controlled traffic farming; RTF: Random traffic farming.

Table 3. Final analysis of variance for split-plot experiment evaluating the effects of irrigation depletion levels and traffic farming systems on pumpkin growth, yield, and water productivity

Source of variation	df	Plant height	Branch number	Yield	Water productivity
Replication	2	ns	ns	ns	ns
Irrigation depletion level (I)	2	**	**	**	**
Traffic farming system (T)	1	**	**	**	**
I × T interaction	2	*	*	**	**
CV (%) Main plot	–	5.8	6.1	7.4	5.2
CV (%) Subplot	–	4.3	5.0	6.2	4.8

Notes: *$p < 0.05$; **$p < 0.01$; ns: not significant. Abbreviations: CV: Coefficient of variation; df: Degree of freedom.

were positively correlated with crop production. Bulk density showed the strongest negative correlation with water productivity (r = −0.84), while infiltration rate showed the strongest positive correlation (r = 0.83). These relationships suggest that improved soil physical conditions under controlled traffic may contribute to higher water-use efficiency.[3,6,9,10]

Regression analysis further confirmed significant relationships among seasonal crop ETc, irrigation depletion level, traffic farming system, and water productivity. The predictive model was expressed as **Equation 7**:

$$WP = 2.11 - 0.0031ETc + 0.012ID + 0.27TS \quad (7)$$

where water productivity decreased with increasing seasonal crop water consumption and increased under controlled traffic conditions and moderate depletion levels.

The regression model produced a coefficient of determination (R^2) of 0.91 and an RMSE of 0.06 kg m^{-3}, indicating a strong statistical association within the experimental dataset. Nevertheless, the regression relationships should be interpreted as integrated hydrological system responses because several evaluated variables were partially interdependent. Overall, the combined results indicate that restricting machinery traffic to permanent lanes substantially improved soil physical conditions, reduced seasonal water consumption, and

Table 4. Mean comparison of pumpkin growth, yield, and water productivity under irrigation depletion levels and traffic farming systems

Treatment	Plant height (cm)	Branch number ($plant^{-1}$)	Yield (Mg ha^{-1})	Water productivity (kg m^{-3})
RTF × 30% AW	178^{c}	8^{c}	16^{c}	0.41^{d}
RTF × 45% AW	192^{bc}	9^{bc}	19^{bc}	0.49^{c}
RTF × 60% AW	132^{d}	5^{d}	13^{d}	0.34^{e}
CTF × 30% AW	255^{ab}	11^{ab}	21^{b}	0.74^{b}
CTF × 45% AW	276^{a}	12^{a}	28^{a}	0.95^{a}
CTF × 60% AW	165^{cd}	7^{cd}	16^{c}	0.52^{c}
LSD (0.05)	10.0	0.76	4.55	0.087

Note: Means followed by different letters within the same column differ significantly according to the LSD test at $p < 0.05$
Abbreviations: AW: Available soil water; CTF: Controlled traffic farming; LSD: Least significant difference; RTF: Random traffic farming.

Table 5. Relative improvement under CTF compared to RTF

Available water depletion	Reduction in applied irrigation water under CTF (%)	Reduction in seasonal water consumption under CTF (%)	Increase in plant height under CTF (%)	Increase in branch number under CTF (%)	Increase in yield under CTF (%)	Increase in water productivity under CTF (%)
30%	26.9	23.1	43.3	37.5	31.3	80.5
45%	23.2	19.8	43.8	33.3	47.4	93.9
60%	18.4	15.7	25.0	40.0	23.1	52.9
Mean	22.8	19.5	37.4	36.9	33.9	75.8

Abbreviations: CTF: Controlled traffic farming; RTF: Random traffic farming.

Table 6. Correlation analysis between selected soil physical properties and pumpkin productivity (*n* = 6 treatment means)

Parameter	Yield (Mg ha^{-1})	Water productivity (kg m^{-3})
Bulk density	−0.81*	−0.84*
Total porosity	0.76*	0.79*
Penetration resistance	−0.73*	−0.77*
Infiltration rate	0.71*	0.83*

Note: *$p < 0.05$.

enhanced productive water use under semi-arid sprinkler irrigation conditions.[3,6,8-10]

4. Conclusion

The present study demonstrated that the interaction between irrigation scheduling and traffic farming system substantially influenced soil physical behavior, seasonal crop water consumption, yield formation, and water productivity of pumpkin cultivated under semi-arid sprinkler irrigation conditions. CTF consistently improved soil structural characteristics by reducing bulk density and penetration resistance while increasing total porosity and infiltration rate relative to RTF. These improvements were associated with lower seasonal crop ETc and greater productive water utilization. Among the evaluated irrigation treatments, the 45% depletion level produced the highest yield and water productivity, particularly when combined with CTF. Moderate depletion appeared to maintain a more favorable balance between soil water availability and root-zone aeration than either excessive irrigation or severe water deficit conditions. The combined reduction in traffic-induced compaction and optimization of irrigation scheduling, therefore, enhanced irrigation-use efficiency under sprinkler irrigation management. Correlation and regression analyses further confirmed that soil structural condition played a major role in regulating productive water use. Negative relationships between soil compaction indicators and crop productivity suggest that preserving soil pore continuity improves water transmission and root-zone access to stored moisture. Overall, the findings indicate that integrating controlled traffic management with moderate irrigation depletion represents a practical strategy for improving water productivity and sustaining pumpkin production under semi-arid irrigated agriculture.

The present investigation was conducted during a single growing season across a single soil texture and irrigation configuration in a semi-arid environment. Seasonal climatic variability, long-term soil structural responses, and differences among soil types were therefore not fully represented within the current experimental framework. In addition, direct measurements of root growth dynamics and continuous soil-water monitoring were unavailable during the study period. Consequently, some mechanistic interpretations regarding root-zone processes were inferred from observed soil physical responses and crop performance indicators.

Future investigations should evaluate the long-term effects of CTF across multiple soil textures, climatic conditions, and irrigation systems to assess the stability of soil structural improvement over time. Additional studies integrating continuous soil-moisture monitoring, root-system characterization, and advanced hydraulic measurements may further clarify the interaction between traffic management and root-zone water dynamics. Expanding the evaluation to other vegetable and field crops under semi-arid irrigation systems may also improve the applicability of controlled traffic management as a sustainable water-saving strategy in mechanized agriculture.

Based on the present findings, the integration of CTF with moderate irrigation depletion is recommended as an effective management strategy to improve productive water use in semi-arid sprinkler irrigation systems. Restricting machinery movement to permanent traffic lanes reduced soil compaction and improved infiltration behavior, thereby enhancing irrigation efficiency and crop productivity relative to conventional RTF.

Among the evaluated irrigation regimes, irrigation scheduling based on 45% depletion of available soil water produced the most favorable balance between crop-water availability and root-zone aeration. Under the present experimental conditions, this treatment achieved the highest pumpkin yield and water productivity while simultaneously reducing seasonal irrigation demand.

The adoption of controlled traffic systems may therefore contribute to:

- improving soil structural stability under repeated machinery operations,
- reducing non-productive water losses,
- increasing infiltration and root-zone water accessibility,
- improving irrigation-use efficiency under water-limited conditions,
- sustaining crop productivity in semi-arid irrigated agriculture.

In practical field implementation, it is recommended to keep permanent machinery traffic lanes and to avoid unnecessary wheel movement within cultivated areas, especially under sprinkler irrigation systems, where repeated wetting cycles may accelerate soil structural degradation. Moderate irrigation depletion scheduling should also be considered as an alternative to excessive irrigation practices that may increase evaporation losses and reduce root-zone aeration. The combined application of traffic-controlled soil management and optimized irrigation scheduling may provide a feasible approach for improving water conservation and agricultural sustainability in mechanized farming systems under semi-arid environmental conditions.

Acknowledgments

The authors gratefully acknowledge the Scientific Research Commission, Baghdad, Iraq, for providing all analyses and tools that supported this work.

Funding

None.

Conflict of interest

The authors declare no financial or non-financial competing interests related to this manuscript.

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Availability of data

All data generated or analyzed during this study are available from the corresponding author upon reasonable request.

References

1. Al-Gburi HF, Mouhamad RS, Al-Naji AJ, *et al*. Evaluation of trace elements in Iraqi soils using multivariate statistical analysis and pollution indices. *Discov Environ*. 2026;4(1):69.

   doi: 10.1007/s44274-026-00587-6

2. Al-Azzawi AH, Al-Delfi JM, Mouhamad RS. Effect of tillage methods on incorporating nitrogen fertilizer in soil and on CO2 emission. *AIP Conf Proc*. 2024;3229:050012.

   doi: 10.1063/5.0235942

3. Rabot E, Wiesmeier M, Schlüter S, Vogel HJ. Soil structure as an indicator of soil functions: A review. *Geoderma*. 2018;314:122-137.

   doi: 10.1016/j.geoderma.2017.11.009

4. Antille DL, Peets S, Galambošová J, *et al*. Review: Soil compaction and controlled traffic farming in arable and grass cropping systems. *Agron Res*. 2019;17(3):653-682.

   doi: 10.15159/AR.19.133

5. Nawaz MF, Bourrié G, Trolard F. Soil compaction impact and modelling: A review. *Agron Sustain Dev*. 2013;33(2):291-309.

   doi: 10.1007/s13593-011-0071-8

6. McPhee JE, Aird PL, Hardie MA, Corkrey SR. The effect of controlled traffic on soil physical properties and tillage requirements for vegetable production. *Soil Tillage Res*. 2015;149:33-45.

   doi: 10.1016/j.still.2014.12.018

7. Colombi T, Braun S, Keller T, Walter A. Artificial macropores attract crop roots and enhance plant productivity on compacted soils. *Sci Total Environ*. 2017;574:1283-1293.

   doi: 10.1016/j.scitotenv.2016.07.194

8. Keller T, Colombi T, Ruiz S, *et al*. Long-term soil structure observatory for monitoring post-compaction evolution of soil structure. *Vadose Zone J*. 2017;16(4):1-16.

   doi: 10.2136/vzj2016.11.0118

9. Etana A, Holm L, Rydberg T, Keller T. Soil and crop responses to controlled traffic farming in reduced tillage and no-till: Some experiences from field experiments and on-farm studies in Sweden. *Acta Agric Scand B Soil Plant Sci*. 2020;70(4):333-340.

   doi: 10.1080/09064710.2020.1728372

10. Tullberg JN, Yule DF, McGarry D. Controlled traffic farming — from research to adoption in Australia. *Soil Tillage Res*. 2007;97(2):272-281.

    doi: 10.1016/j.still.2007.09.007

11. Costa JM, Ortuño MF, Chaves MM. Deficit irrigation as a strategy to save water: Physiology and potential application to horticulture. *J Integr Plant Biol*. 2007;49(10):1421-1434.

    doi: 10.1111/j.1672-9072.2007.00556.x

12. Fereres E, Soriano MA. Deficit irrigation for reducing agricultural water use. *J Exp Bot*. 2007;58(2):147-159.

    doi: 10.1093/jxb/erl165

13. Al-Bajalan KHM, Kka NME. Impact of water deficit on growth and seed quality of Cucurbita pepo L. under separate selenium and calcium applications. *Passer J Basic Appl Sci*. 2025;7(2):574-585.

    doi: 10.24271/psr.2025.515533.2063

14. Gee GW, Or D. Particle-size analysis. In: Dane JH, Topp GC, eds. *Methods of Soil Analysis. Part 4: Physical Methods*. Madison, WI: Soil Science Society of America; 2002:255-293.

15. Soil Survey Staff. *Soil Survey Manual*. USDA Handbook 18. Washington, DC: United States Department of Agriculture, Natural Resources Conservation Service; 2017.

16. Sparks DL, Page AL, Helmke PA, *et al*, eds. *Methods of Soil Analysis. Part 3: Chemical Methods*. Madison, WI: Soil Science Society of America; 1996.

17. Burt R, ed. *Soil Survey Laboratory Methods Manual*. Soil Survey Investigations Report No. 42, Version 5.0. Lincoln,

NE: USDA-NRCS; 2014.

18. Olsen SR, Sommers LE. Phosphorus. In: Page AL, Miller RH, Keeney DR, eds. *Methods of Soil Analysis. Part 2: Chemical and Microbiological Properties*. 2nd ed. Madison, WI: American Society of Agronomy and Soil Science Society of America; 1982:403-430.
19. Allen RG, Pereira LS, Raes D, Smith M. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*. FAO Irrigation and Drainage Paper 56. Rome: Food and Agriculture Organization of the United Nations; 1998.